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THE SESIA-LANZO ZONE, A SLICE OF CONTINENTAL CRUST WITH ALPINE HIGH PRESSURE-LOW TEMPERATURE ASSEMBLAGES IN THE WESTERN ITALIAN ALPS

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The present paper summarizes the literature on the Sesia-Lanzo Zone and Dent Blanche Nappe produced till 1975; it evolved from Internal Report 1 (1974), a collection of factual data previously dispersed in a literature spanning over one hundred years. We have tried to give a unified presentation of the relevant

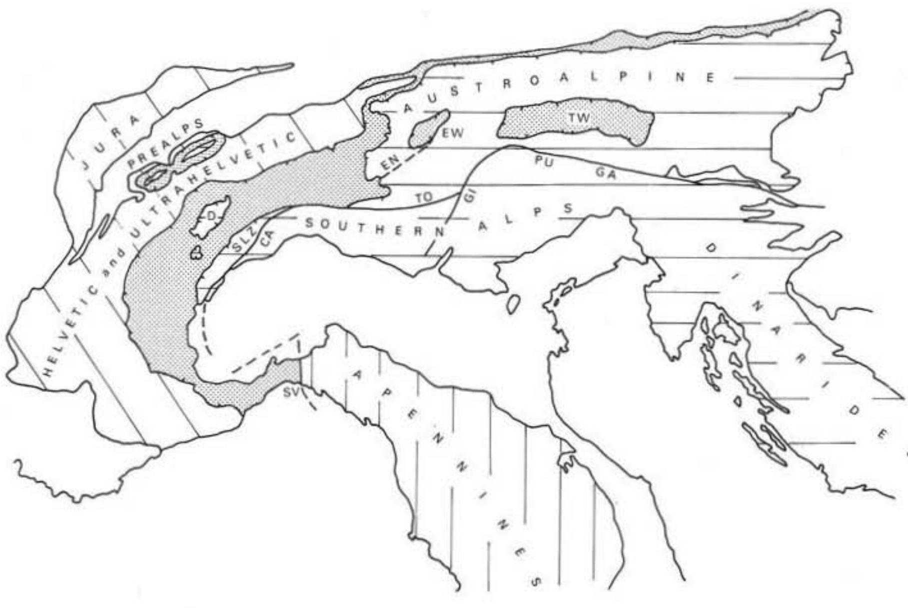

Fig. 1. — *Tectonic sketch map of the Alps.* Stippled: Pennine Nappes; EW = Engadine Window; TW = Tauern Window. CA = Canavese Line; TO = Tonale Line; GI = Giudicaria Line; PU = Pusteria Line; GA = Gailtal Line; SV = Sestri-Voltaggio Line; EN = Engadine Line.

literature; tectonic models of the Sesia-Lanzo Zone metamorphism presented in the last five years are also discussed. A preprint version of this paper (Internal Report 2, 1975) has been distributed to the participants to the Genova meeting (Sept. 24-29, 1976) of the Società Italiana di Mineralogia e Petrologia.

1. Introduction: the Sesia-Lanzo Zone and the surrounding units

The Sesia-Lanzo Zone is one of the main structural units of the internal Western Alps ([1]). The Sesia-Lanzo Zone, in plan view, is an elongated body (25 × 90 Km), trending NE from the river Stura di Lanzo, near Turin, to the Ossola valley, where it narrows, and finally terminates near Locarno (fig. 1 and 2). It comprises polymetamorphic and some monometamorphic rocks and is part of the Austroalpine continental crust. It is characterized mainly by widespread jadeitic pyroxene-garnet-quartz assemblages in paraschists and metagranitoids (Dal Piaz et al., 1972, 1973; Compagnoni and Maffeo, 1973; Hunziker, 1974).

The internal side of the Sesia-Lanzo Zone is marked by the Canavese tectonic line which divides it from the narrow Canavese Zone and from the Ivrea Zone. The Canavese Line consists of a set of faults which may have been active during pre-Alpine times, and certainly during Upper Cretaceous (see the internal plane of the early-Alpine subduction zone, Dal Piaz et al., 1972). It is interpreted as the suture of the narrow Mesozoic intracontinental Canavese basin. After the beginning of the Oligocene period, a new Canavese line formed under conditions involving no crustal shortening or folding. This sharply divides the rising Alpine belt and Lepontine thermal dome from the Southern Alps.

The Ivrea Zone or Zona Dioritico-Kinzigitica Ivrea-Verbano (Franchi, 1905), comprises rocks of deep continental crustal origin that grade eastward into the Strona-Ceneri Zone. Together, they represent the crystalline basement of the Southern Alps (Insubric plate). This basement consists of high-grade metamorphic rocks intruded by Permian granites (e. g. Baveno Granite) and overlain by Permian rhyolites and Mesozoic sediments. The ages of biotites from the Ivrea basement range from 240 to 140 m.y. and are interpreted as cooling ages of the Hercynian metamorphism, which overprints an earlier Ordovician-Silurian metamorphism (Graeser and Hunziker, 1968; Hunziker, 1974).

The southern part of the Sesia-Lanzo Zone is flanked to the southeast by the Lanzo Lherzolite whose contact is marked by partly recrystallized mylonites. The Lanzo massif is considered to be a fragment of subcontinental mantle of the Southern Alps (Nicolas, 1974).

The external side of the Sesia-Lanzo Zone overrides the Piemonte Zone (or Piemonte nappe), also known as the Mesozoic complex of *schistes lustrés* with metaophiolites (« *Calcescisti con Pietre Verdi* » of the Italian literature). The Piemonte nappe is composite, being built up of several sheets and is overthrust onto the Penninic continental crust which forms part of Briançonnais Zone and a nappe comprising the Monte Rosa, Gran Paradiso, Dora Maira and Valosio units.

The Piemonte Zone consists of two composite tectonic units, which are distinguished on the basis of their lithologies, paleogeographic position, metamorphic

([1]) The terms internal and external are referred to the concave and convex side of the Alpine arcuate belt.

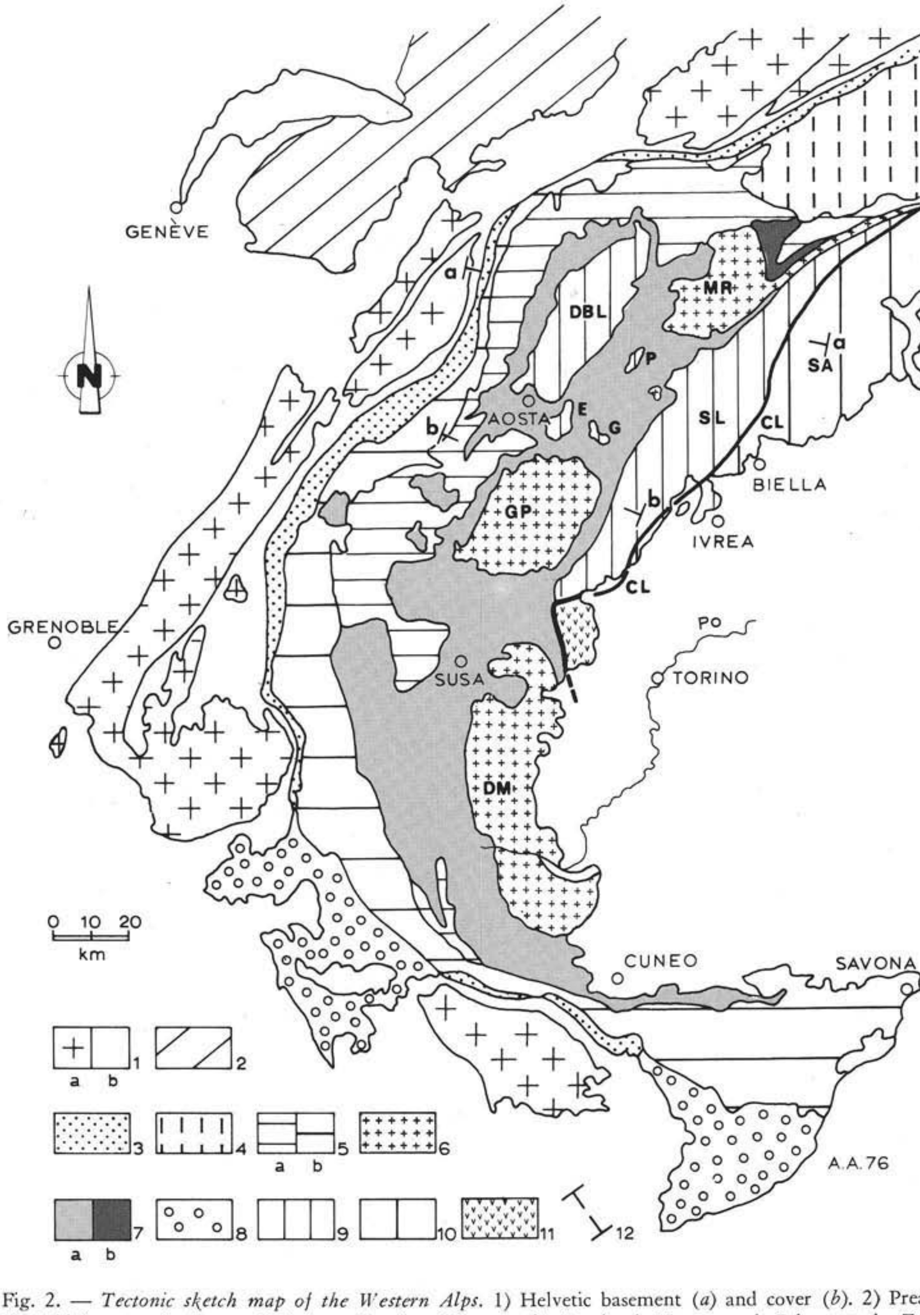

Fig. 2. — *Tectonic sketch map of the Western Alps.* 1) Helvetic basement (*a*) and cover (*b*). 2) Prealps. 3) Subbrianҫonnais Zone. 4) Lower Pennine Nappes. 5) Bernhard Nappe and Brianҫonnais Zone: *a*: pre-Carboniferous basement and internal covers: *b*: late-Paleozoic sequences (+ basement in Liguria?) and external covers. 6) Monte Rosa (MR)-Gran Paradiso (GP)-Dora Maira (DM)-Nappe. 7) *a*: Piemonte Zone; *b*: Antrona metaophiolite syncline. 8) Helminthoid Flysch. 9) Austroalpine units; SL = Sesia-Lanzo Zone; DBL = Dent Blanche- and Mont Mary Nappe; P = Pillonet Klippe; G = Glacier-Rafray Klippe; M = Monte Emilius Klippe. 10) Southern Alps (Ivrea Zone, Strona-Ceneri Zone). 11) Lanzo Lherzolite. 12) Trace of cross sections shown in Fig. 4. CL = Canavese Line.

association and tectonic evolution. Both units originated during Jurassic time in the oceanic basin between the European and the Insubric plate (fig. 3).

The units of external provenance (Western Piemonte Zone or Combin Zone s.l.) consist of rare Permian, Triassic sequences, Liassic schistose marbles and a heterogeneous complex of ophiolite-bearing calcschists. A unique feature of the Combin Zone s.l. is the regularly repeated interbedding of calcschists and prasinites (2). Rare wedges and/or olistolithes of metagabbros and serpentinites are also present in the Combin Zone s.l.. Metacherts (metaradiolarites) are frequently

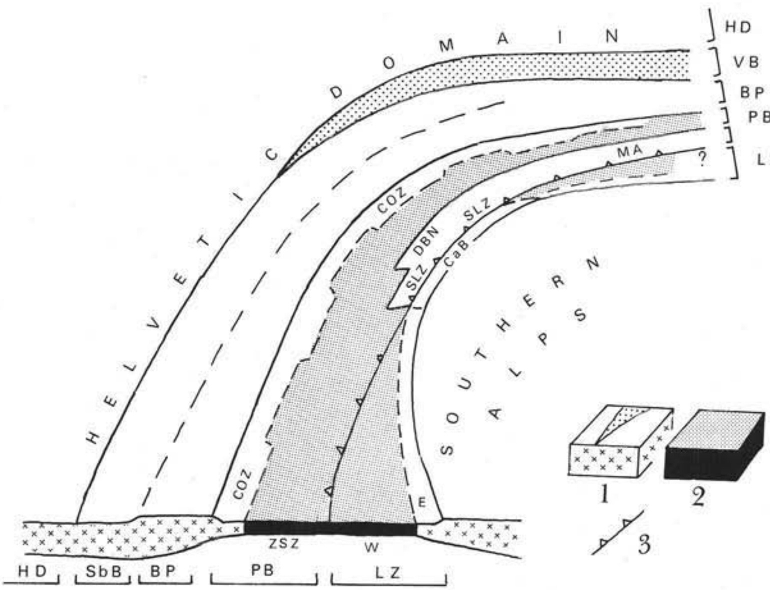

Fig. 3. — *Hypothetical paleogeography of the Central and Western Alps during late Jurassic.* 1) Continental crust of the European (HD, SbB, BP, VB and COZ) and Insubric Plate (DBN, MA, SLZ, CaB, E, Southern Alps). 2) Oceanic crust. 3) Internal boundary of the early-Alpine metamorphism. SbB = Subbriançonnais basin. VB = Valais basin (probably non-oceanic). BP = Briançonnais platform. PB = Piemonte basin; COZ = Combin Zone, non-oceanic basin; ZSZ = Zermatt-Saas Zone, oceanic basin. LZ = Ligurian Zone; W = Western Ligurian Zone (oceanic); E = Eastern Ligurian Zone (non-oceanic); CaB = Canavese basin. SLZ = Sesia-Lanzo Zone; DBN = Dent Blanche Nappe; MA = = Margna Nappe.

associated with the prasinites; sometimes they are manganiferous (braunite, piemontite, spessartite are the most common Mn-minerals). In the prasinites and, sometimes, in the related metasediments there are minor concentrations of layered Cu-Fe sulphides.

The Combin sequences have obvious oceanic affinities but do not constitute

(2) In the French and Italian literature the term « prasinite » (see NOVARESE, 1895, for a discussion) corresponds to chlorite-actinolite-epidote-albite metabasites (sometimes quartz-phengite-carbonate-bearing) derived from submarine basaltic flows and tuffs.

oceanic crust, as they have been deposited over the thinned continental crust of the Penninic margin (European plate) which was the basement of the western side of the Piemonte basin.

The units of internal provenance (Eastern Piemonte Zone or Zermatt-Saas Zone s.l.) show, on the contrary, characteristics of an oceanic crust, although the original basin was probably narrow (Red Sea Type?). They consist mostly of metaophiolites, with large slabs of mantle ultramafics (up to 2-3 Km thick), gabbros (sometimes layered with cumulus textures) and submarine basalts. The emplacement of gabbros and basalts is probably Middle (?) to Upper Jurassic. The Mesozoic sediments consist of pure and impure limestones, graywackes and cherts; the latter are sometimes Mn-rich. They overlie the basaltic flows and may be intercalated with them. Cu-Fe sulphide ores may also occur.

The whole Piemonte basin has been completely tectonized during the Alpine collision between the European and the Insubric plates. It has been subducted and then partly thrust towards the external side of the belt as tectonic slabs (composite Piemonte nappe). Thus the proposed paleogeographic reconstruction (fig. 3) can be regarded only as an approximation. It was proposed by Bortolami and Dal Piaz (1970) and improved later by Elter (1971, 1972), Dal Piaz et al. (1972), Sturani (1973), Dal Piaz (1974 a), Hunziker (1974).

West of the Sesia-Lanzo Zone the Piemonte nappe (or Piemonte Zone) is overlain by the Dent Blanche Nappe, which is subdivided into several units (or Klippen): Dent Blanche s.s., Mt. Mary and Mt. Emilius on the external side; Pillonet and Glacier-Rafray on the internal side (Fig. 4 and 5).

The Sesia-Lanzo Zone and the Dent Blanche Nappe are fragments of a big, composite tectonic unit, ascribed to the Penninic domain by Argand (1906, 1911, 1934, nappe VI). However it is now considered to be of Austroalpine origin (NW margin of the Insubric plate) because of its position with respect to the Tethyan oceanic basin, the complete lack of ophiolites within the Canavese basin and the Austroalpine affinity of its Mesozoic cover (Mt. Dolin and Roisan Zone).

According to Argand the Sesia-Lanzo is the autochtonous root zone of the Dent Blanche Nappe. However more recent studies (Bortolami and Dal Piaz, 1970 and Dal Piaz et al., 1972) showed that the Sesia-Lanzo Zone must be considered part of the Austroalpine nappe.

