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THE IVREA-VERBANO MAFIC ULTRAMAFIC COMPLEX
OF THE ITALIAN WESTERN ALPS:
DISCUSSION OF SOME PETROLOGIC PROBLEMS
AND A SUMMARY ****

RIASSUNTO. — La successione stratigrafica del Complesso Basico ed Ultrabásico dell'Ivrea-Verbano è costituita da: a) peridotiti; b) pirosseniti, gabbro-noriti e anortositi; c) gabbro omogeneo o debolmente stratificato; d) « dioriti » s.l..

Metapeliti ed altri litotipi della Formazione Kinzigitica sono presenti come setti o inclusi nel corpo basico principale il quale ad Est appare in contatto magmatico con tale formazione mentre ad Ovest è delimitato dalla Linea Insubrica.

L'esistenza di peridotiti tettonitiche (rappresentanti il residuo refrattario da fusione parziale di rocce del mantello), distinguibili da altre peridotiti formate da fenomeni di frazionamento, è confermata dalle relazioni di campagna, dalla composizione chimica della roccia totale e delle varie fasi e dalla analisi fattoriale.

Dicchi e « pods » pirossenitici e gabbroici esistenti all'interno delle peridotiti tettonitiche costituiscono i primi frazionati del liquido formatosi per fusione parziale del mantello. La loro successione cronologica testimonia fenomeni complessi di messa in posto e di fusione.

È molto probabile che esistano relazioni tra i pods gabbroici ed il liquido da cui si è frazionato il Complesso Stratiforme.

Osservazioni di campagna, elementi geochimici ed equilibri di fase indicano che il corpo basico principale è una intrusione stratificata anche se, a differenza di altri complessi stratiformi, esso presenta una associazione con peridotiti di mantello ed una tendenza calco-alcalina.

Stime delle condizioni originali indicano che gli ultimi episodi di fusione parziale del mantello sono avvenuti a circa 15 kb e che il complesso si è frazionato ad una pressione di 8-9 kb ed ad una temperatura di 1100-1200° C. Sia le peridotiti tettonitiche che il complesso mostrano di avere subito una ri-equilibratura subsolida ad una temperatura di 800-900° C ed ad una pressione di 8-9 kb.

Il modello evolutivo proposto è il seguente: a) fasi di fusione del mantello con intrusione di magmi in ambiente di crosta profonda; b) frazionamento dei magmi in ambiente orogenico (dinamico); c) aumento termico accompagnato da fenomeni di anatessi nelle rocce della serie metapelitica; d) lento raffreddamento con ri-equilibratura finale a 800-900° C.

ABSTRACT. — The stratigraphy of the Ivrea-Verbano mafic-ultramafic complex consists of: a) peridotites; b) layered pyroxenites, gabbro-norites and anorthosites (Layered Series); c) weakly layered or homogeneous gabbro; d) « diorites » s.l.. Metapelites and other lithotypes of the so-called kinzigitic series occur as septa in the main basic body and at its eastern contact. Epipelutonic granites appear on the East side of the complex. Its western margin is marked by a major fault, the Insubric Line.

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Field relationships, bulk chemistry, mineral composition and factorial analysis indicate the existence of two peridotite types, one belonging to the Layered Series and formed by gravitative differentiation, the other representing refractory residual mantle.

Pyroxenitic and gabbroic dikes and pods occurring in the mantle peridotite represent early fractionates of the liquids formed by mantle partial melting.

They belong to various generations, indicating a complex history of the mantle emplacement and melting. Possibly, a relationship exists between the last gabbroic pods and the liquids that have fractionated the Layered Series.

Field evidence, geochemistry and mineral equilibria indicate that the main basic body is a layered intrusion, although peculiar for its association with mantle peridotites and for its calc-alkalic tendency.

Mineral equilibria indicate that the whole complex underwent re-equilibration at 800-900° C at an approximate pressure of 8 kb. Estimates of the original conditions suggest a temperature of 1100-1200° C and a possible pressure of 15 kb for the early mantle melting episodes and of about 8-9 kb for the fractionation of the layered complex.

The evolutive pattern proposed is: *a*) episodes of mantle melting with intrusion of magmas in the lower crust; *b*) fractionation of the magmas in an orogenic (dynamic) environment; *c*) thermal increase in the country rocks (metapelitic series) with possible anatexis; *d*) slow cooling with final equilibration at 800-900° C.

Introduction

The Ivrea zone is one of the most important geologic features of the Alps. This zone belongs to the southern Alps; it is unaffected by Alpine metamorphism, and is separated from the Pennine and Austroalpine domains by a major tectonic dislocation: the Insubric line (GANSSE, 1968; BORIANI & SACCHI, 1974). Its metamorphism, according to the age determination of GRAESER & HUNZIKER (1968), McDOWELL & SCHMID (1968), KOPPEL (1974), HUNZIKER (1978-79) presents two main events: one at about 470 m.y. and the other at around 300 m.y. It is doubtful if metamorphism flows continuously between the Caledonian event and the Hercynian one.

Geophysically, the Ivrea zone is marked by a gravimetric anomaly that indicates the presence of a low velocity layer at a depth of about 20-40 km, followed upwards (at 5-10 km of depth) by a high velocity zone (see GIESE, 1978-79 for references). This anomaly, which has a NE-SW direction and occurs from Locarno to the south of Ivrea, runs at the eastern side of the Insubric line; the interpretation generally held is that the anomaly reflects the presence of mantle at abnormally shallow depths.

It is generally held that the Ivrea zone represents a section through deep continental crust (MEHNERT, 1975). Lithologically, it is constituted by: *a*) a predominantly metapelitic series, with intercalated minor marbles and metabasite sheets; *b*) a main basic body, predominantly formed by metagabbros (basic granulites of BERTOLANI, 1968 a; CAPEDE, 1968, 1971; BERTOLANI & GARUTI, 1970; SCHMID, 1971 and SHERVAIS, 1978-79) and minor ultramafites; *c*) large peridotite slices occurring as aligned bodies near the western margin of the Ivrea zone. There is general agreement that the metapelite series (the so-called «Kinzigitic Formation»)

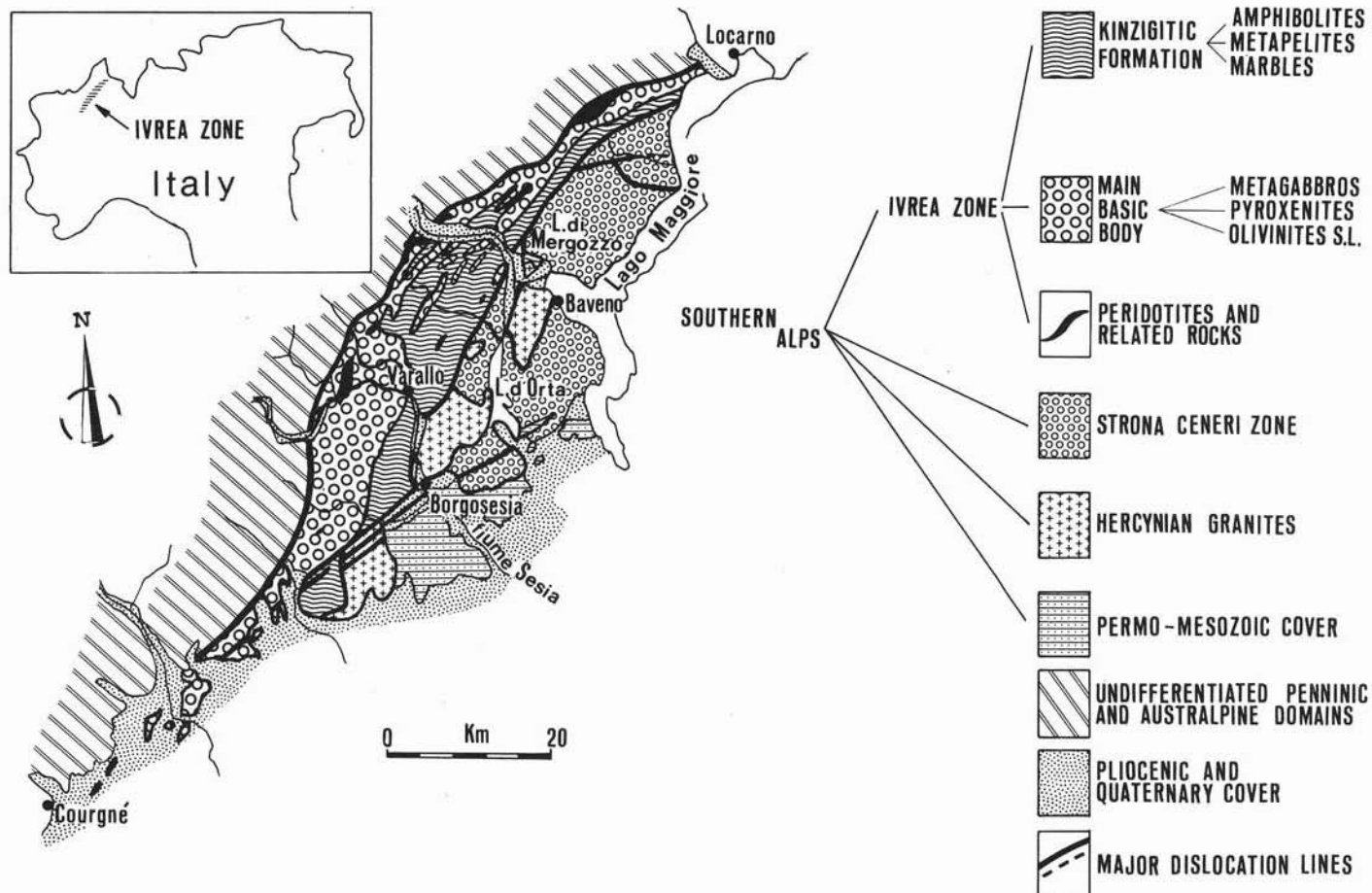


Fig. 1. — General geological setting of the Ivrea Zone (from various sources, mainly from BORIANI et al., 1977; LENSCH, 1971, and unpublished data).

shows a northwestwards increase in metamorphic grade, from amphibolite to granulite facies (BERTOLANI, 1968 b; SCHMID, 1972); to the South-East it is in tectonic contact along the Pogallo line with another predominantly metasedimentary formation (the «Serie dei Laghi», BORIANI & SACCHI, 1973) and is marked by the intrusion of Hercynian epiplutonic granites with contact metamorphism.

The main basic body is, according to BERTOLANI (1968 a) and CAPEDE (1968, 1971), affected by the same metamorphic features as the metapelitic series and should thus belong to the same geological unit. CAPEDE (1971), however, disagrees with the notion that the metamorphic changes are the result of a northwestward prograde metamorphisms; he postulates an older granulite-facies event and a later retrogression, toward the South-East, to amphibolite facies assemblages. A still different opinion is that of RIVALENTI et al. (1975), who have proposed that the main basic body represents a deep-seated layered complex, intrusive into the metapelite series; it should, therefore, be considered a different geological unit.

The peridotites, of which the main massifs are those of Baldissero, Balmuccia and Finero, are generally considered to be mantle material (LENSCH, 1968, 1971; RIVALENTI et al., 1975; CAPEDE et al., 1977 a) emplaced into the deep crust; doubts are cast about its continental or oceanic origin. RIVALENTI et al. (1975) and CAPEDE et al. (1977 a), however, have shown that some of the peridotites may have originated in the crust by fractional crystallization and cumulative processes related to the layered complex. Obviously, these different opinions carry with them rather contrasting ideas about the pre-Alpine history of the Ivrea zone. Any serious evolutive model to be proposed for the Ivrea zone must clearly distinguish the different geological units and offer a sound interpretation of their mutual relationships.

Up to now, the main points of discussion are concerned with four items:

- a) the interpretation that the main basic body was originally (or was not) a layered complex (CAPEDE, 1971; MEHNERT, 1975; SHERVAIS, 1978-79, 1979);
- b) the suggestion that two different peridotite types are actually present (ERNST, 1978; SHERVAIS, 1978-79);
- c) the relationships between the two peridotite types and the main basic body (SHERVAIS, 1978-79, 1979);
- d) the relationships between the main basic body and the metapelite series.

We will examine the available evidence, summarizing on the one hand the studies relevant to these subjects and providing on the other hand, additional unpublished data. We will try to clearly distinguish the different geological units and to establish their mutual relationships and, with this framework as a basis, propose an evolutive model for the Ivrea zone. We are, however, aware that our model will still be largely speculative and that many points will remain obscure till further work clears them up. In this paper particular attention will be put on the section through Sesia Valley, where particularly favourable field conditions, provide for outcrops across all the above-mentioned lithologies.

