275

Stanza Gotteto

PETER STILLE

ON THE GENESIS OF THE AMPHIBOLITES AND HORNBLENDEFELSES IN THE BERISAL COMPLEX

(SIMPLON; ITALY-SWITZERLAND)

(with 28 figures, 9 tables and 1 petrographic map)

PADOVA
Società Cooperativa Tipografica
1980

UNIVERSITÀ DEGLI STUDI
DI PADOVA
BIBLIOTECA DI GEOSCIENZE
554
947
(139)

MEMORIE DI SCIENZE GEOLOGICHE
già *Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova*

Volume XXXIV, pagine 205-246, Padova 1980

PETER STILLE *

ON THE GENESIS OF THE AMPHIBOLITES AND HORNBLENDEFELSES IN THE BERISAL COMPLEX (SIMPLON; ITALY-SWITZERLAND)

CONTENTS

Key words: hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites; their age, origin and genetic relationships; Simplon (Italy-Switzerland).

ABSTRACT

Rocks rich in amphibole form an essential part of the Berisal crystalline complex, the highest tectonic unit in the Simplon area and consist of almost pure hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites.

To reveal their age, origin and genetic relationships, these rocks were investigated using petrographic, geochemical and isotopic methods.

Based on the Rb-Sr data and geochemical criteria it seems probable that the plagioclase-amphibolites, garnet-amphibolites, hornblendefelses and banded-amphibolites are of orthogenic origin.

The use of two component mixture diagrams demonstrates that a genetic connection must exist between the hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites. They reflect a magmatic calc-alkaline series.

The layering of the banded-amphibolites was probably developed by the combination of partial melting and metamorphic differentiation. Because of the genetic relationship of the banded-amphibolites to the plagioclase-amphibolites, garnet-amphibolites and hornblendefelses we can assume for them the formation age of 500 m.y.

This age, laying on the Cambro-Ordovician boundary can be related perhaps to the basic volcanics of the « Alt Paläozoikum » in the « Ostalpin » (Austria), where Frank *et alii* (1976) have found formation ages of 500 m.y. in banded-amphibolites of volcanic origin.

RIASSUNTO

Una parte essenziale del complesso cristallino di Berisal, l'unità tettonica più elevata dell'area del Sempione, è costituita da rocce ricche in anfibolo. Si tratta di fels orneblendici quasi puri, anfiboliti granatifere, anfiboliti a plagioclasio ed anfiboliti a bande. Queste rocce sono state studiate dal punto di vista petrografico, geochimico ed isotopico allo scopo di definirne età, origine e relazioni genetiche.

Sulla base delle caratteristiche geochimiche e dei dati Rb-Sr sembra probabile che tutte le rocce anfiboliche sopra ricordate abbiano origine eruttiva e che siano legate da rapporti di connessione genetica, come dimostrato da significativi diagrammi. Essi indicano una caratterizzazione seriale calcalcalina.

Il layering delle anfiboliti a bande risulta probabilmente dalla combinazione di processi di fusione parziale e di differenziazione metamorfica.

La serie calcalcalina originaria comprendeva pirosseniti (fels orneblendici), quarzo-tholeiiti povere in alcali (anfiboliti a granato), quarzo-tholeiiti (anfiboliti a plagioclasio) ed andesiti (anfiboliti a bande), la cui genesi magmatica risale a 500 m.a. Esse originarono molto probabilmente nel mantello superiore e nella crosta inferiore, mentre la loro presa di posizione nei parascisti del Berisal deve essere avvenuta per iniezione tettonica a freddo.

Queste manifestazioni magmatiche, sviluppate al limite Cambro-Ordoviciano, possono forse essere correlate con le vulcaniti basiche del Paleozoico antico delle Alpi orientali (attualmente anfiboliti a bande), la cui età risalirebbe a 500 m.a. (Frank *et al.*, 1976).

* Mineralogical Institute, Isotope Geology, University of Bern, Erlachstrasse 9a, CH - 3012 Bern, Switzerland.