The Austroalpine and Penninic units of the Western Alps underwent two cycles of Alpine metamorphism. The first one, called the early-Alpine event (90-70 m.y.), occurred under high pressure-low temperature conditions and developed during the early-Alpine subduction. It reached the highest pressure conditions (Jd-Qz assemblages) on the internal side. The second metamorphic event (Lepontine event in the Ossola-Tessin area) developed after the thrusting phase and reached its thermal peak at about 38 m.y.. This event developed a regional overprint ranging from greenschist facies (Western Alps) to amphibolite facies (Ossola-Tessin region). In the Piemonte composite nappe, the Zermatt-Saas Zone s.l. is characterized by regional

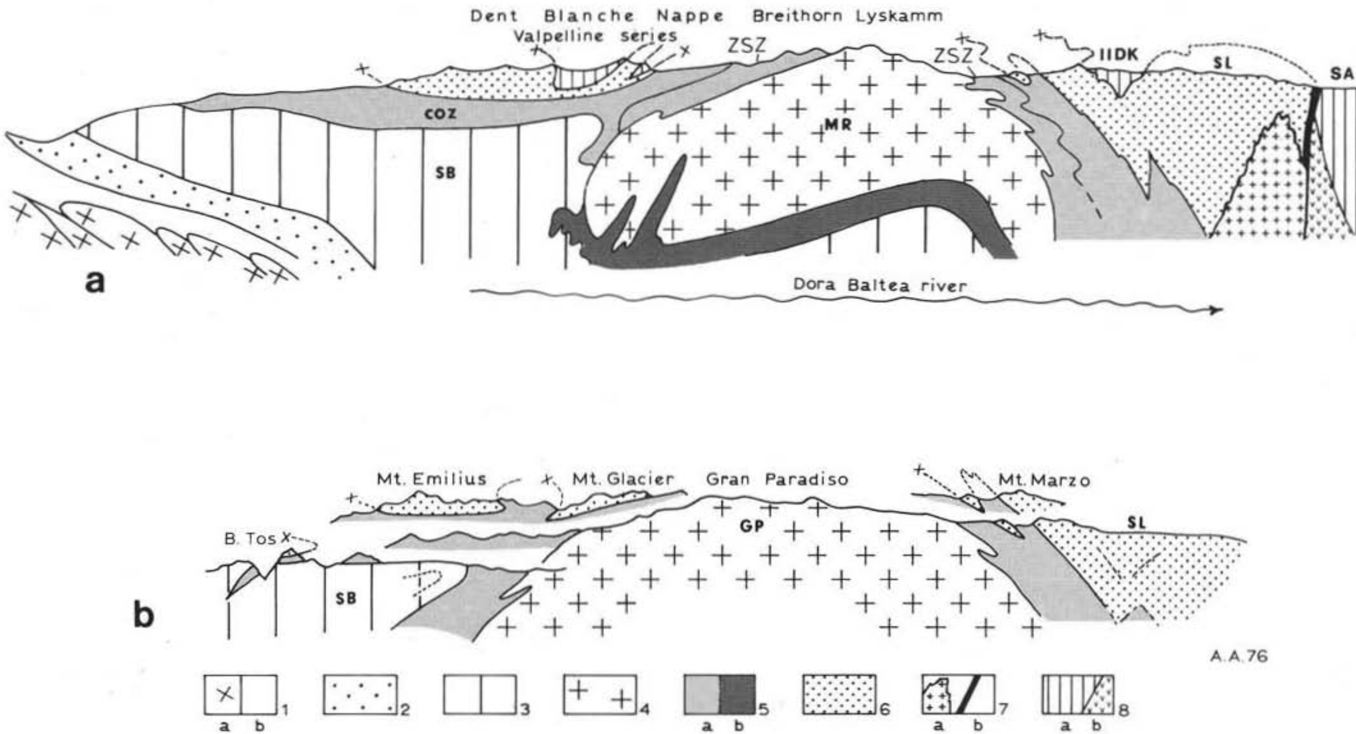

Fig. 4. — *Cross sections through the Northwestern Alps*; for location see Fig. 2. 1) Helvetic basement (*a*) and cover (*b*). 2) Subbriançonnais Zone. 3) Bernhard Nappe and Briançonnais Zone. 4) Monte Rosa (MR)-Gran Paradiso (GP)-Nappe. 5) Piemonte Zone (*a*), Antrona Syncline (*b*). 6) Lower Element of Austroalpine (Sesia-Lanzo Zone (SL), Monte Emilius Klippe, Glacier-Rafray Klippe, Arolla Series). 7) Post-metamorphic magmatism; *a*: syenite-monzonite stocks of Biella and Traversella; b: trachyandesite volcanics. 8*a*) Southern Alps (SA) and Upper Element of Austroalpine (II Zona Diorito-kinzigitica (IIDK), Valpelline Series). 8*b*) Tectonic wedges of subcontinental upper mantle.

occurrence of early-Alpine assemblages. These range from eclogitic (internal side) to blueschist (external side) and are more or less overprinted by the Lepontine greenschist-facies metamorphism. The Combin Zone s.l. bears a 38 m.y. greenschist-facies imprint and does not seem to have suffered the high pressure-low temperature conditions of the early-Alpine phase.

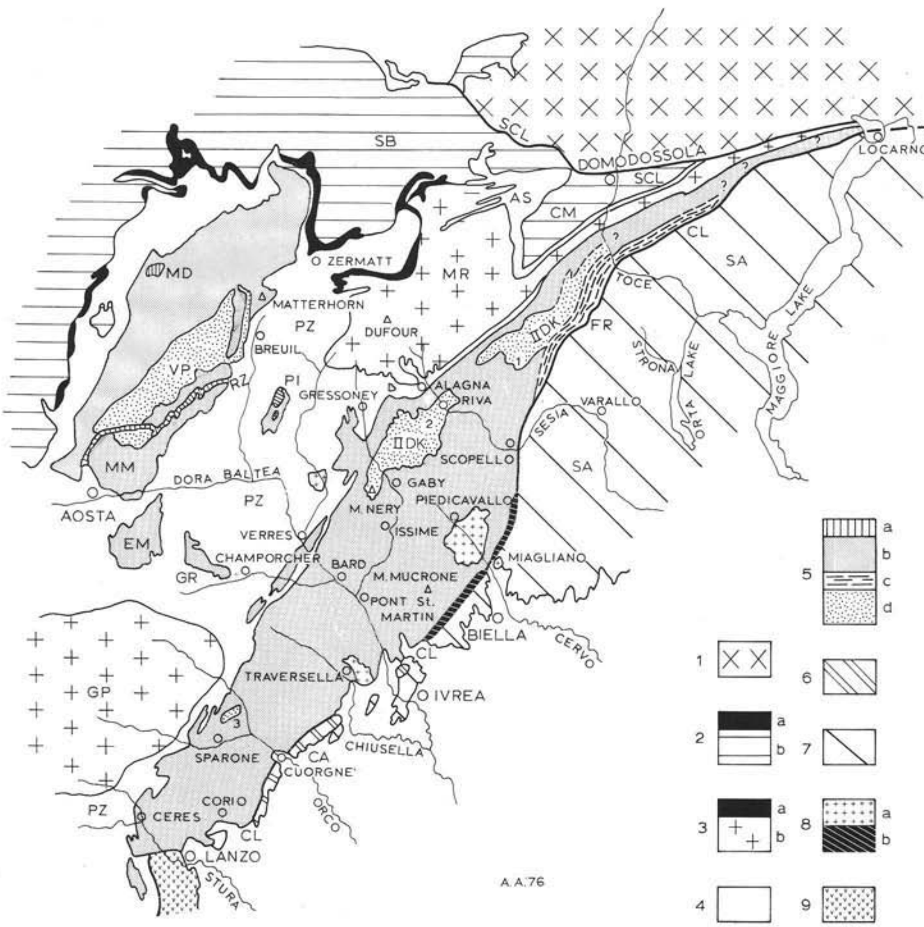

Fig. 5. — *Tectonic sketch map of the internal Northwestern Alps.* 1) Lower Pennine Nappes. 2) Bernhard Nappe (SB) and Camughera-Moncucco Unit (CM); *a*: sedimentary cover; *b*: basement. 3) Monte Rosa (MR) - Gran Paradiso (GP) Nappe; *a*: sedimentary cover; *b*: basement. 4) Piemonte Zone (PZ) and Antrona Syncline (AS). 5) Dent Blanche Nappe and Sesia-Lanzo Zone; *a*: sedimentary cover (Roisan Zone (RZ) and Mont Dolin (MD)); *b*: Lower Element (MM = Mont Mary Klippe; EM = Monte Emilius Klippe; GR = Glacier-Rafray Klippe; PI = Pillonet Klippe); *c*: Fobello-Rimella Schists (FR); *d*: Upper Element; VP = Valpelline Series; II DK = II Zona Diorito-kinzigitica (1: II Zona Diorito-kinzigitica s.s.; 2: Val Vogna-Valle di Gressoney Klippe; 3: Vasaro Klippe). 6) Canavese Zone (CA). 7) Southern Alps (SA). 8) Biella and Traversella stocks (*a*), trachyandesite volcanics (*b*). 9) Lanzo Lherzolite. SCL = Sempione - Centovalli Line; CL = Canavese Line.

Additional references — An Englis review of the paleogeography and structure of the Western Alps, with extensive bibliography, can be found in DEBELMAS and LEMOINE (1970), TRÜMPY (1960, 1973) and G. V. DAL PIAZ et al. (1975). For a summary on the metamorphism the non-Alpine reader is referred to ERNST (1973 a) and to the special issue of the Schweizerische Mineralogische und Petrographische Mitteilungen: « Alpine Metamorphose in den Alpen » (65/2, 1974). For the Ivrea Zone, in addition in the special issue « Symposium Zone Ivrea-Verbano » (Schweiz. Min. Petr. Mitt., 40/1, 1968), see BORIANI and SACCHI (1973), and MEHNERT (1975).

2. Older concepts on the Sesia-Lanzo Zone

The first valuable contributions to the understanding of the Sesia-Lanzo Zone and the Dent Blanche Nappe are by GERLACH (1869, 1871) and GIORDANO (1869).

At the end of the last century, FRANCHI, MATTIROLO, NOVARESE, STELLA and ZACCAGNA began to map the Italian Western Alps on the 1:25.000 scale, for the Italian Geological Survey: 30 years fieldwork produced twenty 1:100.000 sheets [3] and a 1:400.000 geological map of the Western Alps (R. Ufficio Geologico, 1908).

2.1. *Sesia-Lanzo Zone*

FRANCHI, MATTIROLO, NOVARESE and STELLA divided the Sesia-Lanzo Zone into three main lithological complexes (« Gneiss Minuti », « Micascisti eclogitici », « II Zona Diorito-kinzigitica ») and a marginal shear belt [4]. The latter comprises the Fobello-Rimella schists and occurs on the internal side at the north end of the zone.

The northeasternmost part of the Sesia-Lanzo Zone, the Ossola region, was mapped using a different subdivision (STELLA) and will be dealt with separately because of its different lithology and metamorphism.

a) « *Gneiss Minuti* » *Complex*

The term « Gneiss Minuti » (= fine-grained gneisses) introduced by GASTALDI (1871, 1874), represents a sequence of albite-white mica gneisses and schists. They are generally fine-grained, but locally have a porphyroclastic texture (K-feldspar relics). The « Gneiss Minuti » outcrop mostly along the entire external side of the Sesia-Lanzo Zone; the complex contains in its central and northern part several wide areas of metagranitoids (*Sesia Gneisses*). FRANCHI mapped the metagranitoids in several places and also described massive types (1905, 1911), very slightly transformed, with relics of K-feldspar and magmatic amphibole.

b) « *Micascisti Eclogitici* » *Complex*

The « Micascisti Eclogitici » (eclogitic micaschists) were defined by STELLA (1894) and outcrop in the internal Sesia-Lanzo Zone, from Lanzo to the Sesia Valley.

This complex contains micaschists with jadeitic pyroxene-garnet ± glaucophane (of the colourless variety known as gastaldite) ± chloritoid, with intercalated

(3) The Sesia-Lanzo Zone is represented on the sheets Domodossola (15), Monte Rosa (29), Varallo (30), Gran Paradiso (41), Ivrea (42), Susa (55) and Torino (56) of the 1:100,000 Geological Map of Italy. The Dent Blanche Nappe is represented on the sheets Aosta (28), Monte Rosa (29), Gran Paradiso (41) and Ivrea (42).

(4) On the 1:100,000 sheets, however, a more simple division was used, and the first two complexes were combined; however local details were mapped such as the granitoids, mafic rocks, marbles and other units.

eclogites, glaucophanites and marbles (5).

FRANCHI (1901, 1902 c) described the metamorphic evolution of the eclogitic micaschists (*Na-pyroxenes → glaucophane → blue green- and green-amphiboles*) of the Sesia-Lanzo Zone and indicated the rare occurrence of kyanite.

c) « II Zona Dioritico-Kinzigitica »

The name was given because of the close lithological similarity with the Ivrea-Zone or (first) « Zona Diorito-kinzigitica ». ARTINI and MELZI (1900) and NOVARESE (1929, 1931), stressed the intimate association of « kinzigites » (6) with « diorites » and marbles in the area between the Strona and Gressoney Valleys, and in the Orco Valley. STELLA (Varallo sheet) showed the occurrence of similar rocks in the Ossola Valley.

The Italian geologists thought that the three complexes were interfingering within a single unit, the Sesia-Lanzo Zone. Their data and this hypothesis were largely used by ARGAND in interpreting the Sesia-Lanzo Zone as root-zone of the entire Dent Blanche Nappe. Ultimately, NOVARESE (1929) expressed the opinion that the « II Zona Diorito-Kinzigitica » and the Mt. Emilius Klippe were equivalent lithologically, except for the eclogitic metamorphism.

After a gap of about twenty years the study of the Sesia-Lanzo Zone was resumed by MICHEL (1953) who extensively applied the metasomatic theories of JUNG and ROQUES to the Sesia-Lanzo Zone and Gran Paradiso massif; the presence of glaucophane in the eclogitic micaschists and of albite in the « Gneiss Minuti » was ascribed to a large scale late-Alpine metasomatism.

This interpretation was refuted by BIANCHI and GB. DAL PIAZ (1959, 1963), who gave the first modern petrographical, chemical and mineralogical description of some sectors of the Eclogitic Micaschist Complex. Particular attention was paid to the metamorphic evolution of the high pressure-low temperature assemblages. BIANCHI et al. (1965) described in the glaucophanite masses of Corio and Monastero (near Lanzo) primary magmatic assemblages (hornblende, clinopyroxene and saussuritic plagioclase) altered to high-pressure metamorphic minerals and later retrograded to greenschist-facies assemblages.

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(5) FRANCHI, NOVARESE and STELLA delineated in the internal part of the Western Alps a wide zone of « eclogite » facies rocks extending from Liguria to the Sesia Valley. It consists not only of eclogitic micaschists in the Sesia-Lanzo Zone and in the Dent Blanche Nappe (Mt. Emilius), but also of metaophiolites of the Piemonte Zone and of eclogitic boudins in the Penninic continental crust (Monte Rosa and Dora Maira massifs). It must be pointed out that FRANCHI (1897, 1902) recognized also the first occurrence of lawsonite-glaucophane assemblages in the Western Alps, suggesting that the ophiolitic eclogites and the prasinites originated from rocks of basaltic composition. Analogous transformations were described in the eclogitic ophiolites by GB. DAL PIAZ (1928) and by CORNELIUS (1935). These early findings seem to have been forgotten by subsequent workers.

(6) The term « kinzigite » is extensively used in the Alpine literature for sillimanite-garnet-biotite gneisses of the Ivrea Zone and the II Zona Diorito-Kinzigitica. It will be here used as a unit name for the high-grade paragneisses with interbedded marbles and amphibolites. These amphibolites correspond to the « diorites » of the older literature.

New chemical and mineralogical data for the Sesia-Lanzo rocks were also provided by CALLEGARI and VITERBO (1966); OGNIBEN (1968); VITERBO BASSANI and BLACKBURN (1968); FIORENTINI POTENZA and MORELLI (1968); FIORENTINI POTENZA (1969 b); EDGAR et al. (1969).

d) Fobello-Rimella Schists

The Fobello-Rimella Schists (GERLACH, 1869) are retrograded and strongly sheared rocks occurring all along the Canavese Line, on the internal margin of the Sesia-Lanzo Zone, between the Sesia and Strona Valleys (fig. 5). They merge on one side into either « Gneiss Minuti » or « II Zona Diorito-Kinzigitica », and on the other side into rocks of the Ivrea Zone (PORADA, 1967).

e) Ossola Region

This part of the Sesia-Lanzo Zone was mapped by STELLA (Varallo sheet). It shows peculiar lithological and metamorphic features. Eclogitic assemblages are completely lacking in the banded gneisses, kinzigites and metagranitoids. The Sesia-Lanzo Zone on the eastern side of the Ossola Valley has been mapped in detail by REINHARDT (1966) who described high-temperature pre-Alpine metamorphic rocks with Alpine overprinting ranging from greenschist- to amphibolite facies.