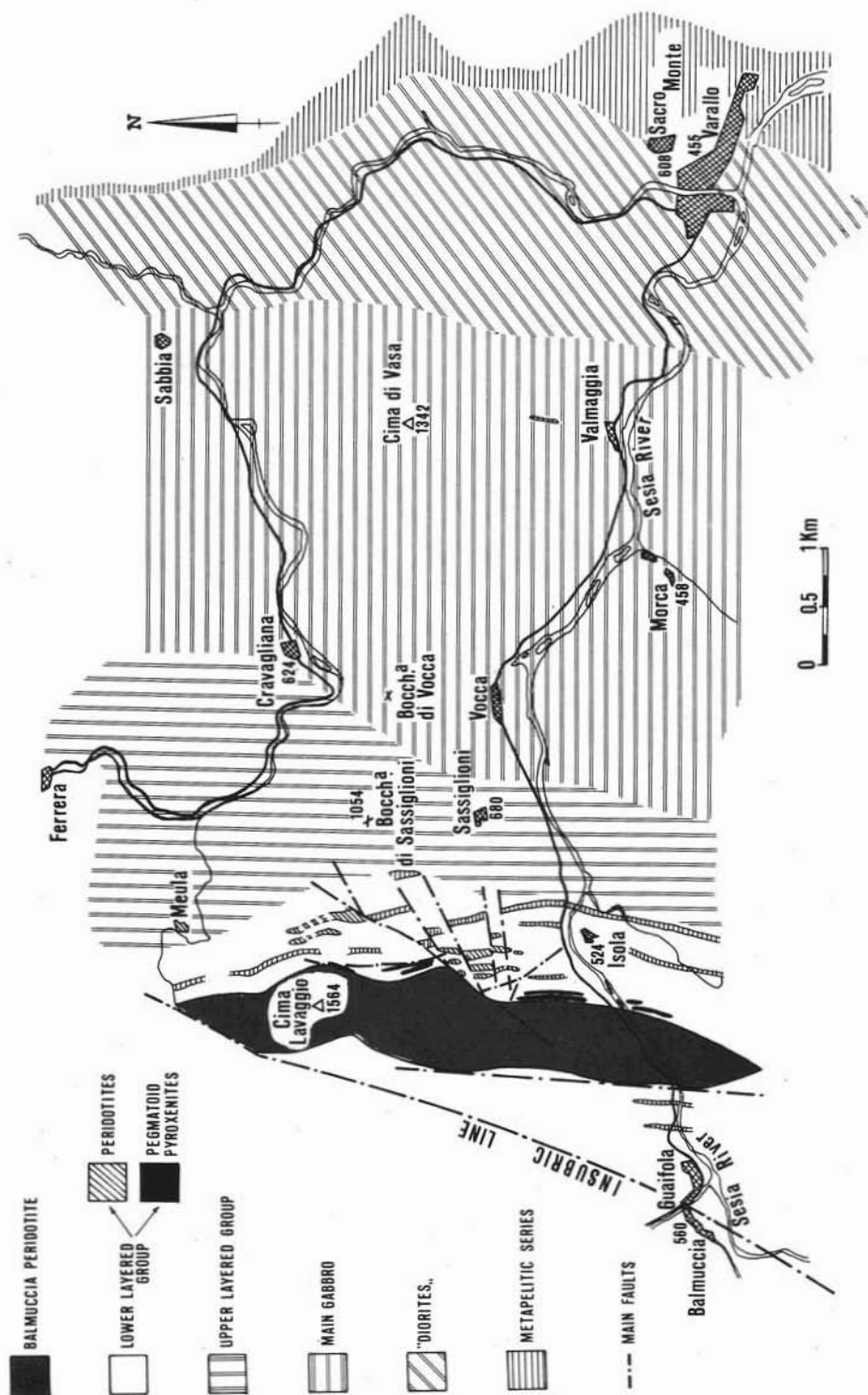


Fig. 2. — Lithological schematic section through the Sesia Valley.

Lithological cross section through Sesia Valley

This section extends from the Insubric line to the town of Varallo. The lithological succession is as follows (cf. Fig. 2):

- a) the main peridotite body of Balmuccia, with associated rocks;
- b) minor peridotites associated with the main basic body;
- c) the main basic body;
- d) « diorites »;
- e) metapelitic series and other felsic rocks.

THE BALMUCCIA PERIDOTITE

The Balmuccia peridotite is to the west in tectonic contact with mylonitized rocks of the main basic body or with Alpine schists. To the east it shows in places a primary igneous contact with the rocks of the main basic body (RIVALENTI, 1978-79). The dominant rock type is a medium-grained clinopyroxene-poor lherzolite, with minor zones of harzburgite and dunite. Hornblende is widespread as a minor phase. Unmixing of pyroxenes suggests that the rock re-equilibrated at lower temperature.

This peridotite displays a tectonite fabric (GARUTI, 1977; GARUTI & FRIOLO, 1978-79); it is mostly foliated, but porphyroclastic and protogranular textures (according to the nomenclature of MERCIER & NICOLAS, 1975) are also common. The more primitive protogranular texture appears as relict in the central part of the body, while foliated and porphyroclastic type predominates towards the contacts.

Two foliations are developed, intersecting each other at low angles. The first foliation is determined by the planar disposition of the minerals and is parallel to a very weak compositional layering. The second foliation is caused by shearing and is generally associated with the porphyroclastic texture.

A particular feature of this peridotite is the presence of dikes, which become more abundant towards the margin. Four different generations were distinguished on the basis of their mutual intersections: the oldest are olivine websterites, followed by the « ariegites » (spinel pyroxenite, cf. LENSCH, 1976) as the second and third generations. The youngest dikes are of pyroxenites and gabbros.

SHERVAIS (1978-79) considered these dikes as layers. Our interpretation however is substantiated by field evidence: if followed along their strike, the attitude of the dike contact changes from apparently concordant (to the regional foliation) to clearly discordant. Moreover the dikes often bifurcate and show apophyses. SHERVAIS (1978-79) divides his « layers » classifying them as belonging to two suites: a Cr-diopside suite, corresponding in part to our first dike generation, and an Al-augite suite (which corresponds to the dikes of our second, third and fourth generation, and another part of our cumulate pyroxenites). The older dikes cut unconformably the older peridotite foliation at a low angle. They are often boudinaged and become concordant with the second foliation, which wraps around the boudins. The second and third generation, although cutting each other, do

not show appreciable mineralogical variations and have the same attitude with respect to foliation. Their strike is irregular and they may pass from sub-concordant to discordant with respect to the first peridotite foliation. They may in part be interpreted as synkinematic intrusions, since they have been folded and show an axial-plane parallel to the first foliation. The folds are enhanced (and the dikes show a superimposed foliation) in the areas where the second peridotite foliation dominates. The fourth generation of dikes has only partially suffered the deformation that has produced the first foliation, and appears, therefore, to be late-kinematic.

Rare dikes also occur in the peridotites of Baldissero and Finero. Like the other rocks of the Ivrea zone, the dikes are re-equilibrated at lower temperatures. The main effect of the re-equilibration is the widespread production of unmixing lamellae in pyroxenes (lamellae of orthopyroxene in clinopyroxene, and viceversa, and of spinel in both pyroxenes).

The peridotite of Balmuccia has suffered partial melting and depletion (CAPEDRI et al., 1977 b): it represents with respect to that of Baldissero a more depleted residue and a less depleted residue than the Finero peridotite (RIVALENTI et al., 1978-79). The dikes are considered as the products of mantle partial melting and melting probably occurred as repeated episodes (LENSCH, 1976; CAPEDRI et al., 1977 a; SHERVAIS, 1978-79).

MINOR PERIDOTITE BODIES

Minor peridotite bodies occur separated from the Balmuccia peridotite, within the main basic body. They generally appear as interlayers within pyroxenites and gabbros. Frequently they display a compositional layering with variations from lherzolites to harzburgites and dunites. Hornblende is again a minor common phase. The westernmost of these minor bodies (i.e. those near the contact with the Balmuccia peridotite) show an easterly gradual passage into pyroxenite which in turn grades sometimes into gabbro.

The peridotites more to the east, besides the just described layering with pyroxenites and gabbros, also show a reaction relationship with gabbroic material. The reaction zone consists of a two centimeter thick pyroxenite band with orthopyroxene towards the peridotite and with clinopyroxene towards the gabbro. These features, indicating a disequilibrium between a gabbroic magma and the peridotites, will be examined in a forthcoming paper.

The textures of these minor peridotite bodies generally show a superimposed deformation producing foliation; but where the deformation is weak, cumulus textures are still in evidence (spinel is observed as an intercumulus phase) as has been shown by GARUTI (1977).

The minor peridotite bodies are considered by SHERVAIS (1978-79), LENSCH (1971) and ERNST (1978), as mantle peridotites, like the major bodies. On the contrary, RIVALENTI et al. (1975) link their genesis to the main basic body and propose an origin linked to gravitative differentiation.

MAIN BASIC BODY

Dominant are gabbroic and pyroxenitic rocks, besides the minor peridotite bodies mentioned above. The series constitutes a recrystallized and deformed suite of meta-igneous rocks that are considered as basic granulites by many authors; foliation is generally conspicuous and parallel to layering. But, as recrystallization never obliterates the primary parageneses, the prefix « meta » has been omitted in this text.

In spite of deformation, the main basic body displays a clear stratigraphy. From the contact with the Balmuccia peridotite to Sassiglioni it is a layered body (Layered Series); to the east, however, layering is weaker or absent. The layers of the western part, starting from the Balmuccia peridotite, show cyclic repetitions of the following types: olivine websterite-pegmatoid pyroxenite, peridotite-pyroxenite-gabbro, websterite-pegmatoid pyroxenite, pyroxenite-gabbro or norite, gabbro or norite-anorthosite. The rocks, within each of those cyclic units, grades into each other. The more mafic portion of each layer generally is to the west with respect to the less mafic or anorthositic portion. The contact between successive layers is generally sharp. The layers with ultramafic members predominate to the west (LLG = Lower Layered Group of RIVALENTI et al., 1975), while to the east peridotites disappear first, then the pyroxenites (ULG = Upper Layered Group of RIVALENTI et al., 1975). The more easterly gabbro shows little layering (MG = Main Gabbro of RIVALENTI et al., 1975); it grades into the Layered Series and passes, to the east, into the so-called « diorites » (see later).

Mineralizations are stratigraphically controlled. Ore deposits of nickeliferous sulphides occur in LLG pyroxenite horizons, generally near inclusions or septa of metapelites. Other rare sulphide deposits occur in the pyroxenite-dikes of the main basic body. Oxide concentrations (ilmenite and ilmenomagnetite) occur in the higher part of ULG (BIGIOGGERO et al., 1978-79 a).

The relevant primary petrographic features are as follows:

- 1) olivine, a major phase in the olivine websterites and peridotites of LLG, appears also as a major constituent in gabbros of ULG;
- 2) the appearance of olivine is followed, shortly afterwards, by the disappearance of orthopyroxene and by the appearance of charnockitic layers;
- 3) spinel occurs in peridotites, pyroxenites and gabbros of the Layered Series, but never in the pegmatoid pyroxenites;
- 4) plagioclase composition ranges from 48 % to 78 % An in the Layered Series and is around 78 % An in MG;
- 5) hornblende is a common phase; its amount increases eastwards and reaches a maximum in MG.

Evidences of re-equilibration are:

- 1) unmixing in pyroxenes;
- 2) growth of garnet, hornblende and spinel.

The unmixing products of pyroxenes are: orthopyroxene in clinopyroxene (and viceversa), opaques (ilmenite) and very rarely plagioclase in clinopyroxene.

Garnet and spinel are reaction products between olivine and plagioclase or orthopyroxene and plagioclase. Spinel-bearing layers occur side by side with garnet layers. The crystallization of garnet is controlled by the bulk composition. It forms only for a $\text{FeO}/(\text{FeO} + \text{MgO})$ (Wt%) ratio ranging between 0.47 and 0.80 and at Al_2O_3 (Wt%) > 15.00 % and CaO (Wt%) > 9.00 %.

« DIORITES »

Relevant papers on the « diorites » of the Ivrea zone are those of CAPEDE (1971) and BIGIOGGERO et al. (1978-79 b). Under the term « diorites », a set of rocks is included that varies from gabbro to monzonite, with transitional types as monzo-gabbro, monzo-diorite, and diorite. They occur at the eastern margin of the main basic body (Fig. 2). More felsic members are generally subordinate with respect to the gabbroic type. The passage to the main basic body is gradational, while the contact with the metapelites to the east is generally knifesharp.