1. INTRODUCTION AND GEOLOGICAL SETTING

The Simplon area in southwestern Switzerland and Italy is part of the Pennine nappe system of the Alps. GERLACH (1869) first recognized the nappe structure in the Simplon region, having previously observed that older crystalline rocks were lying on younger sedimentary rocks. The nappe structure of the tectonic units Berisal, Monte Leone and Antigorio was later confirmed by SCHARDT (1904), and SCHMIDT, PREISWERK and STELLA (1908).

Tertiary time by sediments. Both units, the Mesozoic cover and the crystalline basement, have been involved in the Alpine orogeny which is responsible for the formation of the nappe system. U-Th-Pb age determinations indicate that zircons in the rocks of the crystalline basement were formed during two periods: in the Caledonian, 400 - 500 m.y. and in the Variscan about 300 m.y. ago (KÖPPEL and GRÜNENFELDER, unpublished data). Unpublished data of JÄGER indicates that the Rb-Sr systems of the different Pennine nappes were closed in the Variscan 200-300 m.y. ago.

TECTONIC MAP

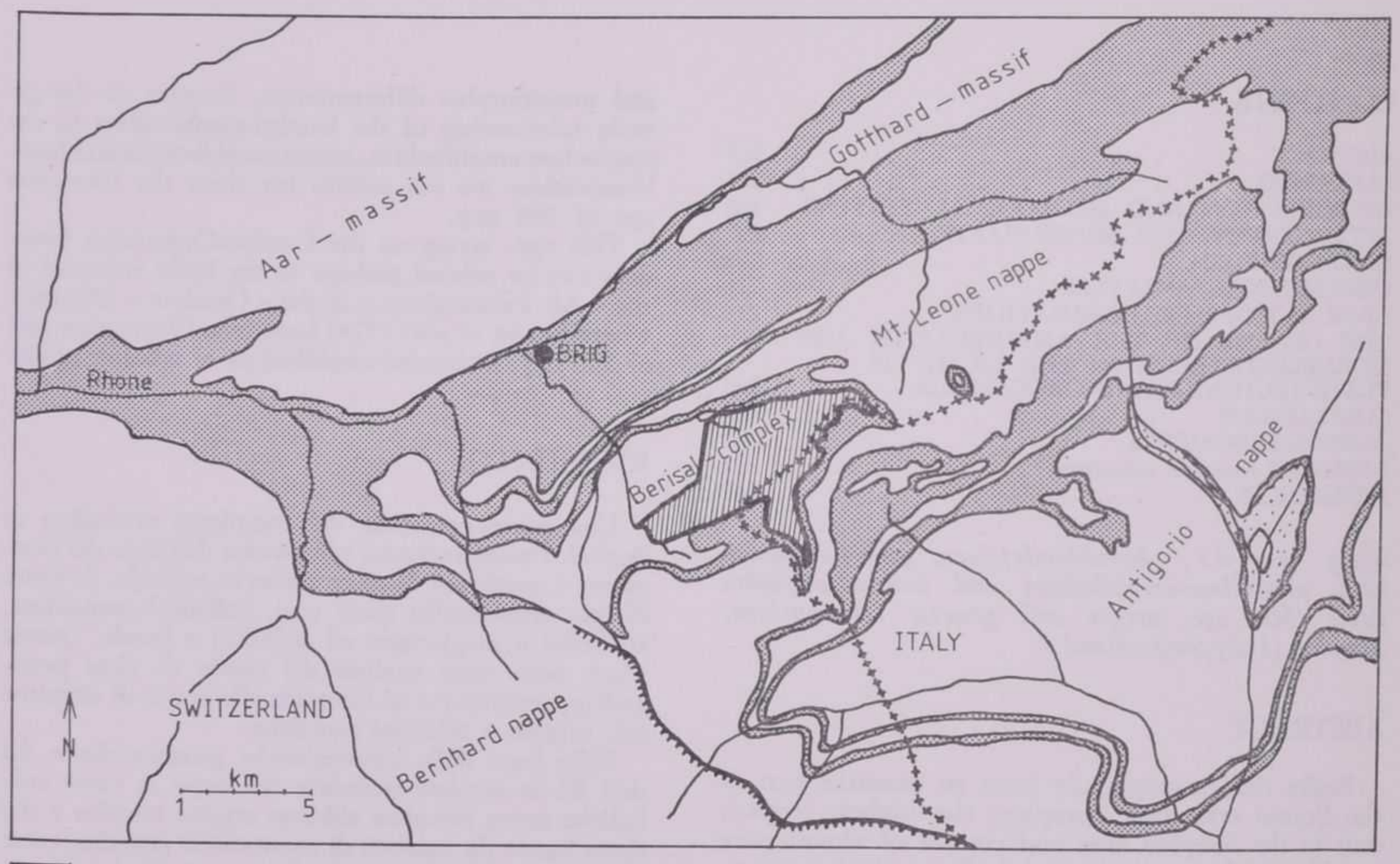


FIG. 1 - General tectonic map showing the investigated area.

The general geology of the area is shown on the tectonic map (Fig. 1). Two general lithologies may be discerned in this region: a crystalline basement and a metasedimentary cover. The crystalline basement of the Pennine nappes consists of quartzo-felspathic and schistose gneisses with or without garnet and biotite. There is a remarkably widespread local occurrence of amphibolite bodies. The nappes represent a pre-Triassic crystalline basement which has been covered in Mesozoic to

The metasedimentary Mesozoic cover consists of Triassic rocks (dolomites, gypsum-bearing and quartzitic rocks), and of calcareous schists and impure marbles, called the « Bündnerschiefer » or « calcescisti ». In the Simplon area it was metamorphosed under almandine-amphibolite facies conditions during the Alpine metamorphism.

The amphibole bearing rocks of the crystalline basement have seldom been investigated. This present study examines in detail the amphibolites

in the Berisal complex, the highest tectonic unit of the nappe pile in the Simplon area.

The different lithological units are shown on the detailed geological map of the eastern part of the investigated area, included at the end of this publication.