Additional references — BAGGIO and FRIZ (1968); BERTOLANI (1964 a and b); FRANCHI (1895, 1896, 1900, 1903, 1905, 1907, 1908, 1911); HERMANN (1938); NOVARESE (1894, 1895, 1901, 1903, 1905 a, 1905 b); STELLA (1894, 1903); VITERBO (1961).

2.2. *Dent Blanche Nappe*

The first detailed description of the lithologies of the Dent Blanche Nappe was given by ARGAND (1908, 1909, 1911, 1934). He distinguished two main formations: the *Arolla Series* and the *Valpelline Series*. The former corresponds to the Arolla Gneisses of Gerlach (1869) and consists of metagranitoids and less common paraschists. The latter (« Valpelline Gesteine » of GERLACH) consists of paragneisses, marbles and metabasic rocks, with granulite- to amphibolite facies assemblages which were interpreted by ARGAND as a thermal product of the Arolla granite. The geological correspondence between the Valpelline Series, the « II Zona Diorito-kinzigitica » and the Ivrea Zone, was repeatedly stressed by NOVARESE (1929, 1931).

Eclogitic micaschists were found in the Mt. Emilius Klippe (NOVARESE, 1904, 1931) and in the Glacier-Rafray Klippe (ARGAND, 1911; DAL PIAZ and NERVO, 1971).

DIEHL, MASSON and STUTZ (1952) mapped in detail the southern part of the Dent Blanche and Mt. Mary Klippen. They defined the chemistry and the mineralogy of the Arolla metagranitoids. Well preserved high-grade assemblages of pre-Alpine age were found in the Valpelline Series.

The large bodies of olivine-bearing gabbros occurring as tectonic intercalations in the Arolla Series of Matterhorn and Mt. Collon were described by BRUNN (1892, 1894, 1899), BARTHOLMÈS (1920) and ARGAND (1908, 1934).

On top of the Arolla Series are some small scattered outcrops of calcareous and detrital Mesozoic sequences (Mt. Dolin Series and Roisan Zone), considered to be relics of the original Austroalpine sedimentary cover.

In ARGAND's synthesis the Dent Blanche Nappe corresponds to the overturned limb of a big recumbent fold, the whole Sesia-Lanzo Zone being its root-zone. On the contrary, SCHMIDT (1906) was convinced that the Dent Blanche Nappe, as a whole, originated from the Ivrea Zone. According to ARGAND the calcschists of the Piemonte Zone are in normal contact with the Arolla Series, which, in turn is in normal contact with the Valpelline Series.

DIEHL, MASSON and STUTZ, however, considered the Arolla and the Valpelline Series as two independent sheets and denied the existence of ARGAND's recumbent fold. They postulated a sliding tectonic style (« *Gleitbretter Tektonik* »), overprinted by several folding phases.

Additional references — AMSTUTZ (1954, 1962); ARGAND (1906, 1908); ELTER (1960); GERLACH (1871); GIORDANO (1869); HAGEN (1948); LUGEON and ARGAND (1905); MASSON (1938); NOVARESE (1901, 1903, 1913); STUTZ (1940); STUTZ and MASSON (1938); WEIDMANN and ZANINETTI (1974).

2.3. *Post-metamorphic Alpine Magmatism*

Stocks and dykes of igneous rocks intrude the Sesia-Lanzo metamorphic rocks. The metamorphic rocks are in turn overlain by volcanics, now only locally preserved.

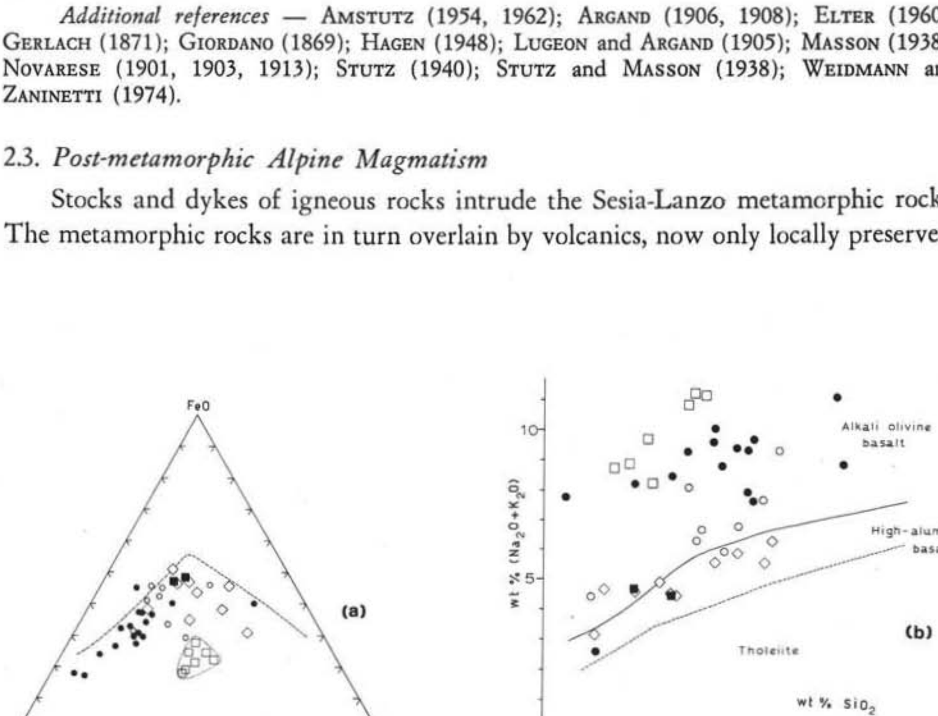

Fig. 6. — *Chemical variation in the Oligocene igneous rocks of the Western Alps. a)* FMA plot; total iron plotted as FeO; dashed line: Hawaii alkaline trend. *b)* Alkali-silica plot; the boundaries between the tholeiite series, the high-alumina series and the alkali olivine-basalt series are after KUNO (1966). Solid dots: Biella stock; open dots: Traversella stock; diamonds: trachyandesite and basalt dikes; open squares: lamprophyre dikes; solid squares: trachyandesite flows.
Data from: NOVARESE (1943, with earlier references); DE MARCO (1958); PEYRONEL PAGLIANI (1961); BIANCHI and GB. DAL PIAZ (1963); DAL PIAZ et al. (1973); DAL PIAZ, unpub. (dikes from Valle Artogna and Becca Torché); BRUNO, unpub. (Traversella stock and dikes from Valchiusella).
(Traversella stock and dikes from Valchiusella).

These rocks were first described by GASTALDI (1871, 1874) and partially mapped on the 1:100.000 scale Geological Map of Italy. Fig. 6 presents bulk chemical variation of these rocks.

a) Biella and Traversella stocks

The Biella stock consists of a core of porphyritic granite surrounded by syenites and monzonites (FIORENTINI POTENZA, 1959). The Traversella stock consists of diorite and monzonite (NOVARESE, 1943). Both produced contact aureoles which in the inner parts reached temperatures corresponding to the K-feldspar-cordierite hornfels facies (CALLEGARI, pers. comm.).

b) Andesite- trachyandesite- and lamprophyre dikes

These dikes occur throughout the Sesia-Lanzo Zone but mainly around the Biella and Traversella stocks. The same andesite and lamprophyre magmatism is extensively developed in the crystalline basement of the Southern Alps and in its Permian and Mesozoic cover and locally also occurs in the Dent Blanche Nappe.

c) Trachyandesite flows with agglomerates and tuffs

Trachyandesite flows, agglomerates and tuffs were firstly discovered by GASTALDI (1871) along the Canavese line. FRANCHI (1901, 1905) and NOVARESE (1929) noted within the volcanic sequence the occurrence of rounded fragments of eclogitic micaschists. This volcanic sequence was interpreted by BIANCHI and GB. DAL PIAZ (1963) and CARRARO (1966) as the postmetamorphic cover of the internal margin of the Sesia-Lanzo Zone. Its limited extent is probably due to the deep erosion which occurred in the Sesia-Lanzo Zone from Oligocene to Recent.

The geochronology of the postmetamorphic magmatism in the Sesia-Lanzo Zone deserves special attention, not only because of the controversy it has provoked, but most importantly for the restrictions it places on the minimal age of the metamorphism in the Sesia-Lanzo Zone and in the Dent Blanche Nappe.

A post-Alpine age (Oligocene) for the Biella and Traversella stocks and the related dikes, based on their structural features, was proposed by NOVARESE (1901). This interpretation was accepted by FRANCHI (1905) and KENNEDY (1931), and recently confirmed by K/Ar age determinations on biotite (30 $\pm$ 1 m.y.: Traversella diorite; 31 $\pm$ 1: Biella syenite; KRUMMENACHER and EVERNDEN, 1960). Four biotites from the Miagliano stock (within the Ivrea Zone, nearby the Canavese Line) give Rb/Sr ages between 30 and 33 m.y. and initial Sr^{87}/Sr^{86} ratios of 0.7070 and 0.7075 (CARRARO and FERRARA, 1968).

The age determination of the dikes was not resolved in the old literature. At that time, some dikes were referred to late- or post-Alpine magmatism, on the basis of their position near the Biella and Traversella stocks, and other dikes were given an unknown age, Permian or Alpine. Dikes found in the Ossola Valley were considered of either Permian or Tertiary age by REINHARDT (1966). A late-Alpine age for the andesite and lamprophyre dikes is suggested by radiometric ages (31 m.y.; DAL PIAZ et al., 1973) and by their crosscutting relationship with Lepontine metamorphics (38 m.y.) of the « Gneiss Minuti » Complex (DAL PIAZ et al., 1971).

The volcanic sequence of Biella was considered by NOVARESE (1929), BIANCHI and GB. DAL PIAZ (1963) and CARRARO (1966) to be of Permian age, by comparison with the Permian volcanics of the Southern Alps. This interpretation was substantiated by CARRARO (1966) and CARRARO and CHARRIER (1972) who found at the base of the volcanic series a detrital level with remnants of plant fossils ascribed to the Carboniferous. Thus the high pressure-low temperature metamorphism in the Sesia-Lanzo basement was considered to be pre-Permian.

This chronological interpretation has been criticized by more recent publications giving new geological, radiometrical and paleobotanical data (DAL PIAZ et al., 1972, 1973; AHRENDT, 1972; SCHEURING et al., 1974; HUNZIKER, 1974). The volcanic-detrial sequence of Biella is now considered to be of Oligocene age, i.e. coeval with the Biella, Traversella and Miagliano stocks and the related andesitic and lamprophyric dikes.

Additional references — AHRENDT (1969); AMATUCCI (1934); BURRI and NIGGLI (1945); COLOMBA (1912, 1915, 1929); COSSA (1876); DE MARCO (1958); DEUTSCH and LONGINELLI (1958); FENOGLIO (1924); FIORENTINI POTENZA (1961, 1969); MATTIROLO (1899); MÜLLER (1912); NIGGLI (1922); NOVARESE (1901, 1935); PEYRONEL PAGLIANI (1959, 1961); PREISWERK (1906); TRAVERSO (1894); WALTER (1950); ZAMBONINI (1905).

2.4. *Geophysical Data*

Some of the more interesting geophysical data available for the internal Western Alps are summarized below.

On the internal margin of the Alpine arc, gravimetric surveys reveal a large positive Bouguer anomaly (fig. 7), called Cuneo-Ivrea-Locarno anomaly (VECCHIA, 1968). A regional magnetic anomaly with the same pattern is found north of Torino (LANZA, 1975, with references).

Seismic surveys (see GIESE and MORELLI, 1975, for a review) reveal the existence of an eastward-dipping zone of high velocities (more than 7 Km/sec.) within the upper crust, with a low-velocity layer underlying it.

These anomalies are ascribed to the so called Ivrea body and their interpretation led to a well known structural model (BERCKHEMER's beak, 1968).

What is less known, but has been pointed out since 1968 by CORON and GUILLAUME, is that the Ivrea anomaly is within the external side of the Ivrea Zone only between Locarno and the Cervo Valley, near Biella. Southwest of the Cervo Valley the anomalous gravity zone shifts into the Sesia-Lanzo Zone. It extends along the axis of the Zone, approximately parallel to the « II Zona Diorito-kinzigitica » and to the boundary between the high pressure-low temperature domain and the greenschist facies domain (fig. 7). Towards the south, the Ivrea anomaly runs parallel with the Lanzo Lherzolite and then enters the area of the Penninic continental crust

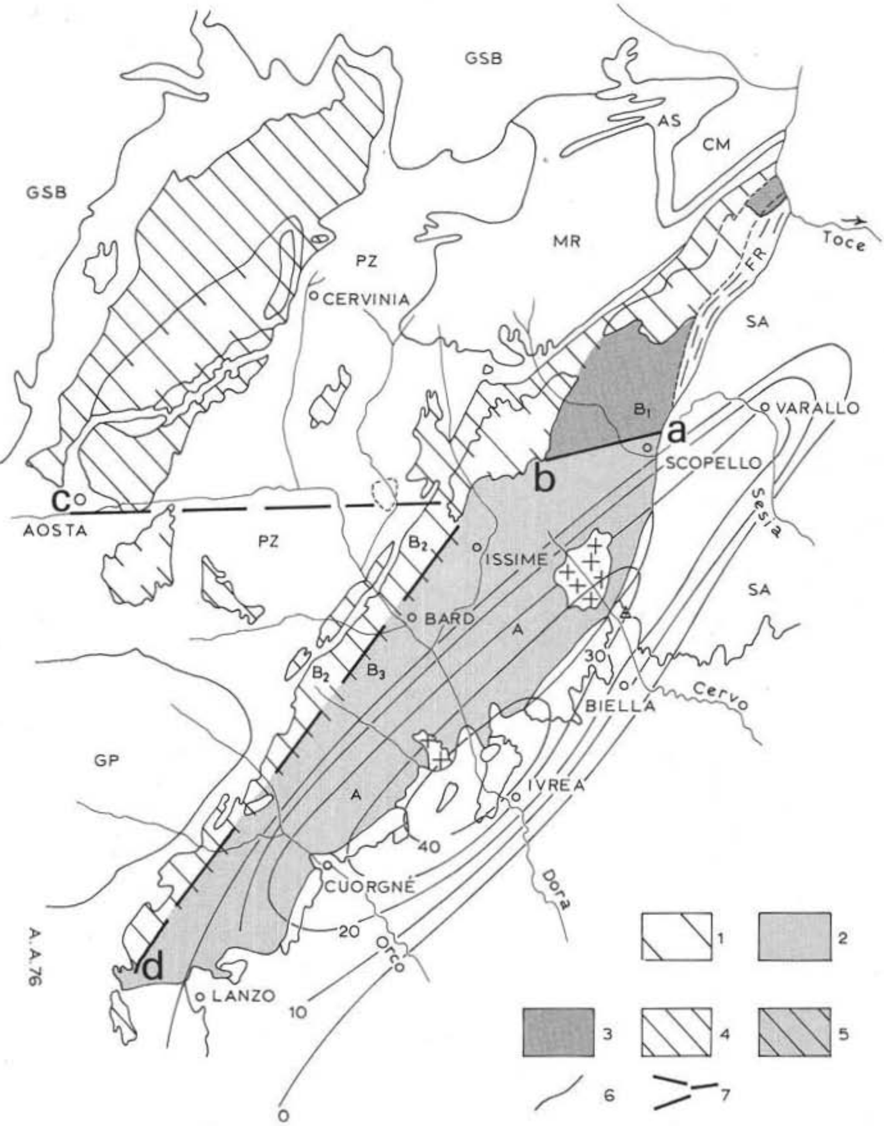

Fig. 7. — *Zoning of the Alpine metamorphism in the Sesia-Lanzo Zone and Dent Blanche Nappe.* 1) Areas of Upper Element with Alpine overprint on pre-Alpine high-temperature assemblages. 2) Early-Alpine eclogitic areas. 3) Early-Alpine non-eclogitic areas. 4) Areas with greenschist-facies assemblages of Lepontine age (glaucophane and aegyrine relics of indeterminate Alpine age occur in the Pillonet klippe). 5) Areas with Lepontine overprint on early-Alpine assemblages. 6) Positive Bouguer anomaly of the Ivrea body, in mgal. 7) Early alpine isogrades. A, B_1, B_2 and B_3 refer to the corresponding subdivisions of the Lower Element of the Sesia-Lanzo Zone. See text for discussion.