Textures in the « diorites » are hypidiomorphic, in contrast with the frequent crystalloblastic texture of the gabbros. Mineralogically, they are composed by plagioclase (40 % An), biotite, hornblende, minor amounts of pyroxenes and sometimes K-feldspar in the most alkalic members.

METAPELITIC SERIES AND OTHER FELSIC ROCKS

The metapelitic series is represented by amphibolite-facies biotite, sillimanite ($\pm$ garnet), graphite-bearing gneisses, amphibolites and marbles at the eastern contact with the « diorites », and by granulite-facies lenses and interlayers within the main basic body.

Angular inclusions of metapelites in the « diorites » have sometimes andalusite. The granulite-facies intercalations in the basic body are composed by « stronalites » (sillimanite-mesoperthite-plagioclase-garnet-graphite $\pm$ clinopyroxene gneisses), pyriboleites and pyriclasites, and very rarely by marbles. Often at the contact between metapelites and rocks of the main basic body there is an horizon of charnockitic lithotypes (quartz-mesoperthite-K-feldspar-orthopyroxene-clinopyroxene gneisses). The metapelitic granulites show a foliation (and banding) concordant with the foliation of the basic body, but their lithological banding is in places discordant (e.g. along the lateral Valle di Gavala) with the layering of the basic body.

Although the pyriboleites of the metapelitic series and the gabbros of the complex have the same rough paragneiss, the first generally do not show subsolidus unmixing in the pyroxenes, as on the contrary occurs in the gabbros (see the section dealing with petrography of the basic body). Moreover it has been shown that, even within the same range of variation for Fe and Mg, gabbros and pyriboleites are easily distinguished by factorial analysis.

Distinction between various peridotite types

Because the lherzolite massif, on the one hand, and the minor peridotite bodies, on the other, have different textures, structures and structural settings, the possibility has to be considered that their genesis is also different. We will use tests based on chemical criteria to settle the matter.

BULK CHEMISTRY

Representative analyses of Balmuccia-massif rocks, of the minor bodies of Sesia Valley and of rocks from the Baldissero body, are reported in Table 1. The range of variation of the minor peridotite bodies is much larger than that of the massifs.

TABLE 1

Average composition of the mantle peridotites of Balmuccia and Baldissero and of the minor peridotite bodies of Sesia Valley

	BALDISSERO		BALMUCCIA		LAYERED SERIES	
	$\bar{x}$ (n=18)	S.D.	$\bar{x}$ (n=33)	S.D.	$\bar{x}$ (n=27)	S.D.
SiO ₂	45.58	1.340	44.41	2.421	40.81	3.006
TiO ₂	0.09	0.031	0.09	0.041	0.36	0.270
Al ₂ O ₃	2.35	0.724	2.25	0.859	3.23	1.799
Fe ₂ O ₃ tot.	9.11	0.606	9.33	0.852	16.14	2.804
Fe ₂ O ₃	2.32(+)	1.101	2.15(+)	0.974	3.30	2.156
FeO	6.44(+)	0.984	6.84(+)	0.809	12.38	3.054
MnO	0.14	0.017	0.14	0.017	0.20	0.048
MgO	39.43	1.706	40.26	2.262	35.22	5.972
CaO	2.75	0.618	2.66	0.823	2.59	1.844
Na ₂ O	0.22	0.037	0.15	0.050	0.23	0.163
K ₂ O	tr		tr		0.01	0.027
P ₂ O ₅	0.00	0.000	0.00	0.000	0.01	0.010
Cr ppm	3092	445.11	3259	719.44	2861	2833.10
Ni ppm	2107	234.18	2095	174.47	1303	438.77
FeO						
FeO + MnO	0.17	0.011	0.17	0.012	0.30	0.063

($\bar{x}$ = average; n = number of samples; S.D. = Standard Deviation; (+) = analyses from ERNST, 1978, are not included). Analyses for Balmuccia and Baldissero are from: LENSCH, 1971; RIVALENTI et al., 1975; CAPEDEI et al., 1977 a; ERNST, 1978 and unpublished data. Analyses for the Layered Series are from: RIVALENTI et al., 1975; CAPEDEI et al., 1977 a; and unpublished data.

The main difference consists in a higher MgO and NiO content of the Balmuccia (and Baldissero) peridotite and their lower abundances in iron (and MnO). The variation in FeO/FeO+MgO ratio of the Balmuccia and Baldissero bodies is very narrow (0.17-0.18), while in the minor bodies it varies between 0.23 and 0.36.

FACTORIAL ANALYSIS

Q-mode multivariate analysis has been applied by CAPEDEI et al. (1977 a) to all the peridotites of the Ivrea zone. The mantle peridotites were completely

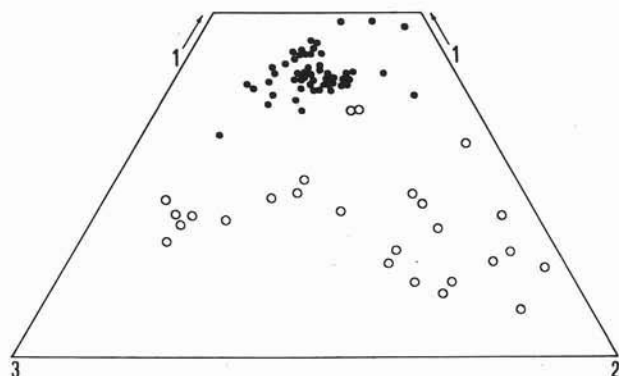


Fig. 3. — Plot of the 3 main factors F1, F2 and F3 which account for 98 % total variance, in factorial analysis (see the text, and CAPEDE et al., 1977 a, for further explanation). Dots: mantle peridotite of Balmuccia and Baldissero; circles: minor peridotite (cumulitic) bodies in Sesia Valley.

discriminated from the minor bodies, considered to represent cumulate rocks. Here the same method has been applied to the Balmuccia and Baldissero massifs and to the minor bodies of the Sesia Valley. Table 2 shows the varimax factor score matrix. A 98 % total variance is accounted for by three factors, reciprocally plotted in Fig. 3. The peridotites represent chemically, beyond any doubt, a separate unit. As expected, the oxides which weight more in the discrimination are Fe_2O_3 tot.,

MgO and MnO . Na_2O , Al_2O_3 and SiO_2 also contribute sensitively to the discrimination.

TABLE 2

Scaled varimax factor scores for Q-Mode factorial analysis of peridotites. This table gives the weight of each variable over the factors

VAR.	F 1	F 2	F 3
SiO_2	1.996	0.367	-0.604
TiO_2	-0.662	1.934	0.383
Al_2O_3	0.241	1.726	0.519
MnO	-0.131	0.964	-1.339
MgO	1.787	-0.279	-1.493
CaO	1.513	1.057	1.517
Na_2O	0.197	0.713	0.283
K_2O	-0.110	0.230	0.031
Fe_2O_3 tot.	-0.733	1.203	-1.950
Cr	0.428	-0.095	-0.016
Ni	0.497	-0.072	0.113

PHASE COMPOSITION

The comparison will be limited to the major phases: olivine, pyroxenes and spinel.

Olivine. The composition of olivine in the Balmuccia body has a very narrow range of variation between Fo 89 and Fo 91, irrespective of the texture of samples and of the accompanying minerals. On the contrary, in the minor peridotites it varies between Fo 75 and Fo 83 (Fig. 4). The fayalite content increases within the same peridotite layer (across strike) from west to east, and in

successive layers. Moreover, the olivines of the Balmuccia rocks, like those of the Baldissero body (and most of the peridotites considered as mantle material), have a NiO content constantly around 0.34, while the NiO content of olivine in the other peridotites is much lower (average 0.17).

TABLE 3

Representative microprobe analyses of clino- and orthopyroxenes and atoms per formula unit (based on 6 oxygens)

	MANTLE PERIDOTITES					DIKES				LAYERED SERIES									
	Mo 9A (s)	Mo 9A (t)	Mo 366 (s)	Mo 366 (t)	Mo 6 (s)	Mo 378 (s)	Mo 281b (s)	Mo 367 (s)	Mo 367 (t)	Mo 935 (s)	Mo 941 (s)	Mo 296 (s)	Mo 1135 (s)	IV 95 (s)	Mo 101 (s)	Mo 948 (s)	Mo 948 (t)	Mo 99 (s)	
SiO ₂	51.22	51.63	51.08	51.00	53.27	51.53	47.76	48.65	47.68	48.43	49.70	47.22	50.05	51.22	48.53	47.68	47.66	50.50	
TiO ₂	0.42	0.41	0.44	0.44	0.35	0.44	1.27	1.26	1.30	1.19	1.20	2.10	1.10	0.45	1.07	1.01	0.99	0.84	
Al ₂ O ₃	6.27	6.18	5.73	5.94	4.74	5.06	8.20	7.55	9.65	6.81	6.52	8.72	6.74	3.84	5.18	7.79	7.70	5.26	
Fe ₂ O ₃	1.11	0.97	1.10	1.12	0.00	0.23	1.25	1.08	1.02	1.82	0.00	1.31	0.53	0.00	1.17	1.46	1.50	0.42	
FeO	1.63	1.94	1.68	1.87	2.89	2.33	4.33	5.19	5.35	4.20	4.84	5.65	8.30	10.58	12.56	6.78	7.87	8.47	
MnO	0.12	0.16	0.09	0.07	0.11	0.09	0.13	0.13	0.13	0.08	0.13	0.13	0.13	0.17	0.25	0.18	0.17	0.13	
MgO	15.29	15.79	15.37	16.06	15.55	14.33	13.39	13.03	13.08	13.28	13.10	11.86	11.79	10.94	9.86	11.98	12.92	12.45	
CaO	21.98	21.46	21.79	20.81	21.98	23.24	21.87	21.00	19.92	21.93	21.46	19.46	20.00	20.15	18.78	21.11	19.23	20.71	
Na ₂ O	1.36	1.29	1.33	1.29	1.05	1.00	0.86	1.22	1.20	1.29	0.87	1.87	1.43	1.14	1.40	1.08	1.01	0.97	
K ₂ O	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	
Cr ₂ O ₃	0.73	0.75	0.83	0.86	0.87	0.71	0.00	0.16	0.13	0.26	0.68	0.00	0.02	0.00	0.00	0.15	0.27	0.00	
Total	100.13	100.58	99.44	99.47	100.81	98.96	99.06	99.27	99.46	99.29	98.50	98.32	100.09	98.50	98.80	99.22	99.32	99.75	
Si	1.858	1.867	1.867	1.860	1.917	1.897	1.777	1.808	1.763	1.803	1.852	1.775	1.857	1.946	1.866	1.790	1.787	1.883	
Al ^{iv}	0.142	0.137	0.133	0.140	0.083	0.103	0.223	0.192	0.237	0.197	0.148	0.225	0.143	0.054	0.134	0.210	0.213	0.117	
Al ^{vi}	0.126	0.126	0.113	0.115	0.118	0.116	0.136	0.138	0.184	0.102	0.138	0.161	0.152	0.119	0.101	0.135	0.128	0.114	
Ti	0.031	0.011	0.012	0.012	0.009	0.012	0.036	0.035	0.036	0.033	0.034	0.059	0.031	0.013	0.031	0.029	0.028	0.024	
Fe ⁺³	0.030	0.058	0.030	0.057	0.000	0.007	0.035	0.030	0.028	0.051	0.000	0.037	0.015	0.000	0.034	0.041	0.042	0.012	
Fe ⁺²	0.049	0.026	0.051	0.031	0.087	0.072	0.135	0.161	0.165	0.131	0.151	0.178	0.257	0.336	0.404	0.313	0.247	0.264	
Mn	0.004	0.005	0.003	0.002	0.003	0.003	0.004	0.004	0.004	0.003	0.004	0.004	0.004	0.005	0.008	0.006	0.005	0.004	
Mg	0.827	0.849	0.837	0.873	0.834	0.786	0.742	0.721	0.721	0.737	0.727	0.664	0.652	0.620	0.565	0.670	0.722	0.692	
Ca	0.854	0.830	0.853	0.813	0.848	0.917	0.872	0.836	0.789	0.875	0.857	0.784	0.795	0.820	0.774	0.849	0.773	0.827	
Na	0.096	0.090	0.094	0.091	0.073	0.071	0.062	0.088	0.086	0.093	0.063	0.136	0.103	0.084	0.104	0.079	0.073	0.070	
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Cr	0.021	0.021	0.024	0.025	0.025	0.021	0.000	0.005	0.004	0.008	0.020	0.000	0.001	0.000	0.000	0.004	0.008	0.000	
SiO ₂	55.15	53.41	54.65	54.01	56.01	50.69	51.36	51.30	51.30	53.24	54.23	50.99	52.20	53.22	49.46	49.50	49.45	51.64	
TiO ₂	0.07	0.09	0.09	0.01	0.15	0.15	0.15	0.28	0.18	0.11	0.20	0.09	0.05	0.11	0.14	0.34	0.16	0.16	
Al ₂ O ₃	2.96	3.63	3.10	4.14	5.64	5.11	6.20	6.20	3.97	4.51	4.23	3.30	2.15	2.16	5.65	5.30	1.93	1.93	
Fe ₂ O ₃	0.98	1.85	1.07	0.92	2.13	1.48	1.52	1.52	0.21	0.21	2.13	0.00	0.00	0.17	1.47	1.44	0.57	0.57	
FeO	5.98	5.13	5.97	5.78	10.87	14.36	14.33	14.33	13.26	11.71	12.85	18.48	21.18	26.18	18.01	17.57	21.74	21.74	
MnO	0.23	0.15	0.16	0.16	0.28	0.27	0.28	0.28	0.23	0.19	0.27	0.35	0.32	0.56	0.33	0.26	0.19	0.19	
MgO	33.98	34.35	33.95	33.34	29.48	27.32	27.26	27.26	28.09	29.72	28.48	23.97	23.25	17.77	23.87	24.04	22.41	22.41	
CaO	0.33	0.42	0.43	0.48	0.39	0.43	0.51	0.51	0.45	0.30	0.52	0.44	0.35	0.68	0.58	0.81	0.64	0.64	
Na ₂ O	0.10	0.00	0.00	0.03	0.03	0.03	0.06	0.06	0.00	0.00	0.04	0.00	0.03	0.04	0.03	0.03	0.03	0.03	
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	
Cr ₂ O ₃	0.25	0.27	0.35	0.53	0.00	0.10	0.00	0.00	0.14	0.31	0.00	0.00	0.00	0.02	0.11	0.27	0.00	0.00	
Total	100.05	99.30	99.77	99.40	99.66	100.61	101.74	101.74	99.77	101.29	99.71	98.83	100.55	97.16	99.69	99.51	99.31	99.31	
Si	1.910	1.865	1.899	1.882	1.814	1.843	1.820	1.820	1.904	1.895	1.841	1.930	1.955	1.943	1.827	1.828	1.936	1.936	
Al ^{iv}	0.090	0.135	0.101	0.118	0.186	0.157	0.180	0.180	0.096	0.105	0.159	0.070	0.045	0.057	0.173	0.172	0.064	0.064	
Al ^{vi}	0.030	0.015	0.026	0.052	0.052	0.059	0.079	0.079	0.071	0.080	0.021	0.074	0.048	0.043	0.073	0.058	0.022	0.022	
Ti	0.002	0.002	0.002	0.000	0.004	0.004	0.007	0.007	0.005	0.003	0.005	0.003	0.001	0.003	0.004	0.009	0.005	0.005	
Fe ⁺³	0.026	0.049	0.028	0.024	0.057	0.040	0.041	0.041	0.006	0.005	0.058	0.000	0.000	0.005	0.041	0.040	0.016	0.016	
Fe ⁺²	0.173	0.150	0.174	0.168	0.325	0.431	0.425	0.425	0.397	0.342	0.388	0.571	0.651	0.860	0.556	0.543	0.682	0.682	
Mn	0.007	0.004	0.005	0.005	0.008	0.008	0.008	0.008	0.007	0.006	0.008	0.011	0.010	0.019	0.010	0.008	0.006	0.006	
Mg	1.753	1.788	1.758	1.731	1.572	1.461	1.441	1.441	1.497	1.547	1.533	1.321	1.273	1.040	1.313	1.324	1.252	1.252	
Ca	0.012	0.016	0.016	0.018	0.015	0.017	0.019	0.019	0.017	0.011	0.020	0.017	0.014	0.029	0.023	0.032	0.026	0.026	
Na	0.007	0.000	0.000	0.002	0.002	0.002	0.004	0.004	0.000	0.000	0.003	0.000	0.002	0.003	0.002	0.002	0.002	0.002	
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	
Cr	0.007	0.007	0.010	0.015	0.000	0.003	0.000	0.000	0.004	0.009	0.000	0.000	0.000	0.001	0.003	0.008	0.000	0.000	