The Berisal complex consists mostly of gneisses and schistose gneisses with or without biotite and garnet, probably representing old pelitic and psammitic metasediments. Intercalations of plagioclase-amphibolites, garnet-amphibolites and banded-amphibolites are very common in the whole Berisal crystalline complex, in particular the plagioclase-amphibolites form massive bodies often more than 30 meters in thickness. The contacts of the amphibole bearing rocks to the surrounding monotonous schistose gneisses are sharp. The transitions between garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites are gradual. The banded-amphibolites mostly appear as separate bodies, the distinct light and dark layers, having thicknesses of several millimeters to several centimeters, being generally separated by sharp contacts.

The very intensive folding, the isoclinal folds, the boudinage and the deformation of some band successions point to the polydeformative history of these rocks.

The hornblendefelses form separate bodies and make up the biggest portion of amphibole-rich rocks in the Bortelhorn (see the detailed geological map at the end of this publication). They occur as lenticular, intensively pressed and stretched intercalations in the schistose gneisses.

In addition light granitic alkali-felspar-gneisses and augengneisses (orthogneisses?) appear in the southern part of the Berisal crystalline complex. They form a small body striking east-west through the whole investigated area, and the contacts between them and the surrounding schistose gneisses are sharp.

2. PETROGRAPHY AND MINERALOGY

The Hornblendefelses (Following German usage) are rocks consisting of more than 90 percent amphibole, with a randomly orientated fabric in which the individuals of amphibole are diablasticaly intergrown. Larger porphyroblasts are embedded in a finer tissue of amphibole. The texture is nematoblastic, seldom lepidoblastic.

The main minerals are two types of amphibole. Often the rock is formed of actinolite, less frequently of a blue-green amphibole which often appears zoned. Diopside, carbonate (both dolomite and calcite) chlorite, epidote/clinozoisite, quartz, biotite and oligoclase are occasionally recorded. Diopside was found only in one outcrop in the most eastern part of the Berisal complex (sample 335); individual crystals are seldom idiomorphic, however relict idiomorphic cores in the pyroxene are observable, containing undetermined needle-like inclusions orientated along the cleavages. In many cases the borders of pyroxene crystals are strongly corroded, with the resulting growth of actinolite/tremolite. From these reactions it is concluded that the rock-forming actinolite must be a metamorphic product of pyroxene probably of Tertiary Alpine age. The pyroxene itself therefore could be of early Alpine (Cretaceous ?) age or pre-Alpine.