(Dora-Maira nappe). Another explanation is that the high-velocity zone and the large positive gravity anomalies mark the position of a mantle fragment dipping internally and underthrusting the Sesia-Lanzo Zone.

3. Modern ideas on the Sesia-Lanzo Zone

The literature discussed above mostly covers the century 1869-1969. The structural and lithological setting, the geochronology and the metamorphic evolution of the Sesia-Lanzo Zone have been more recently modified. These new data, integrated with some preliminary informations from the Sesia-Lanzo work group (1974 field-work), are outlined below.

3.1. *Structural outline of the composite Austroalpine nappe (Sesia-Lanzo Zone and Dent Blanche Nappe)*

Carraro et al. (1970) and Dal Piaz et al. (1971) recognized a sharp mylonitic contact between the « II Zona Diorito-kinzigitica » and the two other complexes of the Sesia-Lanzo Zone. Therefore the « II Zona Diorito-kinzigitica » is not only a lithological complex but also a tectonic unit. Its provenance is outside the Sesia-Lanzo Zone, in the sutured border of the Ivrea Zone. The Sesia Lanzo - Dent Blanche system can thus be subdivided into two tectonic elements, without any trace of interposed Mesozoic sequences (fig. 4). The upper element of the Sesia-Lanzo Zone consists of several Klippen of the « II Zona Diorito-kinzigitica »; the lower element consists of the Eclogitic Micaschist Complex and of the « Gneiss Minuti » Complex. In the Dent Blanche Nappe s.l. the upper element corresponds to the Valpelline Series, the lower element to the Arolla Series (in the Dent Blanche, Mt. Mary and Pillonet Klippen) and to the Eclogitic Micaschist Complex (in the Mt. Emilius Klippe).

3.2. *The Upper Element*

Klippen of the Upper Element outcrop in three different areas of the Sesia-Lanzo Zone (fig. 5); in the northeast, between the Ossola and Sermenza Valleys (II Zona Diorito-kinzigitica s.s.; Carraro et al., 1970; Bertolani, 1971; Isler and Zingg, 1974); in the north, between the Sesia and the Ayas Valleys (« Val Vogna-Valle di Gressoney » Klippe; Dal Piaz et al., 1971) and in the south (small Klippen of Vasaro and M. Cialmera; Carraro et al., 1970). Other kinzigites, commonly strongly retrograded occur in the Aosta Valley near Verres, in the Ayas Valley near Colle Pallasina and at Becca Torché, and in the Orco Valley. It is not yet clear if these kinzigitic sequences actually belong to the Upper Element and are tectonically enveloped by the Lower Element, or if they are pre-Alpine relics of the latter (Boriani et al., 1975).

3.2.1. *Pre-Alpine lithologies*

In spite of structural reworking and metamorphic retrogression of Alpine age, pre-Alpine high-grade assemblages are perfectly preserved in places.

The high-temperature associations mainly belong to the amphibolite facies of Hercynian age (Dal Piaz et al., 1972; Hunziker, 1974) but also contain some relics of older granulite assemblages. The lithologies and mineral assemblages closely resemble those of the Ivrea Zone.

The main lithologies of pre-Alpine age are:

a) kinzigites,
b) amphibolites,
c) marbles
d) ultramafics.

a) *Kinzigites* are rocks with a gneissose to schistose texture, which are locally massive and granulitic, and generally coarse-grained. A small-scale mineralogical layering is present, due to the alternation of biotite-garnet-sillimatite and quartz-two feldspar layers.

The most common assemblages are: biotite-garnet-quartz-K-feldspar ± sillimanite ± plagioclase; quartz-K-feldspar ± plagioclase ± muscovite; plagioclase-garnet.

The high-grade paragneisses are closely associated with *pegmatoids* that form generally concordant intercalations and discordant veins with migmatitic appearance. The pegmatoids are coarse-grained and are composed of quartz-K-feldspar-plagioclase--biotite ± muscovite ± garnet. Generally they appear more retrograded than the associated paragneisses. These pegmatoids seem to represent the anatectic product of the Hercynian metamorphic cycle.

Massive rocks of granulitic appearance (plagioclase-garnet; plagioclase-garnet--quartz-biotite) are locally preserved in the kinzigites.

b) *Amphibolites* are commonly subordinate to the associated gneisses in all the Klippen of the Upper Element and may occur as lens-like bodies or layers from cm to a few m thick. They are mostly massive, fine- to medium-grained, and may show a fine layering of plagioclase-rich and amphibole-rich layers.

The most common assemblages are: brown hornblende-plagioclase ± biotite; brown hornblende-plagioclase-garnet ± biotite ± quartz; brown hornblende-plagioclase-pyroxene-garnet ± quartz.

c) *Marbles* of various thicknesses are interlayered with the kinzigitic gneisses and are an important structural marker. The marbles contain, as pre-Alpine minerals, garnet, diopside, phlogopite, amphiboles, quartz and large white-mica flakes. Alpine metamorphism produced widespread tremolite-actinolite and epidote-group minerals.

d) A small *harzburgite* body outcrops in the upper Artogna Valley, between the Gressoney and Sesia Valleys (Artini and Melzi, 1900; Dal Piaz et al., 1971). The harzburgite consists of olivine (50 to 70 % in volume), orthopyroxene, opaque spinel and locally strongly deformed phlogopite flakes. Along its boundaries the harzburgite is serpentinized (antigorite). Two-pyroxene ± amphibole dikes were also found cutting the body.

3.2.2. *Alpine evolution*

The rocks of the Upper Element commonly show a strong Alpine retrograde metamorphism, the final product being greenschist-facies micaschists and albite-

-amphibolites; the pegmatoids are transformed into white-mica quartzites.

The retrograded rocks exhibit two different Alpine metamorphic episodes. Relics of the *first episode* are only locally preserved. They are: kyanite, blue amphibole, phengite and fine-grained garnet. The blue amphibole, although in small amounts, occurs both in micaschists and in metabasics. In the former it replaces the Hercynian biotite, while in the latter it developes mainly at the expense of brown hornblende (DAL PIAZ et al., 1971). Extensively developed blue amphibole is found only in parts of the Strona Valley (BERTOLANI, 1971).

Kyanite develops as very fine-grained aggregates pseudomorphing sillimanite. Similar kyanite pseudomorphs are also found in the Valpelline Series of the Dent Blanche Nappe.

The second metamorphic episode is of greenschist facies and is more uniformly developed than the first. It is polyphasic and is accompanied by multiple deformation that results in complete textural reworking in some areas. A first phase is represented by: phengite, green biotite, epidote, chlorite, actinolite, albite ± garnet (?) ± scarce stilpnomelane. Locally there is a second generation of stilpnomelane and albite, sometimes with oligoclase rims.

The Alpine metamorphic evolution of the marbles is not fully understood, but the following minerals can be recognized as Alpine: actinolite, epidote, quartz, albite, white mica and chlorite.

3.2.3. *Geochronology*

The various metamorphic events described above in the Upper Element can be dated by radiometric ages or by comparison with other units (Valpelline Series and Ivrea Zone).

The oldest metamorphic event, characterized by high-grade assemblages, may be Hercynian as suggested by a few K/Ar and Rb/Sr ages of micas (DAL PIAZ et al., 1972; HUNZIKER, 1974). These ages confirm the close relationship of the Sesia-Lanzo Upper Element and the Ivrea Zone.

The two latest episodes are Alpine as is apparent from overprinting relationships and from comparison with the metamorphism in other units of the Western Alps, particularly in the Lower Element of the Sesia-Lanzo Zone. The first episode corresponds to the early-Alpine event, the second one to the 38 m.y. event (see DAL PIAZ et al., 1971). The latter, and the related multiple deformations terminated prior to the emplacement of the andesitic and lamprophyric dikes of Oligocene age (DAL PIAZ et al., 1972, 1973).

3.3. *The Lower Element*

The Lower Element is distinguished from the Upper mainly by the occurrence of abundant pre-Alpine (late Hercynian?) granitoids and by different grade of Alpine metamorphism. The granitoids intrude a sequence of high-temperature metamorphics. The old distinction of the Lower Element into two complexes,

« Eclogitic Micaschist » Complex and « Gneiss Minuti » Complex, based on lithological criteria, needs to be modified in view of new petrographical and geochronological data.

A distinction between the two complexes prior to the high pressure-low temperature metamorphism is meaningless because both belong to a single, though heterogenous, pre-Alpine basement; they became distinguishable only during the Alpine history, as areas with prevailing eclogitic or greenschist-facies assemblages respectively. The Eclogitic Micaschist Complex can be considered a portion of the Sesia-Lanzo Zone characterized by early-Alpine eclogitic assemblages (sector A). The « Gneiss Minuti » Complex can be viewed as a sector with greenschist-facies assemblages (sector B) (fig. 7).

Within the « Gneiss Minuti » Complex three new subdivisions need to be introduced (fig. 7):

1) Northeastern sector (sector B1), with no traces of eclogitic metamorphism, characterized by low-grade parageneses (probably of greenschist facies) which are at least partly of early-Alpine age (Dal Piaz et al., 1972; Hunziker, 1974).
2) External sector (sector B2), extending all along the external boundary of the Lower Element and characterized by typical greenschist-facies assemblages of Lepontine age (Hunziker, 1970, 1974).
3) Intermediate sector (sector B3) between A and B2 and between B1 and B2, characterized by overprinting of early-Alpine by Lepontine.

3.3.1. *Eclogitic Micaschist Complex*

Sector A is characterized by early-Alpine eclogitic assemblages. It consists of coarse-grained garnet-bearing *micaschists* (ortho- and paraschists) characterized by widespread occurrence of Na-pyroxenes and blue amphiboles and by numerous interbedded *eclogites* and *glaucophanites*. The complex also contains frequent *marble* layers and lenses, and rare *quartzites*. The high pressure-low temperature minerals of this sector yield radiometric ages of 90 to 70 m.y. and predate the thrusting of the Austroalpine nappes over the Piemonte Zone, which is considered to have occurred at the Cretaceous-Paleocene boundary (Dal Piaz et al., 1972; Hunziker, 1974). This sector extends from the Sesia Valley to the Lanzo Valley, in the internal portion of the Lower Element (fig. 7).

Micaschists — The typical assemblages are: quartz-phengite-garnet $\pm$ glaucophane $\pm$ pyroxene (jadeite to omphacite) $\pm$ epidote $\pm$ paragonite.

The white micas are mainly phengite (fig. 8) and minor paragonite, occurring separately or together in the same rock (Liebeaux, 1975). They may occur as different polytypes in the same specimen; the most commonly observed phengite being the 3T polytype (Fiorentini Potenza and Morelli, 1968; Fiorentini Potenza, 1969 b).

Garnet is represented by several generations; locally the oldest generation is pre-Alpine. Alpine garnets (fig. 9) are almandines (50-60 % Alm), rich in grossular component (25-40 %); pyrope component may amount up to 25 %, but is usually around 10 %; spessartine is very subordinate (0-5 %). If plotted in the triangle Gr-Py-Alm+Sp, most compositions fall close to garnets from type-C eclogites of COLEMAN et al. (1965). A few garnets from eclogitic schists are zoned (LIEBEAUX, 1975), with cores showing Alm contents significantly higher (70-80 %), which possibly represent relics of pre-Alpine garnets; the outer portions of these garnets have compositions close to those of unzoned garnets.

Chemical analyses of Na-pyroxenes from the eclogitic micaschists fall in three groups (fig. 10).

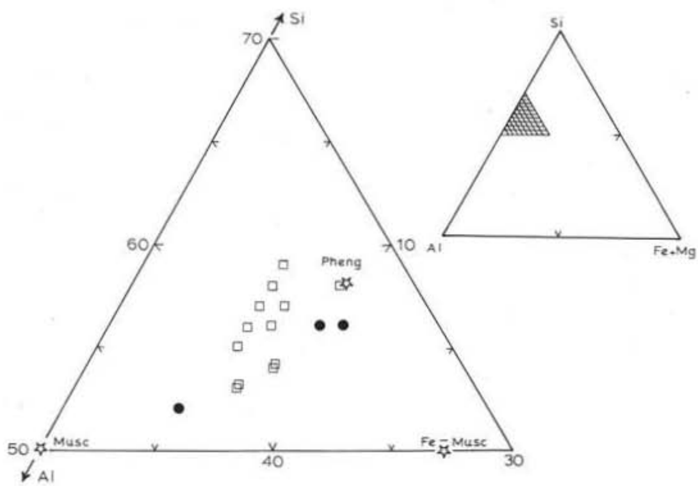

Fig. 8. — Si-$Al_{tot.}$-($Fe_{tot.}$+Mg) diagram for white micas from micaschists (squares) and metabasics (dots) of the Eclogitic Micaschist Complex. Data after FIORENTINI POTENZA and MORELLI (1968), FIORENTINI POTENZA (1969 b), VELDE and KIENAST (1973), LIEBEAUX (1975).

The pyroxenes of the first group are jadeites in which the Jd component ranges from 80 % to over 90 %; the Ac component does not exceed 10 %. In this group fall the Na-pyroxenes from metagranitoids and eclogitic micaschists probably deriving from granitoids. The pyroxenes of the second group are omphacites with Jd component ranging from 45 to 60 %, and Ac usually less than 5 %. These pyroxenes are found in eclogitic micaschists which probably derive from high-grade paragneisses. The third group is represented by second stage-pyroxenes (see p.) showing a marked enrichment in the Ac component and plotting in the chloromelanite field.

Several generations of blue amphiboles were observed in the micaschists; they appear to have grown later than the jadeite-rich pyroxene and may be in stable association with albite. Optically they are glaucophanes of the very light-coloured

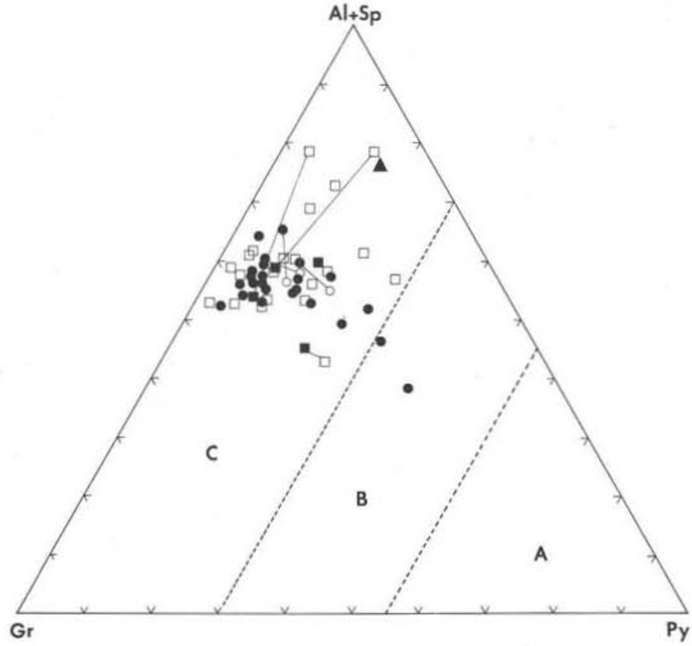

Fig. 9. — *Molecular proportions of garnets from the Eclogitic Micaschist Complex.* Dots: garnets from eclogites, omphacitites and glaucophanites; squares: garnets from micaschists. Tie-lines show zoning from cores (light squares, solid dots) to rims (solid squares, light dots). The composition of one pre-Alpine garnet from II Zona Diorito-Kinzigitica is also shown (triangle). Compositional boundaries of garnets from different types of eclogites after COLEMAN et al. (1965). Data after CALLEGARI and VITERBO (1966), VELDE and KIENAST (1973), LATTARD (1974), LIEBEAUX (1975).