(s) = spot analyses referred to host phase; (t) = traverse analyses, which give an estimate of the phase composition before unmixing. Mo 378, Mo 281b and Mo 367 are pyroxenitic dikes of the first, second and a gabbroic dike of the third generation, respectively.

Pyroxenes. Fig. 5 and Table 3 sets out the differences between the pyroxenes of the Balmuccia massif and those of rocks from the minor bodies. In all the occurrences their composition is variable. But the variations in composition of Balmuccia pyroxenes are weak and correlate with the textures of the sample (GARUTI et al., 1978-79); they are generally richer in Mg and lower in Ti with respect to all the other pyroxenes (Fig. 5).

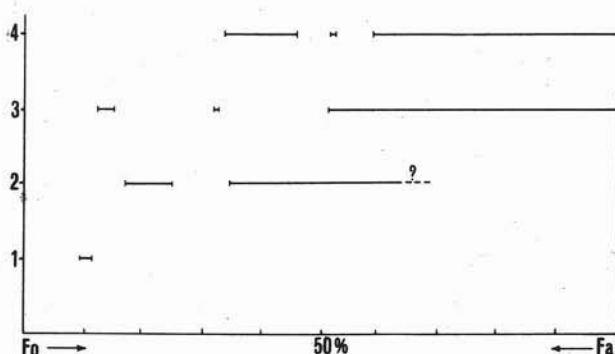


Fig. 4. — Composition and gap of olivine of various layered complexes as compared with that of the Ivrea Complex. 1: Balmuccia peridotite; 2: Layered Series of Sesia Valley; 3: Bushveld; 4: Skaergaard.

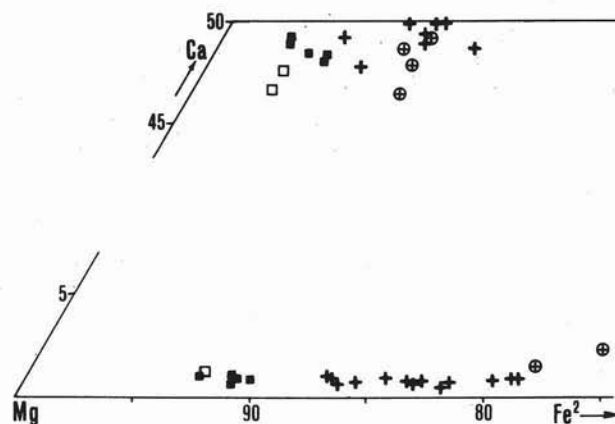


Fig. 5. — Pyroxene quadrilateral for peridotites from Sesia Valley. Pyroxenes from mantle peridotites (Balmuccia); black squares (spots analyses) and open squares (traverse analyses). Pyroxenes from cumulitic peridotites: crosses (spots) and crossed circles (traverses). Note that traverse analyses reduce the miscibility gap.

Spinel. Figs. 6 and 7 show the field of the spinel composition in the Balmuccia and Baldissero massifs and minor bodies. They are completely discriminated in the plot of Fig. 6, where, for a given Cr content, the spinels of the mantle peridotites are constantly richer in Mg. In the plot of Fig. 7 the spinels of the minor peridotites show a general higher Fe^{3+} content; moreover, they are sometimes more aluminous

than Baldissero and Balmuccia spinels. RIVALENTI et al. (1978-79) have pointed out that the composition of spinels in the Balmuccia peridotite varies accordingly with the texture of the rocks. More Al-rich spinels are formed in rocks with

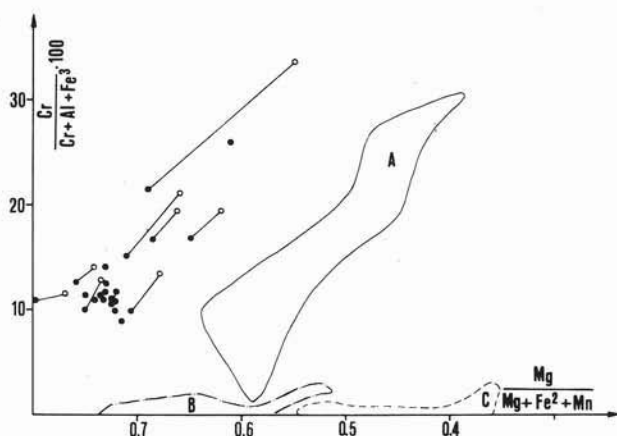


Fig. 6. — Composition of spinels in terms of $Mg/(Mg+Fe^{+2}+Mn)$ and $Cr/(Cr+Al+Fe^{+3})$. Open circles and dots: spinels in the mantle peridotite of Balmuccia; the tie-lines connect rims (circles) and centres (dots) of the same crystal. Fields A, B and C refer to spinels in cumulitic peridotites, pyroxenites and gabbros of the Layered Series, respectively.

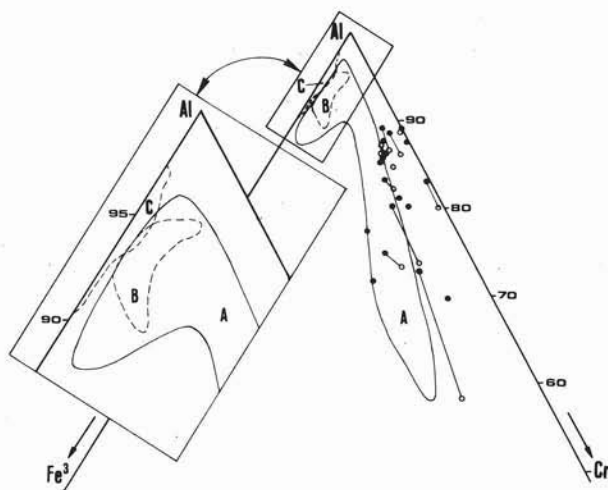


Fig. 7. — Composition of spinels in terms of Al-Cr- Fe^{+3} . Symbols and fields as in Fig. 6. See the text for discussion.

protogranular textures, while the more chromian types occur in foliated and porphyroclastic rocks. These authors have interpreted the relationships between the composition of clinopyroxene and of spinels as determined by a different grade of melting and depletion.

In conclusion, there can be hardly any doubt that the Balmuccia body and the minor peridotites are different. If

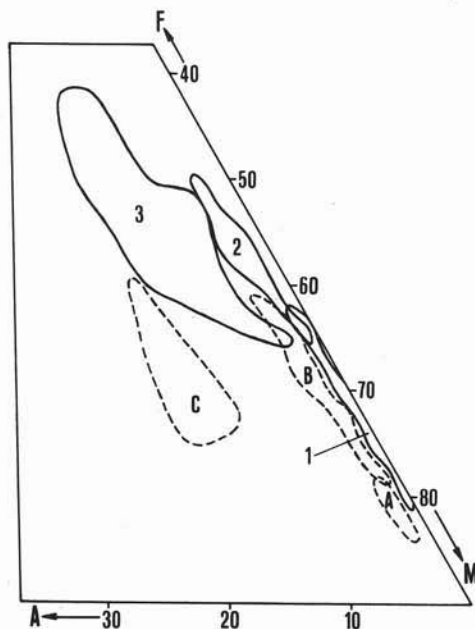


Fig. 8. — AFM plot for dikes of the mantle peridotites, pyroxenites and gabbros, respectively, for the peridotites, pyroxenites and gabbros of the Layered Series (field contoured by continuous line). A: dikes of the first generation; B: dikes of the second and third generation; C: gabbroic dikes and pods in the mantle peridotite: 1, 2 and 3: peridotites (fields contoured by a dashed line) and of the Layered Series. See text for discussion.

an origin as residual mantle material is accepted for the Balmuccia body, then the same origin cannot be proposed for the minor peridotite bodies, unless we admit the possibility of small-scale mantle inhomogeneities (WILKINSON & BINNS, 1977) or, even more unlikely, differences in the causes of melting. A secondary argument against a possible mantle origin for the minor bodies is that their compositions are very much unlike those of the other peridotites, the world over, which are considered by many authors to represent mantle material. Moreover, the minor peridotites are not cut by the dikes that cross the Balmuccia peridotite. It will be shown in the section dealing with the main basic body that the minor peridotites are likely to be fractionation and cumulus products comagmatic with the other rocks of the Layered Series.