The Plagioclase-Amphibolites show a fine parallel texture accentuated by the prisms of amphibole. Major constituents are a blue-green tschermakitic amphibole, actinolite, quartz and plagioclase felspar, determined as oligoclase: accessory constituents are epidote/clinozoisite, chlorite, biotite, carbonate (dolomite and calcite), rutile, ilmenite, haematite, apatite and garnet.

45 to 75% of the mineral constituents of the rock are tschermakitic to actinolitic amphibole. The tschermakite-actinolite ratio is very variable, but the tschermakitic amphibole is dominant. Often the crystals are zoned, with a light to colorless actinolitic core surrounded by a darker, more pleochroic tschermakitic marginal zone. The transition from core to rim is generally not sharp. Microprobe investigations (STILLE, unpublished data) have shown that a series of mixed-crystals exist between actinolite, Mg-hornblende and tschermakite.

Two generations of epidote minerals can be observed: enrichments of newly grown epidote, clinozoisite and zoisite appear relatively often in lenses and fine layers. The old primary epidote is finely distributed throughout the rock, very often zoned and hypidiomorphic and cataclastic in comparison with the newly grown idiomorphic porphyroblasts. It seems that after the formation of the amphiboles, migration and accretive crystallization of the epidote minerals in lenses and fine layers took place (see also section 3).

The Garnet-Amphibolites resemble plagioclase-amphibolites in appearance, texture and structure, but with garnet as the dominant mineral. The results of X-ray and optical investigations to determine the lattice constant and refractive index for five individual crystals are shown in figure 2, a garnet determination chart, after WINCHELL (1968). The average value of the lattice constant is 11.63 Å and the mean re-

fractive index is 1.8, indicating an almandine-rich garnet. The garnet is mostly corroded, in part totally rotten and altered. Important reaction products are epidote, amphibole, biotite and chlorite. In places the garnet shows keliphitic rims of epidote, clinozoisite and zoisite, radially fibrous in appearance. Fine symplectitic growths of amphibole and albite occasionally occur.

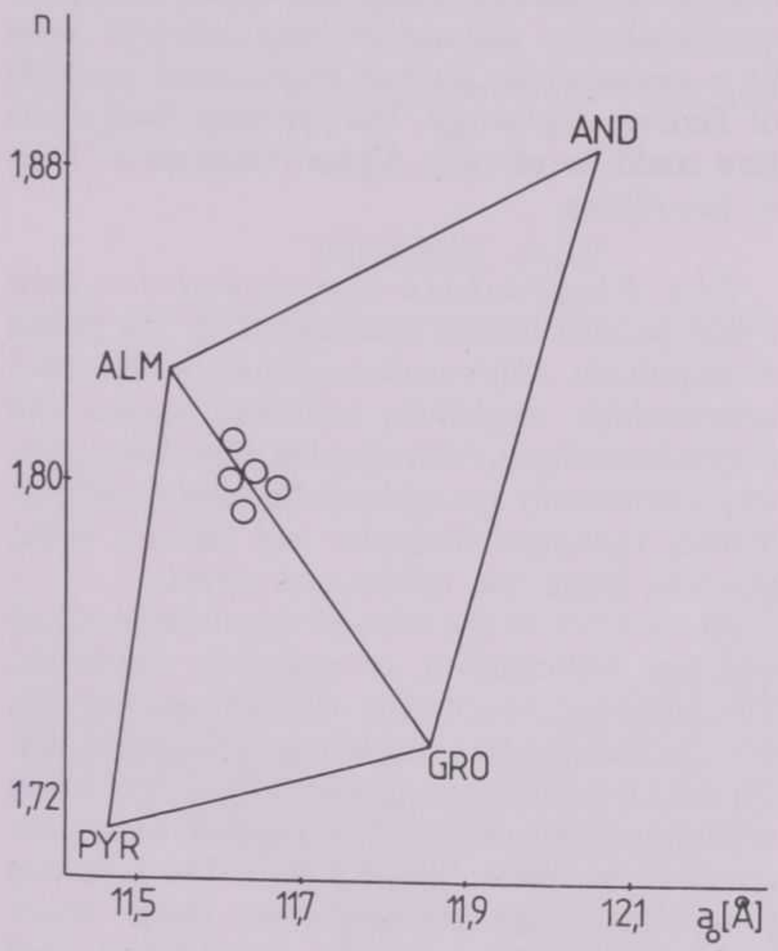


FIG. 2 - Determinative chart for garnets (after WINCHELL, 1958).