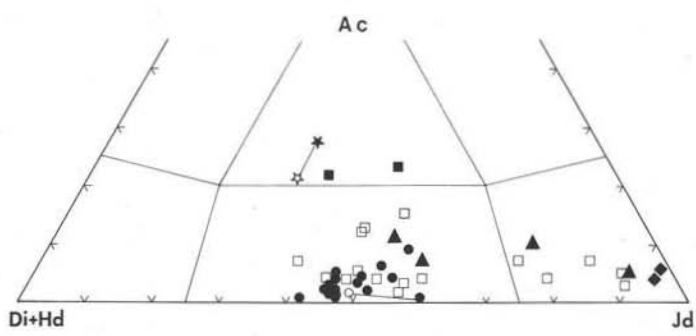

Fig. 10. — *Jd-(Di+Hd)-Ac proportions of Na-pyroxenes from the Eclogitic Micaschist Complex.* — Pyroxenes from micaschists, squares; from metagranitoids, diamonds; from eclogites and glaucophanites, solid dots; from Na-pyroxenites, triangles. Composition of late-stage pyroxenes from eclogitic micaschists (solid squares) and Na-pyroxenites (stars) is also shown. Tie-lines show zoning from cores (solid symbols) to rims. Data after OGNIBEN (1968), EDGAR et al. (1968), VELDE and KIENAST (1973), LIEBEAUX (1975). Compositional fields after ESSENE and FYFE (1967).

variety known as gastaldite. Only few chemical analyses of these amphiboles are presently available. As shown in fig. 11 where they are plotted in the triangle $Fe_{tot.}$-Mg-Al^{VI}, Na-amphiboles from eclogitic micaschists mostly fall in the glaucophane field (as defined by MIYASHIRO, 1957), close to the Gl—Fe-Gl boundary; glaucophanes from metabasics, on the other hand, are more magnesian and plot closer to the Gl—Mg-Rieb tie-line. These relations suggest that the higher content in Fe in glaucophanes from the eclogitic micaschists is possibly caused by differences in bulk chemistry of the host rocks.

The epidote group is generally represented by zoisite with minor clinozoisite, and rare Fe-epidote forming in this order; they represent different stages of metamorphism. Zoisite and probably also clinozoisite can be referred to the early-Alpine event, while the Fe-epidote could be of Lepontine age.

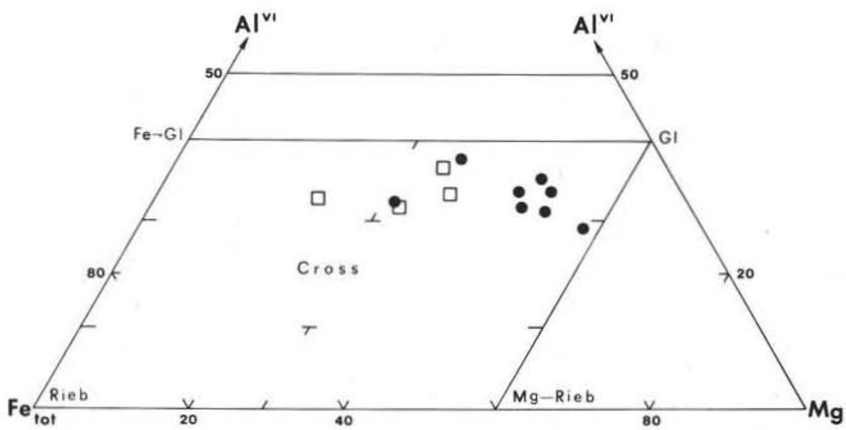

Fig. 11. — *Al^{VI}-$Fe_{tot.}$-Mg plot for Na-amphiboles from the Eclogitic Micaschist Complex.* Amphiboles from micaschists: squares; amphiboles from eclogites, glaucophanites and omphacites: dots. Data from DAL PIAZ et al. (1973) and LIEBEAUX (1975). Compositional fields after MIYASHIRO (1957).

Chloritoid of two generations is a major phase in high-alumina paraschists but is uncommon in other rocks. It appears to be coeval with the first glaucophane generation, but later than kyanite.

Kyanite is very rare and generally pseudomorphs pre-Alpine sillimanite; in the high-alumina paraschists it seems to be older than the first generation of chloritoid (DAL PIAZ et al., 1972).

Rutile is a typical accessory mineral which transforms to sphene, as omphacite becomes unstable.

Locally the micaschists show a weak transformation into greenschist-facies assemblages with development of blue-green to green amphibole, albite, chlorite, green biotite and Fe-epidote.

Metabasics (eclogites and related rocks) are widely distributed within the micaschists as layers or as lenses of variable size (cm to hundred m). In addition to typical eclogites, glaucophane eclogites and glaucophanites with minor omphacitites also occur; these different types may occur together in thinly layered bodies.

The eclogites are generally massive but may exhibit foliations in the glaucophane and/or white mica-rich types.

Bulk chemistry of the eclogites (VITERBO BASSANI and BLACKBURN, 1968; LIEBEAUX, 1975) grossly corresponds to alkaline basalt; almost all the analyses show normative Ol (2-20 %) and about half of them also normative Ne (2-10 %).

The most common assemblages are: omphacite-garnet-rutile ± glaucophane ± ± white mica ± zoisite. Fe-epidotes and blue green-to green amphiboles appear in the partially retrograded types.

More than one generation of omphacite and blue-amphibole is recognized. The available analyses of pyroxenes from the metabasics show omphacitic compositions (fig. 10), with Jd ranging from 45 to 60 %; Ac component is minor, and usually less than 5 %. Minor zoning may occur, Na decreasing and Ca and Mg increasing in the external part of the omphacites (LIEBEAUX, 1975). Secondary pyroxenes, forming in the Na-pyroxenites are strongly enriched in the Ac component and plot in the chloromelanite field (LIEBEAUX, 1975).

Garnet occurs in various shapes and sizes (idioblasts, irregular or atoll-like grains). Chemical data for garnet point to compositions close to Alm_{55-66}-Gr_{35-40} -Py_{5-10} (fig. 9); as in garnets from eclogitic micaschists spessartine component does not exceed a few percents. A few garnets showing Py component significantly higher (up to 40 %) possibly represent pre-Alpine relics.

Lawsonite-bearing metabasites have been found in the internal part of the Eclogitic Micaschist Complex near Alpette (CARON and SALIOT, 1969), and Corio (DAL PIAZ et al., 1972; LIEBEAUX, 1975). At Ivozio, in the lower Val d'Aosta (COMPAGNONI, this volume) and Pont Canavese (LIEBEAUX, 1975) lawsonite also occurs, but as pseudomorphs consisting of zoisite and white micas. These rocks are glaucophanites (DAL PIAZ et al., 1972; LIEBEAUX, 1975) with chlorite, zoisite, white mica and garnet ± quartz; pumpellyite may also occur, rimming the lawsonite (CARON and SALIOT, 1969). The lawsonite-bearing metabasites analized by LIEBEAUX show tholeiitic compositions, with 5 - 10 % normative quartz. Pseudomorphs on lawsonite consist largely of zoisite and white micas (phengite and paragonite), with minor albite ± chlorite, blue-green amphibole and sphene.

Marbles occur as intercalations in the paraschists (a few cm to more than a hundred m thick) often severely stretched and with internal flow structures. The most common assemblages are: carbonates (calcite, ankerite, dolomite) ± phengite ± ± garnet ± zoisite ± quartz.

Particularly interesting is the occurrence of omphacite in these rocks, which often forms at the contact between marbles and micaschists. Other minerals, like

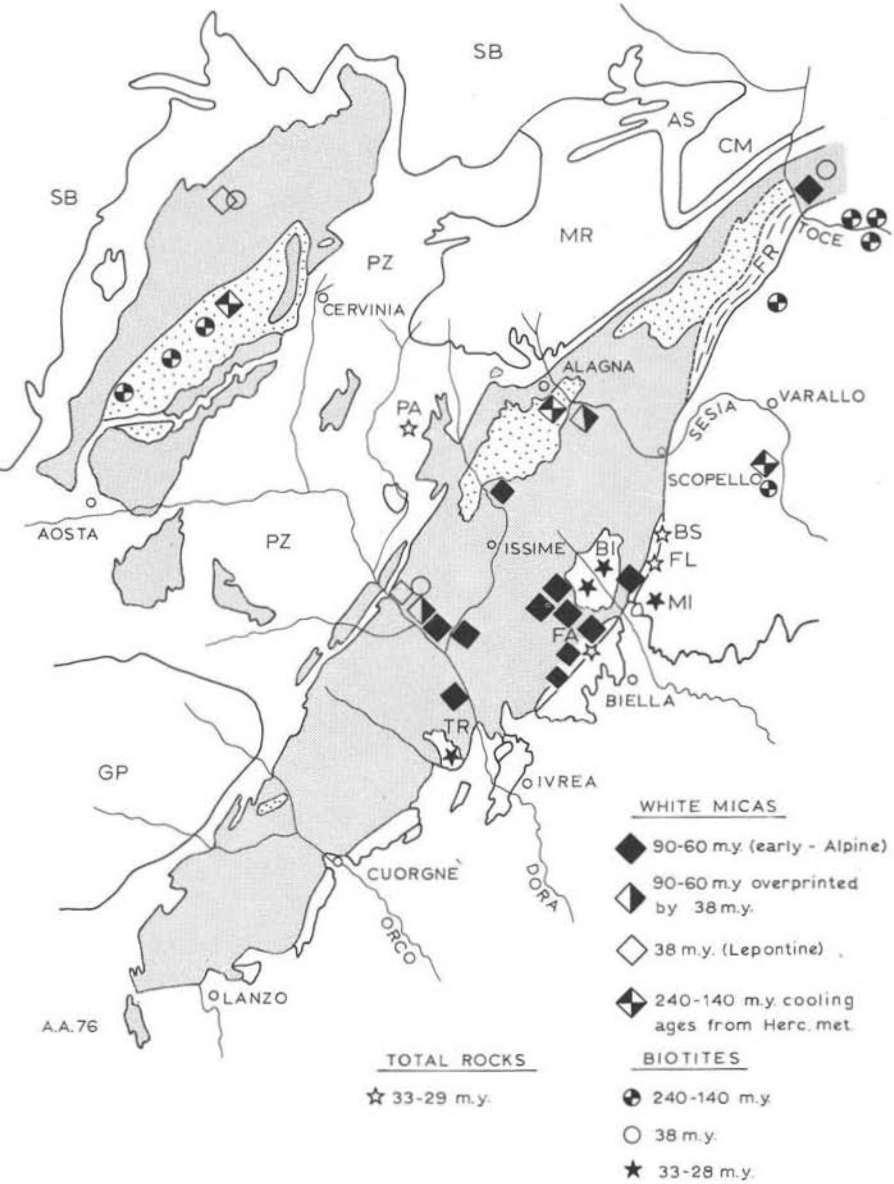

Fig. 12. — *Age determinations from the Sesia-Lanzo Zone, Dent Blanche Nappe, Ivrea Zone and Oligocene magmatic rocks.* See references in HUNZIKER (1974). BI = Biella stock; MI = Miagliano stock; TR = Traversella stock. FA = Favaro trachyandesite; FL = Falletti trachyandesite; BS = Bocchetto Sessera trachyandesite. PA = Pallasina lamprophyre. Stippled areas: II Zona Diorito-Kinzigitica and Valpelline Series.

epidote, albite, tremolite and chlorite are considered to be related to the late greenschist-facies retrogression.

In addition to these marbles, rocks consisting of quartz-carbonate ± white micas ±

± chlorite (similar to the « calcescisti » of the Piemonte Zone) and rare carbonate microbreccias are found locally (e.g. near Quincinetto in the Aosta Valley and near Pont Canavese in the Orco Valley).

Quarzites — In the Eclogitic Micaschist Complex very rare thin layers of quarzites (possibly metacherts) were found near Sparone in the Orco Valley. They contain spessartine ± phengite ± Na-pyroxene ± blue amphibole. The spessartine component in garnet is about 75 % (MINNIGH, pers. comm., 1975).

3.3.2. « *Gneiss Minuti* » *Complex*

Sector B1: Northeastern sector with early-Alpine non-eclogitic assemblages — It consists of metagranitoids, augengneisses and minor paraschists containing mineral assemblages referred to the greenschist facies (DAL PIAZ et al., 1972; HUNZIKER, 1974). This sector is still poorly known and seems to extend from the middle Gressoney Valley (Gaby) to the Ossola Valley (fig. 7). Since the mineral assemblages are essentially the same as those of B2, this sector could not have been distinguished without radiometric dating.

In the B1 sector a metamorphic grading towards sector A occurred during the early-Alpine event. This grading ranged from higher-pressure conditions (southern and central portions of the internal sector of the Lower Element) to lower-pressure conditions in the northeastern sector. Temperature probably remained constant throughout the whole element.

The « Gneiss Minuti » of the sector B1 consist of metagranitoids, augen-gneisses and minor paraschists containing albite, phengite, Fe-epidote, chlorite, actinolite, green biotite ± blue amphibole ± garnet ± zoisite ± rutile. Blue amphibole occurs in a narrow area, rimming the eclogitic zone to the north.

The researches in progress in sector B1 reveal a few mineralogical differences between the early-Alpine greenschist-facies assemblages and those of Lepontine age occurring in sector B2. Zoisite, rutile, garnet and glaucophane are widespread in the former, while they seem to be generally lacking in the latter.

Sector B2: Greenschist-facies sector of Lepontine age (38 m.y.) — This sector approximately corresponds to the « Gneiss Minuti » Complex of the literature and extends all along the external margin of the Lower Element (fig. 7). Mineral assemblages contain albite-phengite-quartz-Fe-epidote ± chlorite ± green biotite ± actinolite ± stilpnomelane; albite is very abundant and commonly poikiloblastic. These assemblages are identical and coeval with those of the Arolla Series in the Dent Blanche Nappe, and similar to the assemblages in the underlying Combin Zone of the Piemonte Zone. In the overprinting sector (sector B3) they overprint the earlier high pressure-low temperature assemblages. K/Ar and Rb/Sr determinations on phengite and green biotite give Eocene ages (HUNZIKER, 1969, 1970, 1974). These assemblages belong to the second episode of the Alpine metamorphism which corresponds to the « Lepontine » thermal dome in the Ossola-Ticino region.

In the B2 sector the most common rock types are fine-grained albite-bearing gneisses with minor prasinites. Chemical data for these rocks and their minerals (phengites, biotites, amphiboles, garnets and stilpnomelane) are reported in LATTARD (1974).

These rocks are commonly banded and consist of leucocratic layers interbedded with layers rich in white micas, chlorite, epidotes and actinolite. The banding is largely a transposition of primary aplitic dikes. Whithin more homogeneous albite-bearing gneisses the original magmatic texture of the porphyritic granitoids can be recognized. The relict minerals belonging to the magmatic assemblage are K-feldspar, brown hornblende, faded brown biotite and largely saussuritic plagioclase. These granitoids, which are mainly transformed into augen-gneisses, occur widely between the upper Sesia Valley and the Champorcher and Chiusella Valley. In places, metagabbros with relics of the primary minerals are also found (Mt. Pinter, upper Gressoney Valley).

The transition from metagranitoids to fine-grained gneisses indicates an igneous origin for at least some of the « Gneiss Minuti ». This field evidence in confirmed microscopically by the occurrence of K-feldspar (more or less transformed into chessboard albite) and of allanite relics. Possibly the rest of « Gneiss Minuti » may have been derived from paraschists (some of wich may even be of post-Hercynian age) but in the absence of relics it is impossible to draw any conclusion. The possible occurrence of acid metavolcanics of Permian age (said by AMSTUTZ, 1971, to be of regional extent) is as yet unproved in the Sesia-Lanzo Zone.

In some parts of this sector very intensively retrograded kinzigitic schists with some marbles and amphibolites are intercalated in the « Gneiss Minuti ». There are relics of pre-Alpine garnet and biotite in the kinzigitic schists and of diopside in the marbles. So far it has not been possible to show whether the association of kinzigitic schists and « Gneiss Minuti » in this sector is primary, or whether the kinzigitic schists are tectonic intercalations of the « II Zona Diorito-kinzigitica » in the « Gneiss Minuti ».

Locally the « Gneiss Minuti » Complex contains intercalations of calcschist-like marbles, sometimes closely associated with distinctive micaceous quartz-garnet rocks which contain as accessory minerals piemontite ± braunite ± ardennite. The latter outcrop in the Lanzo Valley, near Ceres (ZAMBONINI, 1922; GENNARO, 1925). Similar rocks occur near Ciusàl road Hône-Issogne) in the lower Aosta valley.

Sector B3: Overprinting sector — This sector comprises a narrow band of a few hundred meters to one kilometer width and is defined as the area in which high pressure-low temperature minerals, characteristic of the Eclogitic Micaschists, are overprinted by greenschist-facies minerals, characteristic of the « Gneiss Minuti » (fig. 7).