Distinction between the dikes in the Balmuccia peridotite and the lithotypes of the Layered Series

The dikes of the main peridotite body and the pyroxenites in the Layered Series occurring near the contact with the Balmuccia peridotite are considered by SHERVAIS (1978-79) as having the same origin and as having formed under the same set of conditions. We shall show that a direct genetic link, if any, is possible only with the latter dikes, that in general the two «units» cannot have been formed under the same conditions and that they differ in a number of characteristics.

RELATIONSHIPS WITH THE PERIDOTITES

The dikes within Balmuccia never show a gradational contact towards the peridotite. Their relationship to the foliation has been mentioned and it was also discussed that the various generations possibly represent repeated episodes of partial melting occurring during the peridotite emplacement (CAPIEDRI *et al.*, 1977b). On the contrary, the pyroxenites of the Layered Series are true layers

that show compositional layering and often a gradual passage to the peridotite horizons. Gabbro only appears in the last generation of the dikes of Balmuccia. It occurs either as a variation along the strike at the centre of a pyroxenite dike, or in amoeboidal pods contoured by a thin pyroxenite sheet. In the Layered Series, gabbro appears as a transversal variation, in respect to the strike, of the pyroxenite. The contact pyroxenite-gabbro is often gradual.

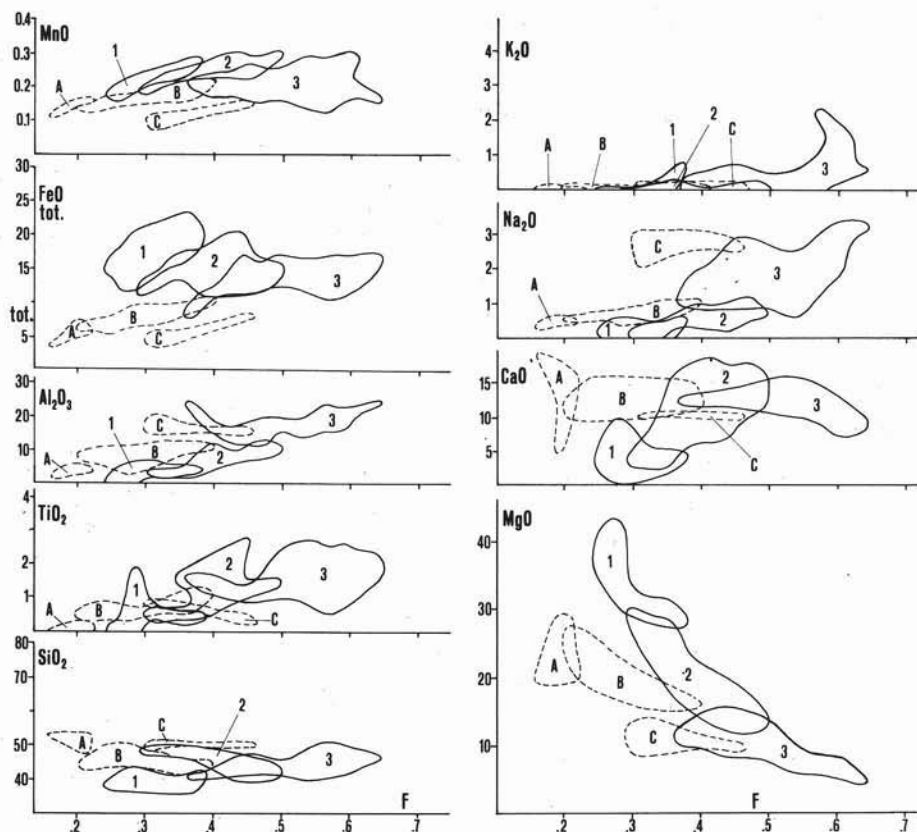


Fig. 9a. — Plot of F ($= \text{FeO}_{\text{tot}}/\text{FeO}_{\text{tot}} + \text{MgO}$) versus the various oxides and Cr and Ni for dikes in the mantle peridotite and for peridotites, pyroxenites and gabbros of the Layered Series. Symbols as in Fig. 8. See text for discussion.

BULK CHEMISTRY

Bulk composition of the dikes in the main massif and of the pyroxenites and gabbros of the Layered Series is conveniently compared in the *AFM* diagram (Fig. 8) and in the plot of $F = (\text{FeO}/\text{FeO} + \text{MgO})$ versus the various oxides (Fig. 9). From these figures it can be seen that the dikes of the older generation have a more primitive composition: they are lower in FeO, Al_2O_3 , Na_2O , and higher in MgO and Cr_2O_3 with respect to the other dikes. Together with the older pyroxenitic dikes they form a differentiation trend characterized by marked

iron enrichment (Fig. 8), both within one generation and from one generation to the other. The variation trends are consistent with the fractionation of clinopyroxene-orthopyroxene-spinel-olivine-plagioclase in this order (CAPEDRI et al., 1977 b).

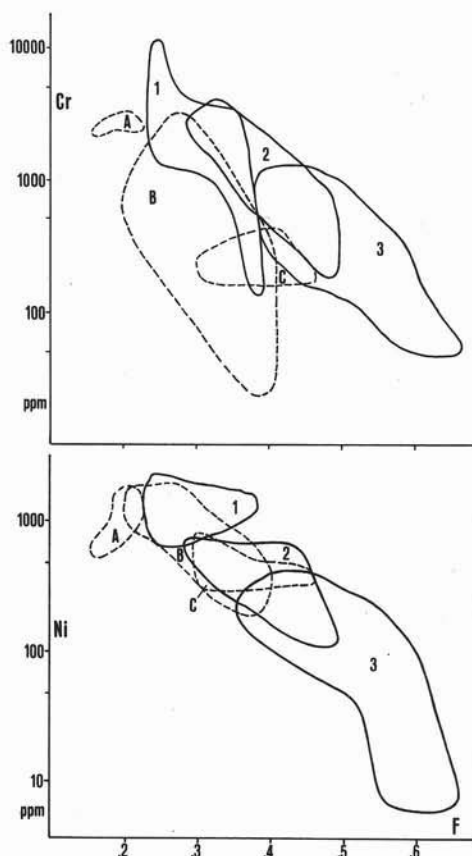


Fig. 9 b. — Explanation as in Fig. 9 a.

Passing into the Layered Series, the pyroxenites and gabbros also follow an iron enrichment trend in the *AFM* diagram of Fig. 8, but, unlike the Balmuccia dikes, pyroxenites and gabbros lie on the same trend. The same appears in the plot of Fig. 9. Their trend is in line with that of the Balmuccia pyroxenite dikes, markedly with those of the last generation, but not with those of the Balmuccia gabbro. The difference between the two gabbro-suites is possibly accounted for by those of Balmuccia being « frozen » residual liquids, while the gabbro of the Layered Series is a fractionation and cumulus product formed together with the pyroxenites.

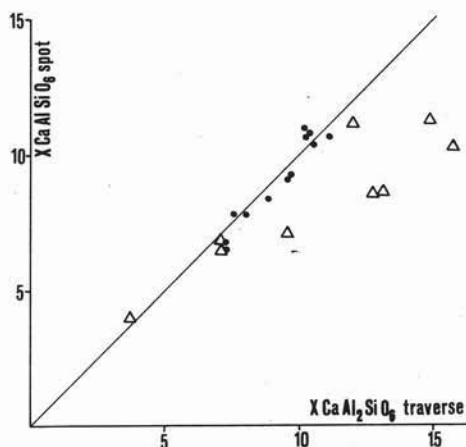


Fig. 10. — Plot of the tschermak content in Ca-rich pyroxenes of the dikes in the mantle peridotites and of pyroxenites of the Layered Series. Triangles = dikes. Dots = pyroxenites of the Layered Series.

However, the gabbros do not follow the trends shown by the pyroxenites, although their *F* ratio partially overlaps that of the pyroxenites. It has been shown elsewhere (CAPEDRI et al., 1977 b) that the gabbros are likely to represent the composition of successive liquids that have fractionated from the pyroxenites and the trend should therefore be a liquid line of descent.

PHASE COMPOSITION

Olivine. Olivine appears in the dikes of the first and second generation, where it is a highly magnesian term and generally bears a forsterite content very close to that of the country rocks (Fig. 4). In the pyroxenites of the Layered Series, olivine only occurs in the olivine-websterites at the contact with the Balmuccia massif and in the pyroxenite layers and associated gabbros, of the eastern-most part of the Layered Series. Its composition is more fayalitic with respect to that of mantle peridotite and dikes (Fig. 4).

Pyroxenes. Clinopyroxenes of the older generation is a chromian diopside, with a maximum Al-content around 5-6 wt% as shown in Table 3 (SHERVAIS, 1978-79; GARUTI et al., 1978-79), while the Al content is much higher in the pyroxenes of the following generations and the chromium content is lower. In the Layered Series, the alumina content is comparatively much lower and both ortho- and clinopyroxene are richer in iron. This results in a difference in the unmixing products of re-equilibration: while pyroxenes of the dikes (second and third generation and pyroxenites of the fourth generation) exolve hercynite lamellae, in the Layered Series they exolve ilmenite or other titanium or iron oxides. The plot of Fig. 10 is a graphic demonstration of this different behaviour: the ratio between an estimate of the tschermak content of clinopyroxene before unmixing and that of the unmixed phase is around 1 : 1 in the Layered Series, while it is lower in the dikes.

The differences shown above are consistent and exclude the possibility of a direct relationship between the dikes and the Layered Series. The dikes display features representative of a relatively high pressure environment (see later paragraph on geothermometry and geobarometry), as shown by the fractionation pattern and by phase composition, with respect to the Layered Series. The only possible and probable genetic link is with the younger Balmuccia pyroxenites and gabbros. As the rocks of the Layered Series continue the fractionation pattern of the dikes, they might be derived by fractionation of liquids represented by the more evolved « frozen » gabbros found within Balmuccia.

The Main Basic Body as a Layered Igneous Complex

Evidence that the main basic body is a layered igneous complex is achieved by comparison of its main features with those of other well known igneous complexes in the world. It will be shown that its bulk geochemistry and phase composition are also consistent with a fractionation and cumulus origin, although in this respect the Ivrea body shows some differences from other layered intrusions.

COMPARISON WITH OTHER LAYERED COMPLEXES

The simplest geometric arrangement common to most layered complexes is that of a lopolith that displays the following gross stratigraphy:

a) a lower part with rhythmic layering, often with graded bedding;

b) an upper part consisting of non-layered gabbro, fading at the top into granophyric or dioritic differentiates. Ultramafic members often occur in the lower part (e.g. Bushveld, Stillwater, Skaergaard hidden zone). Mineralizations are stratigraphically controlled.

Although tilted almost vertically, the stratigraphy of the main basic body of Ivrea compares favourably with this situation. Assuming that the base of the main body is to the west, its lower part is constituted by layers with cyclic repetitions of ultramafic members, fading into gabbros and anorthosite and followed by the huge body of the lightly layered gabbro. The so-called « diorites » may represent the last felsic differentiates of the top. Cumulitic texture is generally obscured by re-crystallization and deformation, but the variation of the phases through the layers is generally consistent with a mechanism of gravitative differentiation.

The gap in olivine crystallization, with the disappearance of orthopyroxene shortly after the entry of the more fayalitic olivine is well documented at Skaergaard, Bushveld and Stillwater (CARMICHAEL & SMITH, 1970; CAMPBELL & NOLAN, 1974). In the main basic body, olivine only appears in the ultramafic members of the base and re-enters the gabbros of the Upper Layered Series. The width of the olivine gap is, however, different in the Ivrea body (see section dealing with phase composition).

The mineralizations are stratigraphically controlled: Ni is found only in the lower pyroxenitic horizons, while ore is represented in the upper part of the Layered Series with Fe-Ti-oxides.

Many of the layered intrusions show an irregularity in the crystallization pattern near their base: fractionation leads to an Mg-enrichment (JACKSON, 1963, 1970). This feature is tentatively explained in several ways, for instance by influx of new gabbroic magma into the magma chamber, or disequilibrium crystallization or chilling effect from the country rock. Whatever the cause, this reversal seems to be a common and constant characteristic. The Ivrea body behaves as the other complexes also in regard to this « irregularity »: the first layers near the base display an upwards Mg-enrichment.