Radiometric data confirm the overprinting and allow extension of this sector towards the northeast. In this area early-Alpine greenschist-facies assemblages are

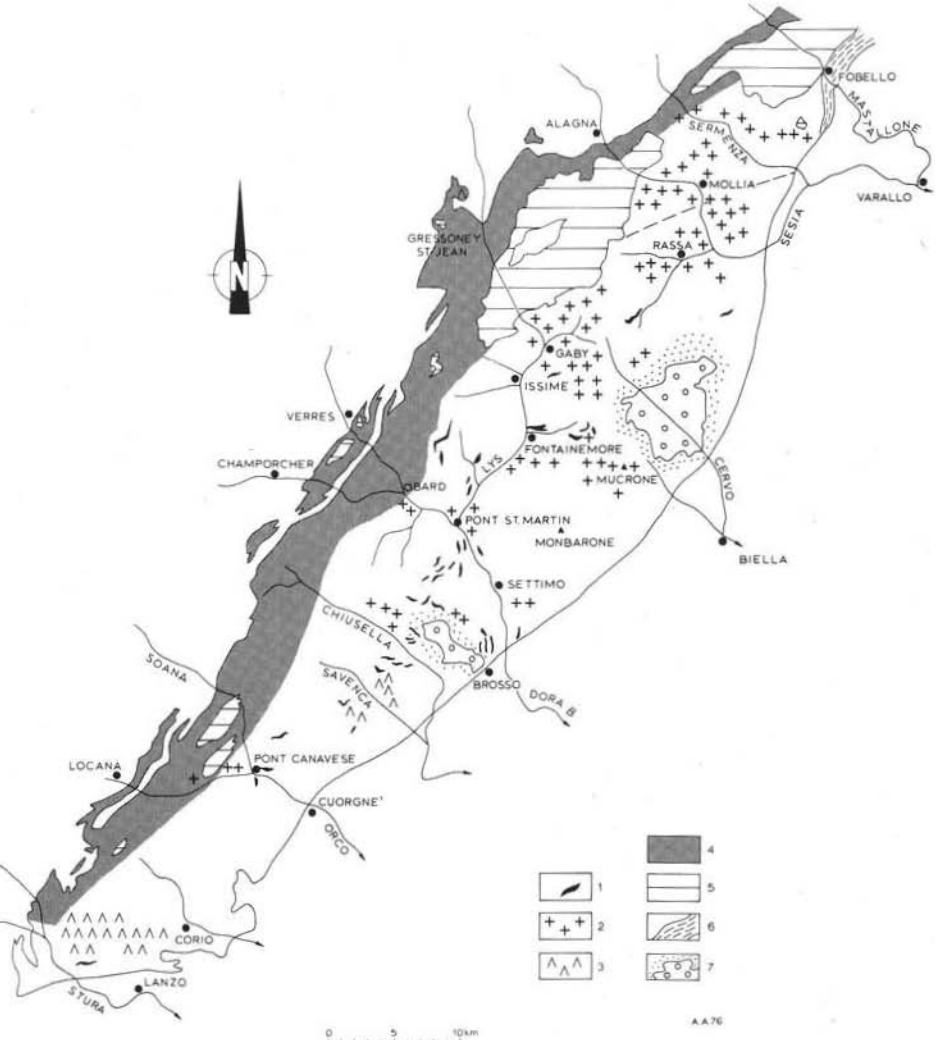

Fig. 13. — *Distribution of pre-Alpine lithologies in the Lower Element of the Sesia-Lanzo Zone.* 1) Paraschists and marbles (black); 2) Silicic to intermediate metagranitic rocks; 3) Metagabbros; 4) Gneiss Minuti Complex; 5) Upper Element; 6) Fobello-Rimella Schists; 7) Tertiary plutonic rocks and contact aureoles (dots). — Data from the 1: 100.000 maps listed in footnote (3); DAL PIAZ et al., 1971, 1973; MINNIGH, pers. comm.; and personal observations.

overprinted by Lepontine greenschist facies. These two events were originally distinguished by dating, but more recently minor petrographical differences have been recognized. The Lepontine assemblages include porphyroblastic albite and green biotite, not found in the earlier assemblages.

3.3.3. *Geochronology*

Fig. 12 shows the location of samples dated by Rb/Sr and K/Ar methods in the Sesia-Lanzo Zone, Dent Blanche Nappe and Oligocene magmatic rocks (HUNZIKER, 1969, 1970, 1974; DAL PIAZ et al., 1972, 1973; BOCQUET et al., 1974). These data are reported and discussed in more detail by HUNZIKER (1974).

Eleven phengites of the Lower Element of the Sesia-Lanzo Zone yield early-Alpine ages (90 to 67 m.y.); eight of them come from the « eclogitic » sector (A in fig. 7) and three come from the greenschist sector (B1) of the northeastern Sesia-Lanzo Zone.

Two micas from the B3 overprinting sector give ages ranging from 90 to 40 m.y.; these mixed ages are interpreted as early-Alpine ages overprinted by Lepontine ages.

Preliminary whole rock data for the Mt. Mucrone metagranitoids give Permian ages, while the relict igneous biotites yield an early-Alpine age.

3.3.4. *Pre-Alpine lithology*

Before 1969 only a few pre-Alpine relics were known in the Sesia-Lanzo Zone: granitoids in the « Gneiss Minuti » Complex and rare gabbros in the Eclogitic Micaschists. Recent investigations have revealed the occurrence of more pre-Alpine relics (Hercynian granitoids and high-temperature paragneisses) both in the Eclogitic Micaschist Complex and in the « Gneiss Minuti » Complex (DAL PIAZ et al., 1972, 1973; COMPAGNONI and MAFFEO, 1973).

The Lower Element consisted of two main lithological complexes before the Alpine orogeny: high-temperature metamorphics and granitoids. Both include metabasics which are now mainly eclogites or prasinites. Small intrusions of gabbroic rocks were associated to the high-temperature metamorphics. Fig. 13 shows the distribution of the pre-Alpine lithologies in the Lower Element.

a) The high-temperature paragneisses

Mineralogical and structural relics of paragneisses with high-temperature assemblages were found in very small areas near the Mucrone Lake (DAL PIAZ et al., 1972, 1973). These paraschists contain numerous pegmatite veins, metabasic nodules and layers and rare marble lenses. In the field the paraschists appear very similar to the kinzigites of the « II Zona Diorito-kinzigitica » and of the Valpelline Series.

Under the microscope the following pre-Alpine assemblages can still be recognized: biotite-garnet-sillimanite-two feldspars-quartz (in the paraschists); two feldspars-quartz $\pm$ biotite $\pm$ muscovite (in the pegmatites). They indicate amphibolite facies conditions of indeterminate pressure.

Within the high-temperature paragneisses the more widespread pre-Alpine relic is biotite: it occurs as red-brown flakes mainly concentrated in the sillimanite-garnet layers. Sillimanite can occur either as millimeter-long nematoblasts or as fibrolitic aggregates; it is very rarely preserved and generally is completely transformed into fine-grained kyanite pseudomorphs (DAL PIAZ et al., 1972). Garnet is coarse-grained and texturally similar to the kinzigite garnets. K-feldspar is generally preserved but the plagioclase is always pseudomorphically replaced by a jadeite-

-zoisite-quartz intergrowth. As elsewhere in the Valpelline Series and the Ivrea Zone it is noteworthy that graphite is quite common in these rocks.

In many areas the appearance in outcrop of the eclogitic micaschists is reminescent of high-temperature paragneisses though pre-Alpine minerals are lacking: under the microscope only the pseudomorphs of phengite + garnet after pre-Alpine biotite are recognizable.

High-temperature paragneisses with interbedded marbles and amphibolites, with a strong greenschist-facies overprint, were also found in the external « Gneiss Minuti » Complex (e.g.: Colle Pallasina and Becca Mortens in the Ayas Valley; between Bard and Verres in the Aosta Valley). However, as seen before (Sector B2, pag. 310), their significance is still in debate.

b) The granitoids

The granitoids are present throughout the Lower Element but are most common in the north of the Aosta Valley, between Mt. Mucrone, Lago della Vecchia, Piedicavallo (Cervo Valley), Gaby (Gressoney Valley) and the Sesia Valley. The granitoids are clearly intrusive, as shown by their sharp and discordant contacts with the surrounding paraschists; swarms of aplite and minor pegmatite dikes crosscut both the paraschists and the granitoids.

The granitoids are represented by biotite ± hornblende granodiorites and tonalites with minor granites (Callegari et al., 1976). Commonly the igneous mineralogy is completely transformed into Alpine assemblages: the only relict igneous minerals are K-feldspar (particularly in the porphyritic granitoids transformed into augen-gneisses) and the characteristic accessory allanite. In a very few areas these rocks escaped pervasive Alpine deformation and the igneous texture is perfectly recognizable.

c) The mafic rocks

The metabasics of the Lower Element can be subdivided into two groups, according to their pre-Alpine lithology:

1) cognate dark inclusions in granitoids;
2) metabasics interbedded in high-temperature paraschists.

1) *Cognate dark inclusions in metagranitoids.* The Sesia-Lanzo metagranitoids are rich, and locally very rich, in cognate dark inclusions [7] the size of which ranges from a few centimeters to one meter. In the Eclogitic Micaschist Complex they can be recognized only as structural relics for they are completely transformed into fine-grained quartz-bearing garnet-omphacite-phengite rocks. In the « Gneiss Minuti » Complex, however, their mineralogy (plagioclase, biotite and minor amphiboles) is still locally well preserved and similar to that of the surrounding

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(7) We call cognate dark inclusions the inclusions in the granitoids referred to as « dark microgranular enclaves » by Didier (1973).

metagranitoids; they differ from the latter only in having a very low quartz content and more abundant biotite and amphibole.

2) *Metabasics interbedded with the high-temperature paragneisses.* The eclogites interlayered with the original high-temperature paragneisses are interpreted as deriving from primary amphibolites and basic granulites because such rocks are commonly associated with the paraschists (« Kinzigites ») in the Ivrea Zone, « II Zona Diorito-kinzigitica» and Valpelline Series. Recently significant remnants of pre-Alpine amphibolites have been found (see COMPAGNONI, this issue).

d) The gabbroids

The primary gabbroic nature of the metabasics of Corio and Monastero (Southern Eclogitic Micaschist Complex) is shown both from microstructural and mineralogical relics (brown hornblende, clinopyroxene and saussuritized plagioclase) and by their bulk chemistry (BIANCHI et al., 1965). A gabbroic body was found in the « Gneiss Minuti » Complex at Mt. Pinter (Upper Gressoney Valley), close to the tectonic contact with the Piemonte Zone calcschists. The gabbros, cut by leucocratic differentiated dikes, are transformed into fine-grained greenschist-facies schists; the contact is marked by a thick mylonite band. Also at Mt. Pinter the igneous mineralogy consists of brown hornblende, clinopyroxene and saussuritized plagioclase.

3.3.5. *Alpine metamorphic evolution*

The Alpine metamorphic evolution of the Lower Element gives a very complex polyphase picture and is characterized by the two main metamorphic events known as the early-Alpine and Lepontine respectively.

a) Early-Alpine evolution

*a.*1) *Eclogitic Micaschists (Sector A).* The first metamorphic phase is characterized by the highest pressure—lowest temperature conditions, the most significant reactions in metagranitoids and paragneisses being: plagioclase → jadeite + quartz + + zoisite, biotite → phengite + garnet + rutile, and sillimanite → kyanite. Such reactions occur partly under non pervasive deformation as shown by the extensive preservation of pre-Alpine magmatic and metamorphic textures.

A second early-Alpine stage is characterized by development of foliations on a regional scale, by recrystallization of jadeite and by growth of omphacite, glaucophane, zoisite and chloritoid. During this stage the typical « eclogitic » ortho- and paramicaschists were formed. Lawsonite too grew during this stage (COMPAGNONI, this volume, p. 359). In the eclogites these two stages cannot yet be distinguished: probably more than one generation of omphacite grew together with garnet, glaucophane, phengite, zoisite and rutile.

The third early-Alpine stage is characterized by the breakdown of the pair jadeitic pyroxene + quartz, with development of albite, white-mica, clinozoisite +

+acmite-rich pyroxene and by the growth of a second generation of glaucophane, then of blue-green amphibole and still later of actinolite. Up to this stage (glaucophanitic-greenschist stage) the eclogitic assemblages survived in the metabasics.

A final greenschist-facies stage locally transforms eclogites into albite-amphibolites with widespread development of albite-actinolite intergrowths.

The first stages of this complex evolution are surely early-Alpine; the age of the last one, characterized by the breakdown of glaucophane, is doubtful.

This stage shows mineralogical features similar to those of the Lepontine event; it differs from the latter in that it lacks green biotite and porphyroblastic albite; moreover it has only a local occurrence. In any case it seems evident that the evolution in the early-Alpine event is characterized by a marked pressure decrease.

a.2) *Northeastern sector, with early-Alpine non-eclogitic assemblages* (*Sector B1*). The data concerning the early-Alpine event in this sector are very scarce. The main transformations of the igneous minerals of the granitoids are as follows: K-feldspar → → albite; biotite → white mica (phengite) ± rutile ± garnet; plagioclase → saussurite (albite + fine-grained zoisite and/or clinozoisite); recrystallization of magmatic quartz to polygonal aggregates.

As previously discussed the phengites of this sector give early-Alpine ages. In places plagioclase is preserved, generally as relics in K-feldspar, indicating that the P-T conditions for its breakdown were not attained.

In the intermediate area between the early-Alpine greenschist-facies sector and the higher-pressure (« eclogitic ») sector, glaucophane (largely transformed) is quite common. In this area too the phengites give early-Alpine ages.

a.3) *Sector B2*. The present knowledge of the « Gneiss Minuti » Complex allows two different interpretations of the early-Alpine metamorphic zonation in this area:

1) The « eclogitic » assemblages developed in the whole Lower Element south of the boundary Gaby-Lower Ayas Valley, but were completely obliterated in Sector B2 by the Lepontine event.

2) South of the boundary Gaby-Lower Ayas Valley the early-Alpine event developed mineral assemblages of lower pressure, as is observed in the Northeastern sector (Sector B1).

b) *Lepontine metamorphic evolution*

This event extends over the external portion of the Lower Element (« Gneiss Minuti » Complex). It is characterized by assemblages typical of the greenschist facies with albite, Fe-epidote, phengite, chlorite, green biotite, ± Mn-rich garnet, ± actinolite, ± stilpnomelane as main constituents.

These minerals belong to stable assemblages, as shown by microscopic observations and by the partition coefficients of Fe and Mg between coexisting biotite, chlorite and amphibole (LATTARD, 1974).

Albite, which is a main constituent of the « Gneiss Minuti », occurs as at least two generations; the second one is later in the textural evolution and develops mainly at the expense of white mica layers. Stilpnomelane also seems to occur as two generations: the first one has a restricted occurrence and coexists with green biotite and chlorite; stilpnomelane II appears later as unoriented sheaf-like aggregates and needles in the groundmass.

Lepontine assemblages are found overprinting early-Alpine assemblages (sector B3) or Hercynian magmatic assemblages (sector B2), but can also occur in rocks (« Gneiss Minuti ») devoid of earlier relics.

In the sector where overprinting relations occur, the most significant transformations are:

Na-amphiboles and pyroxenes	→ albite + actinolite albite + chlorite	± green biotite
garnet	→ chlorite ± green biotite ± epidote	
rutile	→ sphene	
zoisite	→ Fe-epidote	

Characteristic albite + chlorite ± actinolite ± green biotite pseudomorphs, mainly after glaucophane, are common in these rocks.

In the external sector (B2) the minerals of the granitoids show transformations which are completely or largely related to the Lepontine phase (DAL PIAZ et al., 1971).

These transformations are:

K-feldspar	→ chessboard albite → albite + phengite	
plagioclase	→ epidote + phengite + albite	
biotite	→ white mica + rutile → albite + rutile → green biotite ± chlorite	
hornblende	→ actinolite → chlorite → green biotite	± albite

Even where these transformations are almost complete (giving rise to the typical « Gneiss Minuti » appearance) relics of K-feldspar and allanite can still be found, which show that most « Gneiss Minuti » must come from granitoids.

3.3.6. *P-T conditions during the early-Alpine event*

During the early-Alpine metamorphic event the Sesia-Lanzo Zone reached its highest pressures in the Eclogitic Micaschist Complex, which is characterized by:

a) breakdown of albite to produce jadeite + quartz;

b) widespread occurrence of almandine-rich garnet, zoisite, glaucophane and phengitic micas.

Temperatures of 300-400° C and pressures in excess of 8-14 kb were inferred by DAL PIAZ et al. (1972) and COMPAGNONI and MAFFEO (1973) from comparison of the phase assemblages occurring in the Eclogitic Micaschist Complex with experimentally determined P-T equilibria. The inferred pressures roughly correspond to a minimal lithostatic load of 30-40 Km.

The early-Alpine metamorphic gradient in the Lower Element of the Sesia-Lanzo Zone was considered to be characterized by a transition from glaucophanitic greenschist facies assemblages (sector B1) to jadeite-quartz-garnet assemblages (sector A). The early-Alpine high pressure-low temperature metamorphism was believed to evolve through a progressive pressure decrease accompanied by a constant or slightly increasing temperature.

Other estimates of the recrystallization temperature in the Eclogitic Micaschist Complex (VELDE and KIENAST, 1973; LIEBEAUX, 1975) are based on questionable assumptions (e.g. the stable coexistence of jadeite and omphacite with albite); moreover, the temperatures inferred for the northeastern part of the Eclogitic Micaschist Complex by VELDE and KIENAST ($T = 700°$ C with $P_{H_2O} = 11\text{-}12$ Kb) appear much too high in view of the occurrence of chloritoid (not of staurolite) throughout this part of the Sesia-Lanzo Zone.

The P-T conditions inferred for the Sesia-Lanzo Zone mineral assemblages from experimental petrology may be wrong in detail, but not in order of magnitude. The experimental data show that for the development of the early-Alpine high pressure-low temperature metamorphism a kynematic model is required which allows the achievement of high pressures and their subsequent decrease in a relatively short time.

It is necessary that this process be rapid in order to avoid the conversion of the high pressure-low temperature assemblages into amphibolite-facies assemblages due to the otherwise unavoidable rise in temperature. For this reason we also believe that the initial temperature (during the highest pressure) must have been below 500° C. This petrological interpretation agrees with that proposed by P. BEARTH (1967, 1974) for the high pressure-low temperature metamorphism in the meta-ophiolites of the Piemonte Zone.

3.4. *Structural Data*

Detailed structural work is in progress in the Gressoney Valley and in the Bard and Mt. Mucrone areas.

Thrusting of the Upper over the Lower Element is found to post-date the high-pressure metamorphism and to be, in turn, overprinted by later folding. At present a minimum of four generations of folds is recognized in all areas in rocks belonging to both the Upper and Lower Element. At least three of these generations (F2-F4) post-date the thrusting. Of the three the earlier two (F2 and F3) are cut by andesite dikes and must therefore be older than 30 m.y.. No overprinting relationships are known between the youngest folds (F4) and the dikes. In all the three areas the last three fold generations are represented by large scale structures so that the overall structure is very complex. This is almost certainly true also of the whole Sesia-Lanzo Zone and means that structural interpretations should not be made without detailed analysis of small scale structures.

3.5. *Dent Blanche Nappe*

The Dent Blanche Nappe shows the same tectonic duality as the Sesia-Lanzo Zone and a very strong lithological and metamorphic analogy.

The Upper Element (Valpelline Series) corresponds to the « II Zona Diorito-kinzigitica ». The Lower Element comprises the Arolla Series (equivalent to the « Gneiss Minuti » Complex of the Sesia-Lanzo Zone) and Eclogitic Micaschists (equivalent to the Eclogitic Micaschists Complex of the Sesia-Lanzo Zone). The former occurs mainly in the Northern Klippen (Dent Blanche Nappe s.s., Mt. Mary, Pillonet) and the latter only in the Southern Klippen (Mt. Emilius and Glacier-Rafray).

1) *Pre-Alpine lithology and evolution*. The *Upper Element* consists of granulites, high-temperature paragneisses, amphibolites and marbles. The pre-Alpine evolution can be outlined as follows (Boriani et al., 1974, 1975; Hunziker, 1974):

a) deposition of a pelitic sequence, with minor carbonate rocks, accompanied by igneous activity (pre-Ordovician);

b) granulite-facies event (Ordovician-Silurian);

c) low-pressure (cordierite) amphibolite-facies metamorphism of Hercynian age (Carboniferous?), with subsequent cooling ages of micas of 200-180 m.y. (Dal Piaz et al., 1972; Hunziker, 1974).

In the *Lower Element*, the Arolla Series mainly consists of late-Paleozoic granitoids (mostly granites and granodiorites, Stutz, 1940); their original assemblages are rarely preserved, and they are mostly transformed into greenschist-facies orthogneisses and albite-bearing « Gneiss Minuti » (Arolla Gneisses of the older authors). The stratified gabbro complexes occurring as tectonic intercalations in the Arolla Series of Matterhorn and Mt. Collon comprise two pyroxene ± olivine gabbros with minor plagioclase peridotites and anorthosites (Dal Piaz, 1974 a).

The Eclogitic Micaschists of the Mt. Emilius Klippe comprise metagranitoids and more abundant paraschists derived from high-grade paragneisses, with marbles and metabasics, very similar to the kinzigitic sequence (Bearth et al., in prep.).

2) *Alpine Metamorphism*. In the *Upper Element* the Alpine metamorphism is very similar to that of the « II Zona Diorito-kinzigitica »: i.e. it is polyphase, of low temperature, heterogeneously distributed and occurs mainly in areas of strong Alpine deformation. The earliest Alpine assemblages in the kinzigitic sequence are characterized by kyanite + phengite + garnet ± chloritoid. An important difference with respect to the « II Zona Diorito-kinzigitica » is the apparent lack of blue amphibole.

In the *Lower Element* early-Alpine eclogitic assemblages are found in the Mt. Emilius Klippe (well preserved) and in the Glacier-Rafray Klippe (as relics). Glaucophane- and aegirine-relics (of indeterminate Alpine age) occur in the Pillonet Klippe. No traces of high pressure-low temperature minerals have been found in the Dent Blanche- and Mt. Mary Klippen which seem to have escaped the eclogitic metamorphism.

The second metamorphic event (Lepontine, 38 m.y.) produces greenschist-facies mineral assemblages in both tectonic elements.

In the *Upper Element,* the Lepontine retrogression is very irregularly distributed and occurs mainly in areas of more intense deformation. The Lepontine event produces a partial to complete recrystallization of the Hercynian metagranitoids and metamorphics in the Northern Klippen of the Lower Element (Dent Blanche, Mt. Mary, Pillonet); in the Mt. Emilius and Glacier-Rafray Klippen these assemblages strongly overprint the earlier high pressure-low temperature assemblages.

3) *Alpine folding*. The entire Dent Blanche Nappe shows polyphase Alpine folding with longitudinal and transversal trends. These deformations are also visible on a regional scale and give rise to tectonic enveloping of the Upper Element by the Lower Element and of the Dent Blanche Nappe by the Piemonte Zone.

4. Discussion

The Sesia-Lanzo Zone and the Dent Blanche Nappe provide evidence of a high pressure-low temperature metamorphism taking place in the continental basement and overprinting pre-Alpine metamorphics and granitoids. The occurrence of jadeite-quartz-garnet-zoisite assemblages in the continental crust is most uncommon throughout the rest of the world. Furthermore the high pressure-low temperature assemblages of the Austroalpine system are now embodied in the topmost crystalline elements of the Western Alps nappe pile. Thus we believe that the Sesia Lanzo-Dent Blanche system represents an unusual tectono-metamorphic situation very significant from a geodynamic point of view.

4.1. *Alpine metamorphism in the Austroalpine system*

4.1.1. *Early-Alpine event*

The occurrence of eclogitic and greenschist-facies assemblages of the same age in adjacent sectors of the Lower Element enabled Dal Piaz et al. (1972) to approximately locate an early-Alpine isograde (line a-b in fig. 7).

This line divides an internal Northeastern sector characterized by greenschist-facies assemblages, from an internal Southern sector, characterized by eclogitic assemblages. Throughout the external sector of the Sesia-Lanzo Zone, the Lepontine metamorphism masks the western extent of the early-Alpine metamorphic zones and related isogrades; the early-Alpine metamorphism of the Sesia-Lanzo Zone is sharply bounded to the south-east by the suture of the non-ophiolitic Canavese basin, which was interposed during Triassic to Cretaceous times between the Austroalpine domain and the Insubric domain (Southern Alps).

In the Dent Blanche Nappe, the picture is even more complicated by the tectonic dismemberment of the Lower Element. However, possible extension of the early-Alpine isogrades beyond the Sesia-Lanzo Zone can be argued. The Lower Element of the Dent Blanche Nappe did not reach the pressure conditions of the Eclogitic Micaschist Complex. This is proved by the widespread occurrence of relict igneous plagioclases in metagranitoids. In the Eclogitic Micaschist Complex (e.g. Mt. Mucrone) on the contrary the plagioclases are always transformed into jadeite + + zoisite + quartz.

It is therefore concluded that in the Northern Klippen of the Dent Blanche Nappe (Dent Blanche Nappe s.s., Mt. Mary and Pillonet) the early-Alpine metamorphism, where developed, should have comprised greenschist-facies assemblages.

The Southern Klippen of the Dent Blanche Nappe (only consisting of Lower Element) show on the contrary widespread high pressure-low temperature assemblages. These parageneses are locally well preserved at Mt. Emilius, whereas they are intensively transformed by the later greenschist-facies Lepontine episode in the Rafray-Glacier Klippe.

It is believed that the early-Alpine isograde in the Lower Element of Dent Blanche Nappe should run approximately along the Aosta Valley (line b-c in fig. 7). Taking into account these data and the early-Alpine isograde preserved in the Sesia-Lanzo Zone (line a-b), it was proposed that all the Sesia-Lanzo Zone between the Aosta and Lanzo Valleys underwent high pressure-low temperature conditions during the early-Alpine metamorphic event.

This means that the « Gneiss Minuti » of this sector should represent the original « eclogitic micaschists » completely transformed during the Lepontine phase. However, significant high pressure-low temperature relics seem to be lacking in this sector (see also LATTARD, 1974).

Another hypothesis can be proposed for the present position of the early-Alpine isograds, which takes into account the Lepontine deformations. According to this hypothesis the early-Alpine isograds have been folded and transposed; it is therefore possible that the isograds could be transposed into approximate parallelism with the major axis of the Sesia-Lanzo Zone and could at present run — masked by the Lepontine overprint — across the « Gneiss Minuti » Complex, between the Aosta and Lanzo Valleys (line b-d in fig. 7).

Such a discussion is relevant to the paleogeographical reconstruction. The first interpretation enables us to directly connect the Southern Dent Blanche Klippen to the external Sesia-Lanzo Zone margin, while the second hypothesis obliges us to refer these Klippen to some internal part of the Eclogitic Micaschist Sector.

However, any new interpretation of the evolution of the Sesia-Lanzo Zone - Dent Blanche System must take into account the following points:

1) The early-Alpine metamorphism has different characteristics in the two structural elements of the Austroalpine system. In the Upper Element the high pressure-low temperature assemblages of the « II Zona Diorito-kinzigitica » and Valpelline Series are very similar. On the other hand a metamorphic facies transition can be observed in the Lower Element.

2) The high pressure-low temperature assemblages occur not only close to the thrust planes but are homogeneously distributed throughout the Lower Element.

3) The early-Alpine isogrades do not intersect the tectonic boundaries of the Lower Element, i.e. they do not enter the Upper Element or the underlying Piemonte Zone, but are cut by the thrust boundaries. Thus the early-Alpine high pressure-low temperature metamorphism predates thrusting and is not dependent on depth in the nappe pile.

4) In the Eclogitic Micaschist Complex the early-Alpine isograds are still unconformable to the length of the Sesia-Lanzo Zone and the Canavese Line. The early-Alpine metamorphic gradient rises to the South and lies almost parallel to the thrust planes.

The foregoing data lead to the following conclusions:

The early-Alpine metamorphism predates the final thrusting of the Austroalpine system over the Piemonte Zone, and of the Upper Element over the Lower Element. The early-Alpine metamorphism is therefore preserved in « tectonically transported rock bodies ». It originated before the present development of the nappe pile and its subsequent folding.

4.1.2. *Lepontine event of 38 m.y.*

The second Alpine metamorphic episode (Lepontine) needs to be discussed further. It is well known that its isogrades cut the nappes discordantly (Frey et al., 1974, with references). In the Ossola-Ticino region, where the Lepontine reached amphibolite-facies conditions, the metamorphism is typically post-tectonic with respect to the main deformations (« Lepontine crystallization »).

Several authors (Ellenberger, 1958; Niggli, 1970) believe that the Lepontine metamorphism is related to the geothermal readjustement produced by the nappe pile. Others (e.g. Wenk, 1962, 1970; Thompson, 1976; Streckeisen and E. Wenk, 1974), on the contrary, believe that it is the consequence of a thermal dome, of deep origin, unrelated to the nappe overburden.

With regard to the Sesia-Lanzo - Dent Blanche system, the occurrence of the 38 m.y. metamorphic event in the Lower Element appears to be unrelated to the tectonic load resulting from the Upper Element. The Upper Element, in places, overlies « Gneiss Minuti » of Lepontine age but elsewhere overlies eclogitic micaschists of early-Alpine age. Furthermore, the maximum magnitude of the

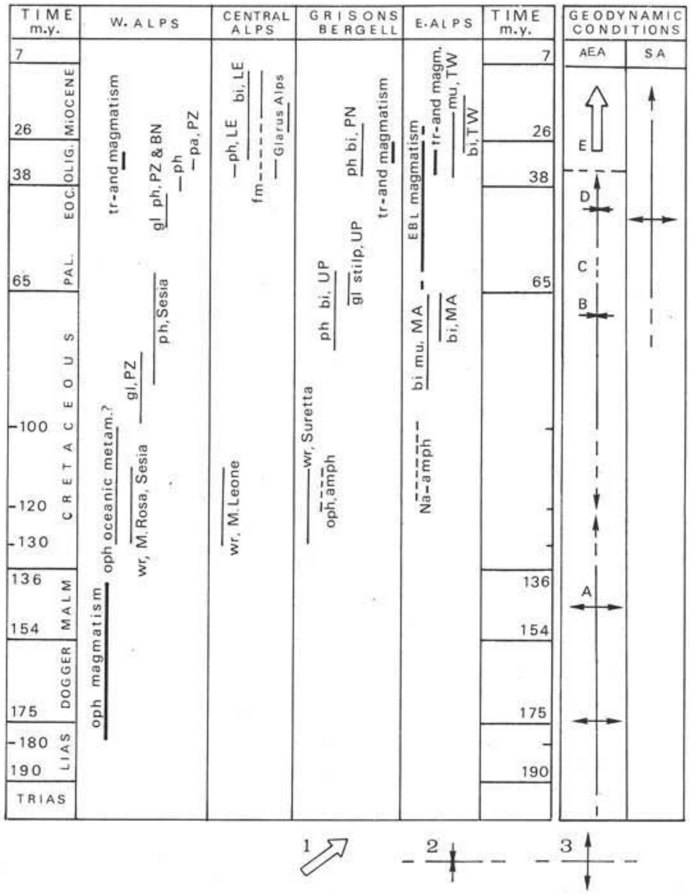

Fig. 14. — *Age determinations of ophiolite emplacement, « oceanic » metamorphism and Alpine metamorphism in the Alps* (after Frey et al., 1974; simplified). The general trend of geodynamic conditions in the external and axial zones (AEA) and in the Southern Alps (SA) is shown by arrows: 1) uplifting; 2) convergence; 3) divergence. Main events in the Alpine history are: opening of the oceanic basin (A); subduction, high pressure-low temperature metamorphism and thrusting (B); Paleocene restoration (C); crustal shortening and Lepontine metamorphism (D); uplift (E).
Oph = ophiolite; wr = whole rock; gl = glaucophane; ph = phengite; pa = paragonite; tr-and = = trachyandesite; bi = biotite; mu = muscovite; stilp = stilpnomelane; amph = amphibole; fm = fissure minerals. PZ = Piemonte Zone; BN = Bernhard Nappe and Briançonnais; LE = Lepontine Nappes; UP = Upper Pennine Nappes; PN = Pennine Nappes; MA = Middle Austroalpine; EBL = Euganei-Berici-Lessini; TW = Tauern Window.

presumed tectonic load, even allowing for what has been subsequently removed by gravitational slidings and by post-Oligocene erosion, is inadequate to produce the greenschist-facies assemblages in the Lower and Upper Element. Therefore we believe that in the Austroalpine System the Lepontine metamorphism is related to a thermal dome and not simply to burial by nappes. It is worthwhile to note that the thermal peak of this metamorphic event is only 7-8 m.y. older than the trachyandesitic magmatic cycle.

In the Ossola-Ticino region, the internal boundary of the thermal dome would correspond to the Insubric Line that divides a Northern domain (Pennine Zone) with an Alpine metamorphic imprint, from a Southern domain (Southern Alps) lacking Alpine metamorphism.

In the Northwestern Alps the internal boundary of the Lepontine metamorphism is no longer coincident with the Canavese Line, but it traverses the Sesia-Lanzo Zone.