BULK GEOCHEMISTRY

Main sources are the papers of RIVALENTI et al. (1975) and of BIGIOGGERO et al. (1978-79 b). Their data, integrated with unpublished analyses, are plotted in the diagrams of Figs. 11 and 12. The trend of variation in the Layered Series (LLG and ULG) is generally consistent with a fractionation scheme involving olivine as an early liquidus phase, followed by orthopyroxene, clinopyroxene and plagioclase. The layers show an evident upwards (eastwards) iron enrichment. The main gabbro and « diorites » show a narrower range of variation with respect to the Layered Series, with lack of extreme composition, which suggests that cumulus processes were ineffective there. Other important geochemical features of main gabbro and « diorites » are their marked enrichment in K, Zr, and Ba with respect to the Layered Series and their more alkalic composition in the more differentiated members

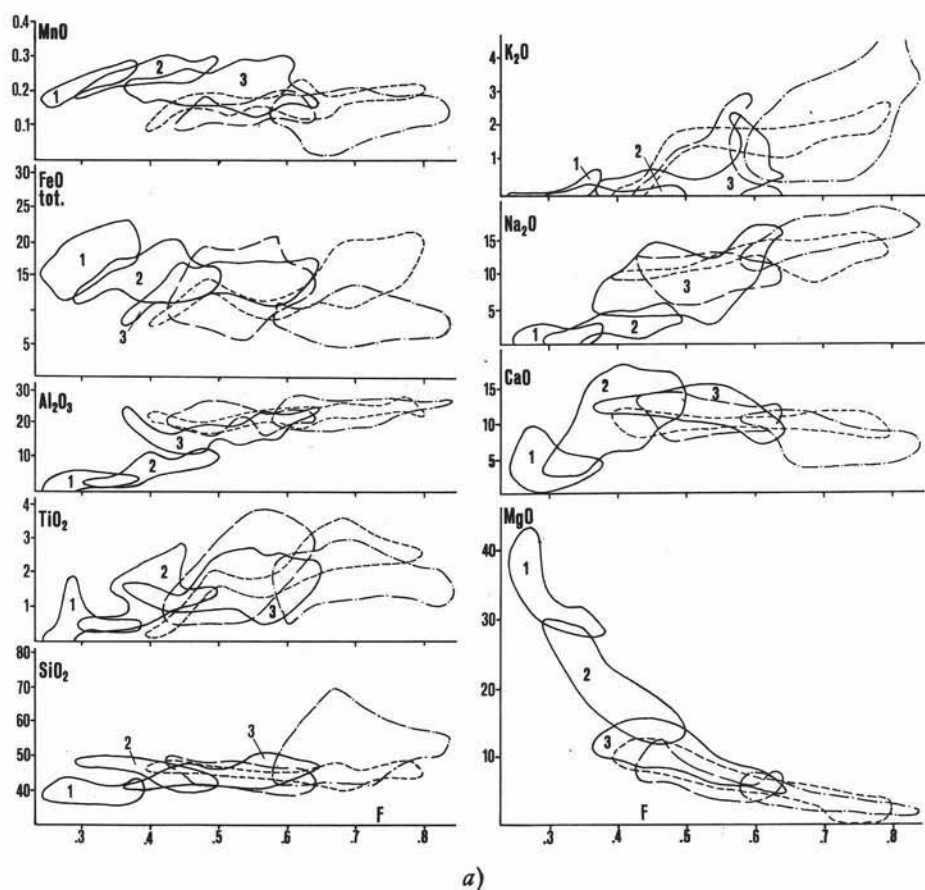


Fig. 11 a. — Explanation as in Fig. 11 b.

(as found by BIGIOGGERO et al., 1978-79 b). «Diorites», together with part of the gabbros display a calc-alkaline tendency, which can be seen in the *AFM* plot. A calc-alkaline behaviour is also supported by the discrimination diagrams of PEARCE & CANN (1973) and of MIYASHIRO (1974), discussed by RIVALENTI et al. (1975) and BIGIOGGERO et al. (1978-79 b) (see, as an example, Fig. 13). These features have been explained as a fractionation characterised by an upward water enrichment, which causes on one hand the precipitation of Ti-magnetite in the least differentiated terms of the main gabbro (see Ti-plot of Fig. 11), and on the other hand, the enrichment of incompatible elements in the main gabbro and «diorites».

The row fractionation scheme of the Layered Series fits in well with the fractionation of a basaltic magma under relatively high *P*-load and low oxygen fugacity.

PHASE COMPOSITION

Olivine. Olivine composition is compared with that of other layered intrusions

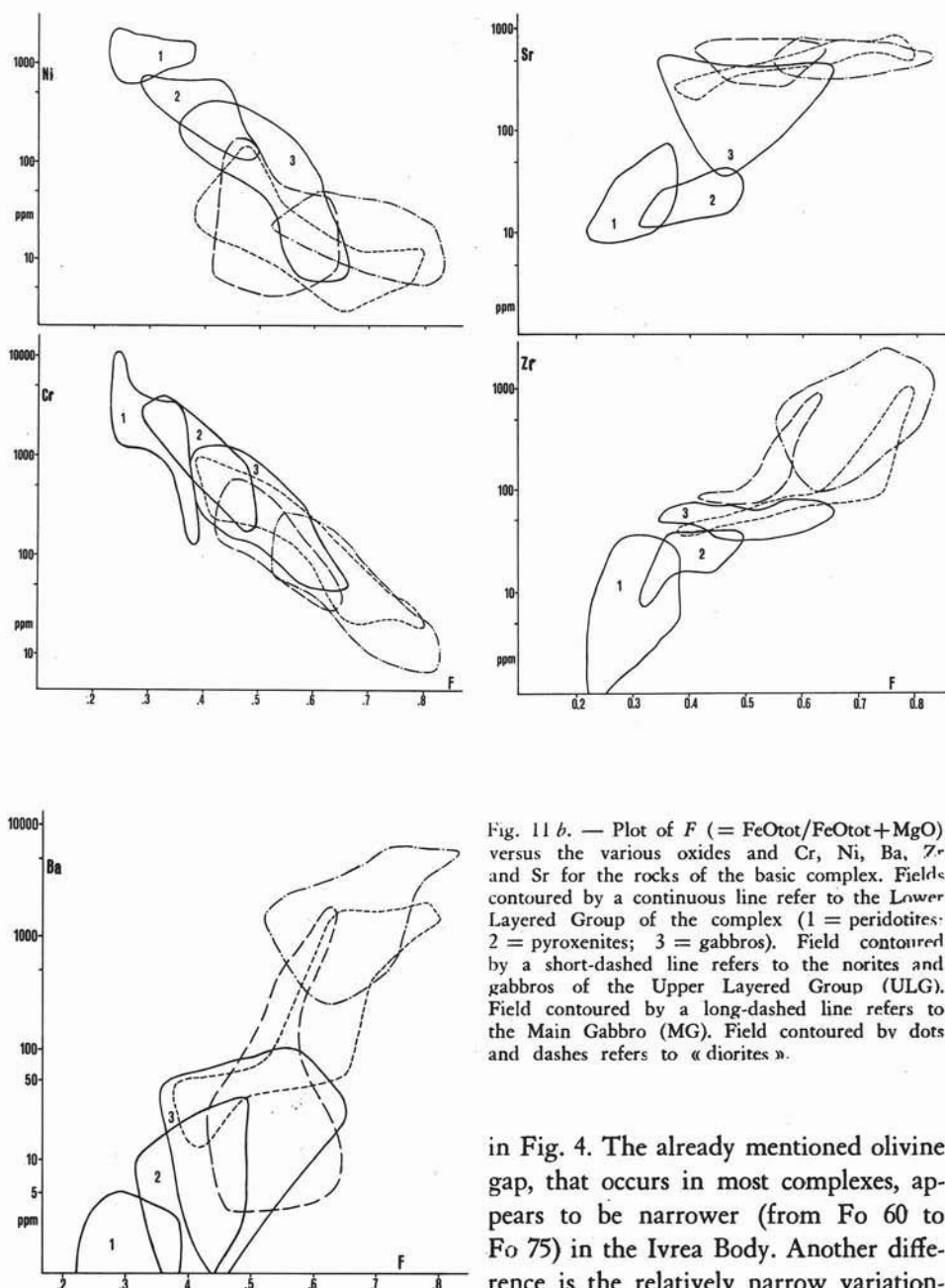


Fig. 11 *b*. — Plot of F ($= \text{FeO}_{\text{tot}}/\text{FeO}_{\text{tot}} + \text{MgO}$) versus the various oxides and Cr, Ni, Ba, Zr and Sr for the rocks of the basic complex. Fields contoured by a continuous line refer to the Lower Layered Group of the complex (1 = peridotites; 2 = pyroxenites; 3 = gabbros). Field contoured by a short-dashed line refers to the norites and gabbros of the Upper Layered Group (ULG). Field contoured by a long-dashed line refers to the Main Gabbro (MG). Field contoured by dots and dashes refers to « diorites ».

in Fig. 4. The already mentioned olivine gap, that occurs in most complexes, appears to be narrower (from Fo 60 to Fo 75) in the Ivrea Body. Another difference is the relatively narrow variation-field of olivine in gabbros, where the most fayalitic terms are not below Fe 35. The gap is generally interpreted as a consequence of the variation in silica activity during fractionation at decreasing T (CAMPBELL &

NOLAN, 1974; CARMICHAEL et al., 1970; NICHOLLS et al., 1971). The difference in the composition of the limiting phases between the Ivrea Body and the other complexes may be interpreted as a difference in P .

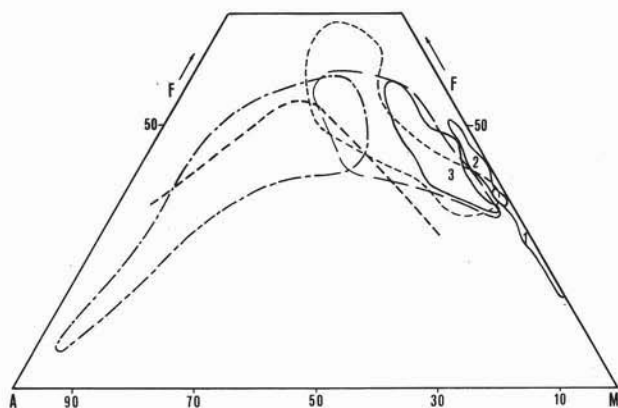


Fig. 12. — AFM plot for the basic complex. Fields as in Fig. 11. Heavy-dashed line separates the tholeiitic from calc-alkaline field.

Pyroxenes. Pyroxenes are, as already mentioned, re-equilibrated with production of subsolidus unmixing lamellae. Re-equilibrated host phases and estimates of their composition before unmixing are reported in the pyroxene quadrilateral of Fig. 14. Their range of variation is generally narrower than that of other complexes, except that of Jamberlana (CAMPBELL & NOLAN, 1974) and Great Dike. Most analyses,

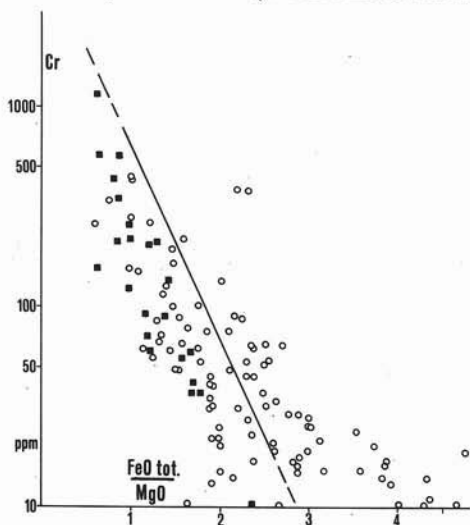


Fig. 13. — Variation diagram of Cr against $\text{FeO}_{\text{tot}}/\text{MgO}$. Heavy line separates the tholeiitic from the calc-alkaline field (after MYASHIRO, 1974). Open circles: «Diorites»; black squares: Main Gabbro.

however, refer to the Layered Series, very few to the main gabbro and none to the «diorites». It is possible that future work will show a wider range of variation. Pigeonite is never found in the Ivrea complex, although the thick exolutions of orthopyroxene in host clinopyroxene of the pegmatoidal pyroxenites in the lower part of the Layered Series may represent an inverted term of the pigeonite series. Pyroxenes of the Ivrea basic body are also characterized by higher Al content with respect to those of the other layered intrusions (according to the characters tabulated by JACKSON & THAYER, 1972). Another difference from the Skaergaard and Bushveld situations is shown in the composition of the last orthopyroxene crystallizing

together with the olivine in the gabbros: here it is of En 54, while it is En 46 at Skaergaard and En 40 at Bushveld (CARMICHAEL et al., 1970).

Spinel. Spinel composition varies between picotites and magnesian hercynites. Cr-bearing types are limited to peridotites, while the others occur in pyroxenites and gabbros (Fig. 6 and 7). No high-Cr spinel occurs in this complex. RIVALENTI et al. (1978-79) have pointed out that spinel becomes progressively richer in alumina (and Fe^{3+}) with increasing fractionation.

Amphibole. The composition of calcic amphibole varies very little through the series. The main variation consists of a decrease of Ti at increasing stratigraphic height. According to the I.M.A. classification reported by LEAKE (1978) it is a pargasitic hornblende.

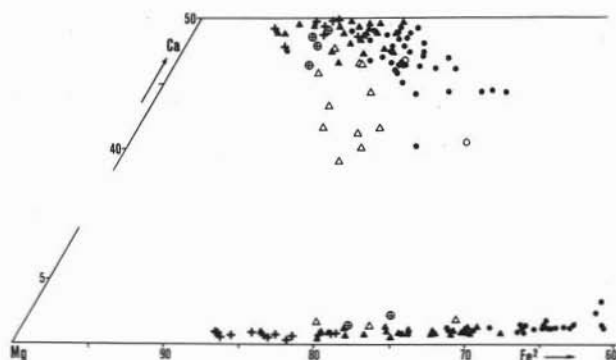


Fig. 14. — Pyroxene quadrilateral for the layered units of the basic complex. Peridotite: crosses (spot analyses) and crossed circles (traverse analyses); Pyroxenites: black triangles (spots) and open triangles (traverses); Gabbros: dots (spots) and circles (traverses).

In conclusion, it has been shown that the main basic body displays most of the characteristics common to the layered complexes. No mechanism other than gravitative differentiation could explain the stratigraphic arrangement of the Layered Series. Consistent differences with respect to classic layered intrusions are:

- 1) the association with mantle tectonites;
- 2) the calc-alkalic tendency;
- 3) the composition and range of variation of the main mafic minerals (see also the characteristics tabulated by JACKSON & THAYER, 1972, for layered complexes).

Geothermometry and geobarometry

Current geothermometers based on olivine, pyroxenes and spinels have been applied to the peridotite massif of Balmuccia, the minor peridotite bodies, dikes in the mantle peridotite, and the Main Basic Body. Results concern whole phase estimates prior to unmixing (traverse analyses) and spots on unmixed phases, i.e. hosts and lamellae. While the first should give an indication of the physical

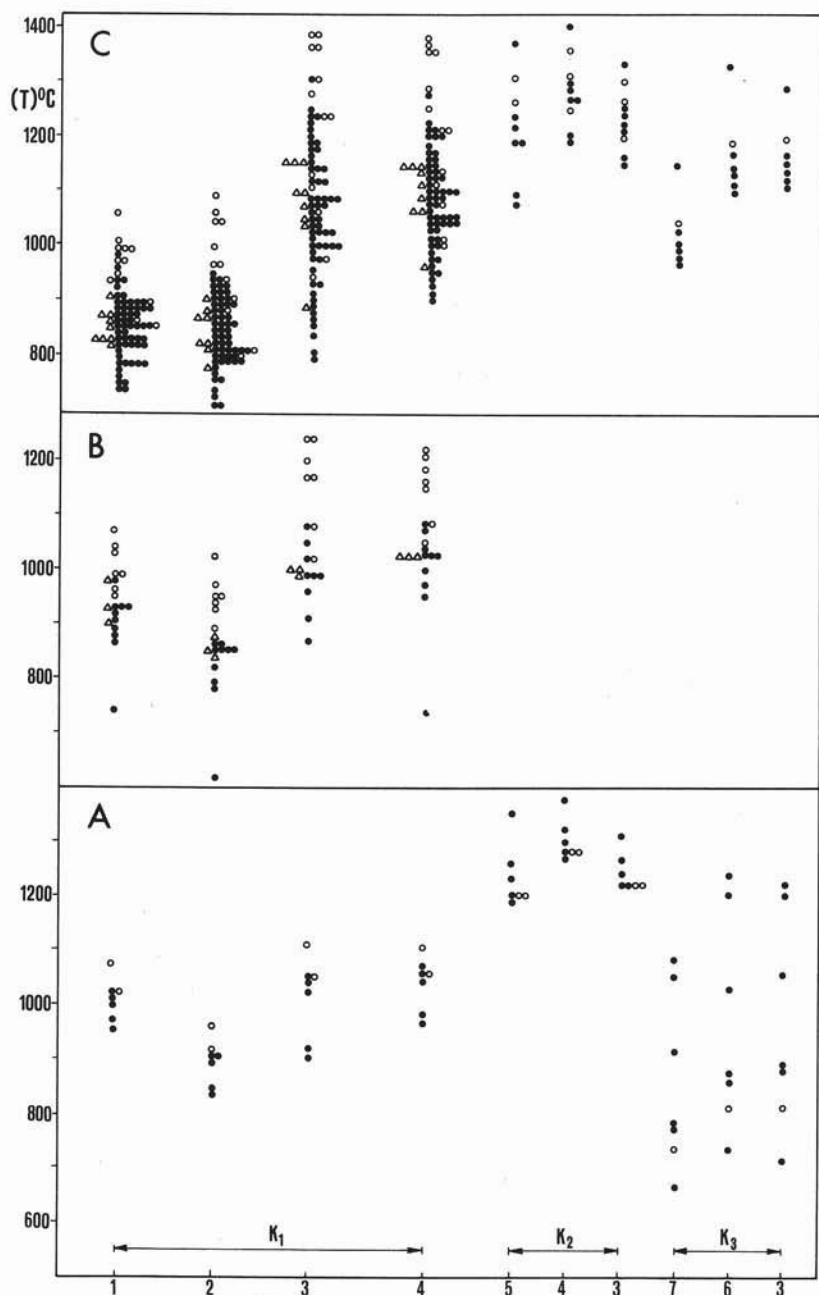
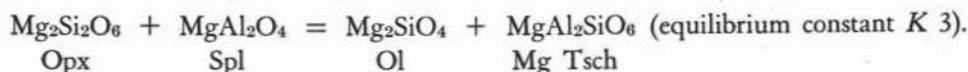
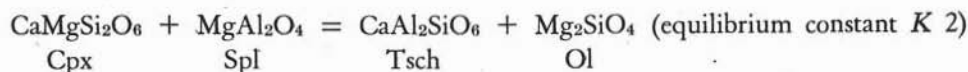
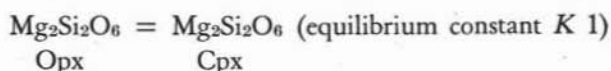


Fig. 15. — Synoptic table of the temperatures determined according to various geothermometers. See text for definition of K_1 , K_2 , and K_3 . Dots are temperature determinations on re-equilibrated phases (spots); circles are temperatures determined on estimates of the whole phase composition before unmixing (traverses); triangles refer to host and coexisting exolved phase. A: mantle peridotites; B: dikes in the mantle peridotite; C: Layered Series. References: 1 - WOOD & BANNO, 1973; 2 - WELLS, 1977; 3 - MORI, 1977; 4 - HERZBERG & CHAMPAN, 1976; 5 - BACON & CARMICHAEL, 1973; 6 - OBATA, 1976; 7 - MAC GREGOR, 1974.

conditions at the time of crystallization, the second should provide indications as to the conditions during re-equilibration. The exchange equilibria are:



The results of calculations, carried out according to the geothermometric equations reported by various authors, are plotted in Fig. 15. The *K* 1 temperatures are calculated for compositions ranging from gabbros to peridotites, while *K* 2 and *K* 3 temperatures only refer to peridotites, because the experimental works for these equilibria only concern such compositions. The values of the temperature calculated vary, within the same equilibrium, from one author's equation to the next. This suggests the possibility of some inconsistency in the thermodynamic data. The variation is not such, however, as to prevent at least the qualitative use of the geothermometers. The main points are:

- 1) the lowest values are found in the *K* 1 equilibrium; the traverse analyses, however, give consistently higher temperatures (100-150° C) than the respective spot analyses;
- 2) provided that the same equilibrium from the same author is used, the temperatures are similar in mantle peridotites, dikes and in the main basic body;
- 3) the temperatures where alumina content of pyroxenes is involved are of the same order of magnitude as the *K* 1 temperatures referring to the traverses.

A higher *K* 2 and *K* 3 temperature with respect to *K* 1 can be interpreted in many ways. It may depend on insufficient knowledge of the crystalline solution involved (for instance, ideal or non-ideal Al-Cr interactions in spinels) or be due to a different degree and rate of re-equilibration for the reaction involved as proposed by HERZBERG & CHAPMAN (1976), and MORI (1977). If this last possibility holds true, there is a possible disequilibrium in these pyroxenes between iron and magnesium and their tschermak contents.

Current geobarometry concerning mafic and ultramafic rocks is based on the distribution of alumina between pyroxenes and coexisting alumina-rich phases (plagioclase, spinel, garnet), as the reactions involved are those with the large ΔV . It has been shown (OBATA, 1976; HERZBERG, 1978; WOOD, 1974) that for the lherzolite composition the alumina isopleths have a negative slope in the plagioclase lherzolite and a positive slope in the garnet lherzolite, while they are *P*-independent in the spinel lherzolite facies. In the gabbro and pyroxenite compositions the alumina isopleths are *P* dependent also in the spinel facies (OBATA, 1976; HERZBERG, 1978).

TABLE 4

Estimate of the original and re-equilibration pressure for the main basic body and for the dikes in the mantle peridotite of Balmuccia.

Uncertainty is of ± 2 Kb

MAIN BASIC BODY

Samples		T (°C)	P1	P2	P3	P4
Spots	Mo 18	900			7	
	Mo 21	960			6	
	Mo 22	930			8	
	Mo 24	990		11	7	
	Mo 47	950			7	
	Mo 55	1050		7	7	
	Mo 57	960			6	
	Mo 63	950				6
	Mo 92	940			7	
	Mo 94	930				7
	Mo 98	880			9	
	Mo 99	930				8
	Mo 113	930				8
	Mo 298	1020		8	7	
	Mo 300	950		8	7	
	Mo 938	930			9	
Traverses	Mo 92	1020			6	
	Mo 948	1040			7	
	Mo 955	1000			8	

DIXES

Samples		T (°C)	P1	P2	P3	P4
Spots	Mo 367	890			8	
	Mo 371	960	8		6	
	Mo 373	980			7	
	Mo 378	970	9			
	Mo 383	1050		7	6	
Traverses	Mo 367	1080			16	
	Mo 373	1090			15	
	Mo 383	1100		15	14	
	Mo 385	1180			17	

Spots = composition of the re-equilibrated phases.
 Traverses = estimate of the original composition of the phases. T = Temperature assumed from WOOD & BANNO (1973) or HERZBERG (1978).
 $P1$ = Pressure determined from reaction: $Mg_2Si_2O_6 + MgAl_2O_4 = Mg_2SiO_4 + MgAl_2O_6$ according to OBATA, 1976. $P2$ = Pressure determined from reaction: $0.5 Mg_2Si_2O_6 + 0.5 CaAl_2Si_2O_8 + 0.5 MgAl_2O_4 = 0.5 CaMgSi_2O_6 + MgAl_2SiO_6$ according to OBATA, 1976. $P3$ = Pressure estimate from Al^{VI} in orthopyroxene, according to OBATA, 1976. $P4$ = Pressure estimated from reaction: $Ca_2MgAl_2Si_3O_{12} = CaMgSi_2O_6 + CaAl_2SiO_6$ according to HERZBERG, 1978.