4.2. *Alpine orogenic evolution and geodynamic models*

4.2.1. *Distribution of the early-Alpine event in the Western Alps*

A high pressure-low temperature event occurs in other units of the Western Alps. In some areas it is proved to be of early-Alpine age (fig. 14) and elsewhere, though not yet demonstrable, it is believed to be of the same age:

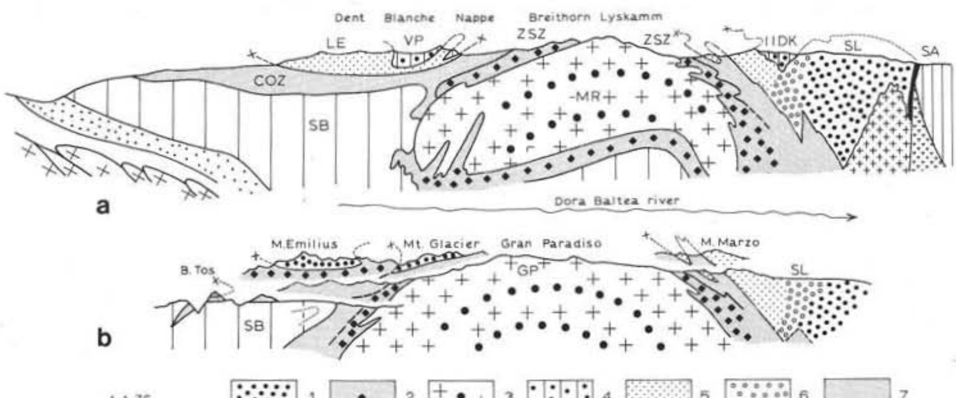

Fig. 15. — *Distribution of the early-Alpine assemblages in the internal Northwestern Alps.* 1) Eclogitic assemblages in the continental crust. 2) Eclogitic assemblages in metaophiolites of the Zermatts-Saas Zone. 3) Eclogitic assemblages in metabasics of the Monte Rosa-Gran Paradiso Nappe. 4) Kyanite-chloritoid-glaucophane-garnet assemblages in high-grade rocks of the Upper Element. 5) Assemblages of low-grade greenschist facies; their occurrence in the Arolla Series (LE) is tentatively suggested. 6) Assemblages with glaucophane, but lacking jadeite, intermediate between 1) and 5). 7) Low-grade assemblages. The distribution of early-Alpine assemblages in the Bernhard Nappe is not shown for lack of data.

a) The sheets of oceanic crust of the Piemonte nappe contain high pressure-low temperature assemblages ranging from eclogitic (internal side) to lawsonite-glaucophane ± Na-pyroxenes (external side). Their age has been determined radiometrically (Bocquet et al., 1974) and by overprinting relations in the Western Alps (Dal Piaz, 1974 b). These assemblages do not include the later generation of Na-amphiboles and locally occurring lawsonite; some of these can be attributed to more recent metamorphic phases (Hunziker, 1974; Bocquet et al., 1974; Caron, 1974). It also seems possible to trace in some areas an isograde for the high pressure-low temperature metamorphism in the oceanic part of the Piemonte nappe. As in the Sesia-Lanzo Zone the pressure increases towards the internal side.

b) Relics of eclogitic associations, very likely of early-Alpine age (certainly post-Hercynian and pre-Lepontine), occur in the metabasic lenses of the internal Pennine crust (Monte Rosa, Gran Paradiso and Dora-Maira); kyanite-phengite-chloritoid ± glaucophane ± garnet assemblages are developed after the high-temperature paraschists and the Hercynian granitoids (BEARTH, 1952; DAL PIAZ, 1966, 1974 b; COMPAGNONI and PRATO, 1969; COMPAGNONI and LOMBARDO, 1974). A Cretaceous age has been postulated by VIALON (1966) for the metamorphism of the Dora-Maira nappe.

c) In the Bernhard nappe, several generations of Na-amphiboles occur, the oldest of which is early-Alpine (BOCQUET et al., 1974; HUNZIKER, 1974). Finally in a few places in this domain jadeite-quartz assemblages are known (BOCQUET, 1974, with references).

The whole Alpine metamorphism in the Bernhard nappe, has long been considered to be of Tertiary age on the basis of stratigraphic observations (RAGUIN, 1925; ELLENBERGER, 1958). However this interpretation has recently been questioned and requires further confirmation principally with respect to the age of the jadeite-quartz assemblages (BOCQUET, 1974). All these assemblages have been more or less intensively overprinted by the greenschist facies metamorphism (FREY et al., 1974, with references).

The distribution of the high pressure-low temperature assemblages in the North-western Alps (fig. 15) confirms what is observed in the Sesia-Lanzo Zone and Dent Blanche Nappe, i.e. sharp differences in early-Alpine metamorphic grade from one unit to another or from one sheet to another. The best evidence is provided by the occurrence of the Combin Zone (which has never bee nsubjected to high-pressure conditions) of the Piemonte nappe between the eclogitic micaschists of the Austroalpine Lower Element and the eclogitic metaophiolites of the Zermatt-Saas Zone (DAL PIAZ et al., 1972; KIENAST, 1973).

Sometimes adjacent sheets show nearly analogous high pressure-low temperature associations (i.e. Monte Rosa/Zermatt-Saas Zone; Glacier-Rafray Klippe/eclogitic metagabbros of the Savoney Valley), but in detail they are still different.

We can conclude also that on the regional scall the *early-Alpine high pressure-low temperature assemblages in the Western Alps predate the thrusting phase; the early-Alpine isogrades do not crosscut the thrusting planes of the nappe pile, but have been displaced by them*. Secondly, the different early-Alpine metamorphic assemblages of each nappe indicate that every unit (or couple of units) should have experienced an independent metamorphic and structural evolution during the early-Alpine event.

Keeping in mind the paleogeographic setting and the distribution of the high pressure-low temperature metamorphism in the Western Alps, the following conclusions must be drawn: the early-Alpine metamorphism occurs not only within the sutured oceanic Piemonte basin, but in contrast to current models of continental collision, it occurs also within the squeezed out Austroalpine and Pennine continental margins. Hence the same tectonic event, capable of producing high pressure-low temperature conditions, must have involved narrow, marginal zones of both the opposite continents as well as the intervening oceanic crust.

4.2.2. *Regional significance of the Upper Cretaceous event*

Evidence of an early-Alpine tectonic event in the Western Alps is recorded also in some sedimentary sequences as indicated by the occurrence of the well known Cretaceous Flysches and by stratigraphic and structural observations in the French Western Alps and in the Southern Alps (Lemoine, 1972; Haccard et al., 1972, with references).

The regional significance of the Upper Cretaceous event is confirmed in the central and Eastern Alps, where Kober (1955), Tollmann (1963), Oberhauser (1964), Clar (1965), Woletz (1967), Müller (1973) and Trümpy (1973) postulated a Cretaceous tectonic event, mainly on the basis of sedimentological and stratigraphic criteria. An early-Alpine metamorphic event (90-65 m.y.), followed by a Tertiary tectono-metamorphic event has been radiometrically dated in the Eastern Alps (fig. 12) by Oxburgh et al. (1966), Cliff et al. (1971), Schmidt et al. (1967), Miller et al. (1967), Harre et al. (1968), Cliff et al. (1971), Satir (1974).

4.2.3. *Discussion of tectonic models*

Experimental work indicates pressures equivalent to 30-40 Km depth of burial for the high-pressure rocks of the Western Alps. We do not believe that such high pressures can be explained by tectonic overpressure models (see e.g. Rutland, 1964; Brace et al., 1970) nor they can be explained by burial by the nappe pile, since this can be shown to have been too thin (Dal Piaz et al., 1972; Dal Piaz, 1974 b; Hunziker, 1974). The only reasonable possibility therefore is a subduction model (Hunziker, 1970, 1971, 1974; Ernst, 1971, 1973 a, 1975; Dal Piaz, 1971, 1971 a and b; Dal Piaz et al., 1971, 1972, 1973; Bocquet, 1974; Laubscher, 1975). Oxburgh & Turcotte (1968), Oxburgh (1972), Dal Piaz (1974 a and b), Dietrich (1974), Hawkesworth et al. (1975) proposed an analogous interpretation for the Central and Eastern Alps and for the Apennines.

Others have ignored or underestimated the geodynamic significance of the high pressure-low temperature metamorphism in considering only the paleogeographic and kinematic evolution of the Alpine chain (Laubscher, 1970, 1971; Giese et al., 1970; Dewey and Bird, 1970; Boccaletti et al., 1971; Scholle, 1970; Roeder, 1973).

All proposed models appear too simple to explain the complexity of the Alpine tectonic and metamorphic evolution. This situation undoubtedly arises from the still incomplete knowledge of the characters and distribution of the Alpine metamorphism in the Western Alps. Furthermore, structures coeval with the high pressure-low temperature early-Alpine event have not yet been deciphered at a scale large enough to show the sense of regional coupling. However, consensus is apparent on a few points. Evidently, the western Alpine chain is produced by a continental collision with closing of the intervening oceanic basin, followed by a subsequent thermal and tectonic episode (Eocene-Lower Oligocene) involving further shortening of the crust and finally buoyant uplift (Oligocene to Recent). The latter phase is accompanied by trachyandesitic magmatism and surficial sliding possibly due to gravity [8].

ERNST's first model (1971) implies the subduction of a single large plate which comprises the European continental margin, the ophiolite basin and the Sesia-Lanzo Zone. This plate is subducted under the Southern Alps without disrupting the main paleogeographic setting. A regular monophase metamorphic zonation results from this dynamic event. Pure buoyant uplifting allows the preservation of the high pressure-low temperature associations. In later models (ERNST, 1973 a, 1973 b, 1975) the complexity of the metamorphic pattern in the Northwestern Alps is considered and the original single plate is dismembered in an imbricated subduction zone, with external younging of progressively lower-grade metamorphic recrystallization; westward stepping of the subduction zone accounts for the uplifting of the more deeply subducted internal parts.

DAL PIAZ et al. (1972) and HUNZIKER (1974) have proposed a different model which takes into account two tectono-metamorphic events in the Western Alps. The early-Alpine event (90-70 m.y.) produces subduction tectonics with related eclogitic to greenschist-facies and lower-grade assemblages. The closing of the Piemonte basin involves thrusting under a low thermal regime. This model also suggests a subduction process involving a plate that is subdivided into several sheets interplaying in a complex way. In this view relative displacements between the sheets and different subduction velocities can be justified and a progressive north-westwards migration in time and space of the subduction zone is more feasible. The internal limit of the subduction zone is represented by the early Canavese line.

A rapid rise of fragments of oceanic and continental crust from a depth of 30-35 Km in the subduction zone is required in order to preserve the newly formed early-Alpine metamorphic associations of the Sesia-Lanzo Zone. According to DAL PIAZ et al. (1972) a 25-35 Km rise appears to be accomplished not simply by vertical uplift, but mostly by movements with a significant oblique component, consistent with the subduction geometry but with opposite sense of translation. This process leads to the first major thrusting phase (early-Alpine). The early-Alpine event is followed by a period of tectonic inactivity relatively to the surface (TRUMPY's, Paleocene restoration).

From Eocene to Lower Oligocene a thermal dome develops, producing the second metamorphic event (38 m.y., Lepontine) and activating polyphase ductile deformation, giving rise to large scale folding of the nappe pile leading to pronounced crustal thickening.

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(8) References to the classic works of LUGEON, SCHARDT, GAGNEBIN and SCHNEEGANS on gravitational tectonics in the Western Alps can be found in HILLS (1963, p. 337-338) and GOGUEL (1965, p. 239-240).

The general uplift of the axial part of the nappe belt [9], the deposition of the marginal Molasse (Middle Oligocene to Recent) and the trachyandesitic magmatism (33-25 m.y.) mark a sharp change in the tectonic regime and the beginning of the extensional conditions.

In the Mio-Pliocene new nappes involving only the sedimentary cover developed at the margins of the chain; it is said that they are related to gravity tectonics and do not necessarily imply a significant amount of shortening in the crystalline basement.

4.2.4. *Oligocene magmatism and timing of continental collision*

Two important topics deserve further discussion:

a) the geodynamic significance of the Oligocene magmatism, and

b) the timing of the continental collision in the Western Alps.

The Oligocene magmatism of the internal Northwestern Alps is represented by volcanic and plutonic rocks. The volcanics comprises andesites, trachyandesites and lamprophyres, with minor basalts including shoshonitic types [10]. The plutonic rocks range from granites to monzonites and quartzdiorites.

The Oligocene magmatism has a peculiar distribution both in space and in time: it occurs not only in the overriding Insubric plate (Southern Alps), but also in the Austroalpine and — locally — in the Piemonte nappe. That is to say it occurs also in the sutured subduction zone, with a maximum distribution in a band along the Insubric line. Volcanic graywackes of Upper Eocene-Lower Oligocene age, containing up to 90 percent andesite fragments, occur in the external part of the Western Alps (Grès de Taveyanne: Martini, 1968; Thônes syncline, Champsaur, Clumanc, St. Antonin syncline: Biju-Duval & Gubler, 1961), but the source area of this volcanic material is still unknown.

The Oligocene magmatism develops after the continental collision and thus does not represent a volcanic belt of circum-pacific type [11]. Dal Piaz et al. (1972, 1973) suggested relating the Oligocene magmatism to the early-Alpine subduction of the Piemonte oceanic crust [12]. The time gap (over 30 m.y.) between subduction and magmatism according to them may be due to lack of crustal extension until Middle Oligocene. At this time extension begins and melting becomes possible. This interpretation requires a post-collisional rotation of the subducted oceanic plate up to the dip of the present Canavese line, or an originally vertical subduction zone, as proposed by Laubscher (1970).

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(9) Clark and Jaeger (1969) quantitatively evaluated the uplift rate as 0,4-4,0 mm/year.

(10) New work on the geochemistry and geochronology of these rocks is in progress.

(11) An Upper Cretaceous andesitic magmatism was recently ascertained in the overriding Insubric plate in the Central (Gansser, 1968; Casati et al., 1976) and Eastern Alps (Gatto et al., 1976).

(12) In the present authors' opinion the Oligocene magmatism cannot be related to Oligocene subduction of the more external Valais basin, because this basin does not seem to have had an oceanic crust.

A simpler mean of explaining the Oligocene magmatism has been proposed by TRÜMPY (1973, 1975). According to this model, closing of the oceanic basin, subduction, continental collision and thrusting occurred during the « Meso-Alpine » phase (Upper Eocene-Lower Oligocene); crustal shortening would amount to at least 300 Km. This model, however, is not tenable because it ignores both the high pressure-low temperature assemblages and the Upper Cretaceous magmatism, and their petrological significance. Furthermore it cannot be applied to the Western Alps.

An intermediate solution has been devised by LAUBSCHER (1975). A very long subduction episode, occurring from Upper Cretaceous to Eocene, explains the early-Alpine metamorphism and the Oligocene magmatism. This model, actually, implies a very wide oceanic basement, which contradicts the sedimentological evidence of the Piemonte Zone. Moreover, the sinking into the mantle of such a huge volume of oceanic crust should have produced an extended Upper Cretaceous to Oligocene volcanic belt of circumpacific size. No trace of such a belt has yet been found in the Alps. In addition a very long subduction phase such as that postulated by LAUBSCHER poses additional difficulties to the rapid exuming required for the subducted materials to escape thermal reequilibration of the early-Alpine high pressure-low temperature assemblages.

5. Conclusions

The preservation of superposed Alpine metamorphisms in the Sesia-Lanzo Zone - Dent Blanche Nappe and Piemonte metaophiolite nappe makes it possible to discuss the feasibility of applying theoretical plate-tectonics models to the Western Alps.

The most peculiar feature of the Alpine evolution appears to be the marked duality of its: 1) pre- and 2) post-collisional, tectonic, metamorphic and magmatic history.

1) The pre-collisional history of the Western Alps, even if it is broadly consistent with an Andean-type evolution, differs from this model in some essential aspects:

a) subduction and high pressure-low temperature metamorphism involve both continental and oceanic crust;

b) andesite activity within the overriding plate is rare;

c) there is an apparent lack of high-temperature metamorphism (paired belt) in the overriding plate.

Continental collision in the Western Alps does not result in exhumation of the subducted materials in the form of tectonic mélanges but in the form of nappes in which the continuity of large units and their deformation history are preserved.

2) The post-collisional evolution of the Western Alps seems to be characterized by:

a) the occurrence of a thermal dome of regional extent (Lepontine metamorphism) overprinting the earlier high pressure-low temperature belt, and

b) by crustal shortening and thickening accompanying folding of the early-Alpine nappes.

The latter process is followed by extensional conditions leading to the andesite magmatism and buoyant uplift.

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