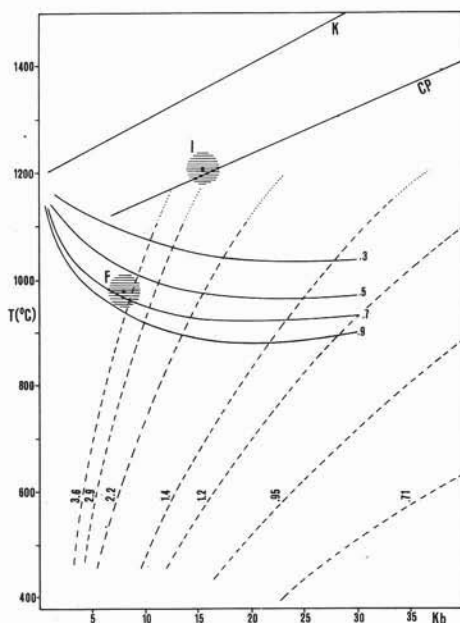


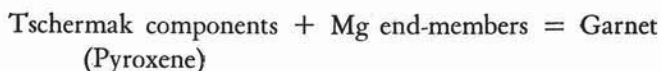
Fig. 16. — Original (I) and final (F) PT conditions for the Balmuccia peridotite. Pressure is that estimated from the partial melting products (dikes). Solid lines: K, and C.P. are dry peridotite solidi according to KUSHIRO et al. (1968) and CHAPMAN et al. (1977), respectively: 0.3, 0.5, 0.7 and 0.9 are peridotite solidi with various $X'H_2O$ contents (MYSEN & BOETTCHER, 1975). Dashed lines: Geotherms of CHAPMAN & POLLOCK (1977) for increasing heat flow from 0.71 to 3.6 HFU.

Geobarometry should therefore be applicable to all compositions of gabbro, pyroxenite and peridotites, except for the spinel lherzolites.

OBATA (1976) provides a method for estimating P in spinel pyroxenites and gabbros, while WOOD & BANNO (1973), WOOD (1974), and HERZBERG (1978) provide thermodynamic data and equations for estimating P in garnet bearing ultramafic and mafic rocks. The use of their equations implies that the phases are in equilibrium and that the formation of garnet is directly related to the breakdown of pyroxenes. As far as equilibrium is concerned, it has been

shown while dealing with geothermometry that, besides insufficient knowledge of ideal-non-ideal behaviour of the crystalline solutions involved, the high K_2 and K_3 temperatures may represent, or be near to, the original T . As garnet is clearly a secondary product, formed during re-equilibration, there is a possible disequilibrium between pyroxenes and garnet. As for the second condition, the present garnet is always formed by reaction between mafic phases and plagioclase, and not as an exsolution product of pyroxenes.

Obviously the volume change of the reaction:



is different if anorthite substitutes for the tschermak component. The equations of WOOD (1974), and HERZBERG (1978) might therefore be not directly applicable. However at equilibrium there is a control of the garnet composition by that of pyroxenes. In conclusion, it seems that the geobarometers may be used only with caution and for indicative purposes.

It has been shown by SHERVAIS (1979), on the basis of a few data, that the pressure estimated by the method of WOOD (1974) varies between 3 and 12 kb for an ideal solution model, and is about 11 kb if the equation related to a non-ideal model, and containing an empirical correction for iron, is used. Geobarometry of OBATA (1976), related to Al^{VI} and to the equilibrium plagioclase-spinel-clino-orthopyroxene, and that of HERZBERG (1978) is reported in Table 4. Reasonable re-equilibration P is around 8-9 kb with a scatter of the data between 6 and 11 kb. Geobarometry applied to the traverses of pyroxenes (obviously only for Obata's geobarometers) gives a pressure of about 14-15 kb in the dikes of the mantle peridotite. This figure might be taken as indicative of their original P of crystallization. The reliability of these results can be qualitatively evaluated by the following considerations. Garnet crystallization is controlled by bulk composition (see the re-equilibration effects in the main basic body): the most magnesian gabbros have spinel coexisting with pyroxenes and anorthite, as main aluminiferous phases, while garnet only develops at a certain level of iron and alumina contents. This means that the main basic body falls close to the «gabbro-granulite» boundary, and that this boundary is overcome only depending on the composition. From the data of OBATA (1976) and HERZBERG (1978) such a boundary might be placed between 8 and 10 kb at 850° C for iron-free systems. The boundary is moved to lower P for iron-bearing compositions (GREEN & RINGWOOD, 1967, 1972; RAHEIM & GREEN, 1974), so that the figure above must be considered as a maximum value and a pressure around 8 kb is reasonable for the present assemblages. The estimated composition of the original phase (traverse) results in a higher tschermak content in the clinopyroxenes of the dikes, which exsolved spinel with respect to those of the Main Basic Body (especially those of the Layered Series). There is moreover no evidence that the dikes passed through a garnet-facies. This implies (if the grids of HERZBERG (1978) and OBATA (1976) are correct) that assuming

an original T 100-150° C higher than that of re-equilibration and similar to that of the dikes and the Main Basic Body, the pyroxenes of the dikes are crystallized at higher P , possibly around 15 kb (accounting for their Mg-rich composition), with respect to those of the basic body. In the latter, cooling without P variation may be sufficient for explaining their features.

As for peridotites, their spinel facies allows to place a lower P limit around 8 kb and a higher limit at about 20 kb, although the upper limit might be moved to higher P depending on the Cr/Al ratio. Their possible pressure interval therefore fits well with the estimated pressure for the dikes. A pressure lower than 20 kb is also indicated by the presence of amphibole that, according to MYSEN & BOETTCHER (1975), becomes unstable at high pressure (ERNST, 1978).

Geotectonic history and emplacement model for the Ivrea Complex

Arguments that have been shown so far and that are relevant for reconstructing the geotectonic history of the Ivrea Complex, are as follows:

- 1) the peridotites are in part of mantle origin and in part are formed by fractionation of a basaltic magma;
- 2) the Main Basic Body is a layered igneous complex;
- 3) the dikes in the mantle peridotite are formed by fractionation of mantle melts in various episodes, or directly represent the « frozen » mantle melt (the gabbros);
- 4) re-equilibration temperatures are similar in the dikes, mantle peridotite and the Main Basic Body, and vary around 850° C; original T is around 1100-1200° C;
- 5) re-equilibration pressure is equal in the dikes and the basic body around 8 kb, while the original pressure is higher in the dikes than in the basic body.

Before proposing an evolution model, it is necessary to discuss:

- a) the relationships between mantle peridotite and Main Basic Body;
- b) the meaning of re-equilibration;
- c) the oceanic versus continental origin of the peridotites;
- d) the geotectonic environment where the Main Basic Body has formed (as a layered complex).

RELATIONSHIPS BETWEEN THE MANTLE PERIDOTITES AND THE MAIN BASIC BODY

The close association of mantle peridotites and a layered complex suggests the possibility that they are genetically linked via partial melting and fractionation. No direct definitive proof has been as yet reached on this point. There is however some indication that supports this possibility. It has been shown that the gabbroic dikes and pods of the mantle peridotite are always more primitive than the Layered Series rocks and that, at least graphically, they behave as possible parents with respect to this last. Accounting for the close spatial association, a genetic link seems to be highly probable. Further support, besides the igneous contact Layered Series-mantle peridotite, is given by a plagioclase pyroxenitic dike of the mantle peridotite that crosses the contact with the Layered Series and fades into a pyroxenite layer.

If a genetic relationship is accepted, the last mantle products may have crystal-

lized in conditions similar to those of the layered complex (SHERVAIS, 1978-79; 1979) i.e. at a pressure of about 8-9 kb and a temperature of about 1100° C.

MEANING OF THE RE-EQUILIBRATION TEMPERATURE AND PRESSURE

The lowest values of T and P are considered by SHERVAIS (1979) as indicative, as far as the Balmuccia massif is concerned, of the mantle emplacement conditions into the crust, and for part of the Layered Series of a metamorphic act in the granulite-facies. We propose another possibility, i.e. that the mantle emplacement has occurred at higher T , that the pressure of 8-9 kb represents the intrusion of the magma into the lower crust, that the re-equilibration T , equal from mantle to Main Basic Body is representative of the cooling under deepseated conditions.

The first two points rise from the observations made above on the relationship mantle-Main Basic Body. As for the last point, although the effects of a metamorphic act or of cooling should formally be similar, they have obvious different geotectonic meanings. The possibility of re-equilibration by cooling is substantiated by the following facts:

- 1) the primary paragenesis is always recognizable in the rocks of the complex and never in the metabasites intercalated with the metasediments;
- 2) had the complex suffered a major metamorphic act, its grade could not have been in a facies lower than that of granulite, otherwise the preservation of original features such as those shown in the preceding paragraphs would be very improbable;
- 3) the intrusion of the complex has a clear thermal effect on the country rocks as shown by SCHMID & WOOD (1976). The authors have proposed that the granulite facies metamorphism was determined on metapelites by the intrusion of the magma. Had the complex been metamorphosed afterwards together with metapelites such a thermal effect would have most likely been obliterated;
- 4) the equilibrium temperature does not vary appreciably through the complex down to the «diorites», where the country rock is in amphibolite facies.

GEOTECTONIC ENVIRONMENT OF THE MANTLE PERIDOTITES

If the estimated original conditions of the peridotites are reported in the grid of Fig. 16, they plot close to the dry peridotite solidus. They plot above the solidus if a slightly hydrated peridotite model is considered: a moderate hydration is suggested by the widespread, although minor, occurrence of hornblende. The re-equilibration conditions plot well below the solidus. Together with the original conditions, they define an evolutive pattern apparently indicative of an oceanic affinity. They also plot close to the 3.6 HFU geotherm of CHAPMAN & POLLOK (1977). However, as also SHERVAIS (1979) points out, these arguments are not sufficient in order to assume an oceanic origin for the Balmuccia body.

Another argument, that might favour an oceanic affinity, is the direct link of the mantle peridotite with the Layered Complex, that is a possible feature of oceanic associations but is uncommon in continental environments.

If a genetic relationship is accepted, the last mantle products may have crystallized. On the other hand, relatively high pressure cumulitic bodies are uncommon both in oceanic and continental situations. An indication is given by the relationship between the mantle peridotite, its partial melting products, and between these and the Layered Complex. It has been shown, that a genetic relationship between the mantle melting and the Layered Complex is highly probable. If this is the case, the final emplacement of the peridotite and the crystallization of the liquids cannot have occurred in conditions very different from a P of about 8-9 kb and at a T of 1100-1200° C, i.e. under a cover of 25-35 km. Such a thickness may correspond to a continental rather than to an oceanic environment (SHERWAIS, 1979). The possibility of continental origin also conforms with the distinction made by NICOLAS & JACKSON (1972) of the lherzolites as continental bodies and the harzburgites as oceanic peridotites, in the mediterranean area. An attempt to estimate the geothermal gradient of the zone may be undertaken in the following way. Assuming that re-equilibration represents a cooling episode and not a metamorphic act, its temperature must be representative of the thermal equilibrium between the magma and the environment. Estimating a 30 km thick crust, the geothermal gradient has to be about 25-30° C/km.

GEOTECTONIC ENVIRONMENT OF THE LAYERED COMPLEX

It has been shown that the Ivrea-Verbano Layered Complex differs both from oceanic and continental mafic ultramafic bodies for a number of characteristics, but mainly for the calc-alkaline fractionation trend of a part of its members (MG and «diorites») and for its association with mantle peridotites.

Generally accepted relationships between magma composition and geotectonic environment indicate that the calc-alkaline magmas are associated to orogenic areas. In the case of the Ivrea body, an orogenic environment is supported also by the dynamic textures of the rocks and by the migmatitic phenomena and granites occurring at the eastern margin of the complex. The possible direct relationship between mafic complex and mantle peridotites, the high geothermal gradient and the estimated thickness of the crust (about 30 km) at the time of the intrusion suggest that the Ivrea body was emplaced in an environment similar to the continental side of a continental margin.

THE MODEL

On the basis of the points examined above, we propose the following evolutive model for the Ivrea zone:

- 1) mantle regional uplifting during an orogenic act, in an environment comparable with that of the continental side of a continental margin, and under a crust about 30 km thick;
- 2) episodes of partial melting in the mantle, concomitant with the adiabatic uplifting, with fractionation of liquids at progressively decreasing pressure (between 20 and 10 kbar);

- 3) intrusion of the magma into the lower crust, already in the granulite facies, concomitant with the mantle final emplacement during the general uplifting of the area;
- 4) concomitant fractionation of the magma batch or batches in the orogenic dynamic environment;
- 5) thermal increase in the rocks adjacent to the intrusion; slow cooling with reaching of thermal equilibrium between complex and country rock at about 850° C;
- 6) possible anatexis caused by heating;
- 7) possible further deformation, not registered by changes in phase composition or by other metamorphic effects.

Geochronological data provided by HUNZIKER (1978-79) do not contrast with such a model. He has shown that two main metamorphic thermal events occur at 470 and about 300 m.y. The author does not make any inference that the two acts are separated. In our picture, the older metamorphism might represent the metamorphic peak before the intrusion, which should have occurred some time between Caledonian and Hercynian. The second thermal peak may be connected with the intrusion of the complex. If this is the case nothing as old as 470 m.y. should be found in the Layered Complex. In effect nothing has as yet been found, but studies on this point are in progress.

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