The Banded-Amphibolites show an interlaminate layering similar to that of the plagioclase-amphibolites, but on a larger scale. The thickness of the individual bands varies in the range of millimeters to centimeters. The mineralogy is very similar to the plagioclase-amphibolites. The light layers show no lepidoblastic texture and amphibole and epidote minerals are rare. They contain a high proportion of plagioclase (oligoclase) and especially quartz, together forming more than 90% of the layer.

3. METAMORPHISM

3.1. BANDED-AMPHIBOLITES, AN EXPRESSION OF METAMORPHIC DIFFERENTIATION

The genesis of the thin layers in the banded gneisses is uncertain; five mechanisms are suggested here. The layering may be of sedimentary, or magmatic origin; it may be a product of deformed and stretched migmatitic restites and leucosomes (terminology of MEHNERT, 1968). The layering may be the direct result of metamorphic differentiation, or the combination of metamorphic differentiation with one of the first three mechanisms. In this section only the influence of metamorphism upon the layering is considered in respect of petrographical, mineralogical and geochemical evidence.

Deformation, recrystallization and diffusion are important mechanisms during dynamic metamorphism and may convert an originally nearly homogeneous rock into a layered succession by metamorphic differentiation involving, according to ESKOLA (1932), an interaction of both mechanical and chemical factors.

3.1.1. *Macroscopic and Microscopic Observations*

The hornblendefelses of the Berisal complex show a randomly orientated fabric in which the individual crystals of amphibole are diablastically intergrown. In contrast to the hornblendefelses the plagioclase-amphibolites exhibit moderate segregation into lenses and stripes usually less than one millimeter in thickness. The pronounced parallel texture is accentuated by the prisms of amphibole aligned in s-planes.

The banded-amphibolites show the same layering but on a larger scale, with the single layer thicknesses varying in the range of millimeters to centimeters. The subdivision into dark and light layers corresponds to foliation and lineation, and gradations between light and dark layers rarely exist. The contacts with surrounding schistose gneisses are mostly sharp. The felsic portions of the banded successions show granoblastic plagioclase and varying amounts of quartz. Both the fine layering of the plagioclase-amphibolites and the pronounced layering of the banded-amphibolites could be a product of metamorphic differentiation, deformation and recrystallization. The intensity of deformation was very important for the degree of metamorphic differentiation. Microscopic and macroscopic investigations have shown that the segregation increases with increasing degree of deformation, the mafic layers becoming poorer in quartz and felspar, the felsic layers poorer in mafic minerals. The contacts, between felsic and mafic layers are more sharply developed in strongly deformed band successions than in undeformed bands, suggesting that the processes of mechanical mineral segregation as described by WENK (1936) might have been important.

Local differences in stress and fluids permit the differentiation of the original material of the banded-amphibolites in different ways and to varying

degrees. Chemically these processes have the consequence that the mafic portions become enriched in Fe, Mn, Mg, Ca and Ti whilst Si, Na and K are concentrated in the felsic portions. In comparison with the dark layers, which show a relatively homogeneous chemical analysis over the whole area of investigation, the light layers show very scattered values. Such variation might be attributable to SiO_2 dissolved in fluids.

Thus according to microscopic and macroscopic observations, the layering observable today could be considered as a metamorphic product. It is not possible to say whether a primary magmatic layering existed in the rock before metamorphism, the differentiation only being accentuated during the metamorphic events. It is possible that restites in the form of nodules and hardrocks at first swam in a leucosome and only during the polymetamorphic events were they deformed and stretched, with the resulting layering observable today.

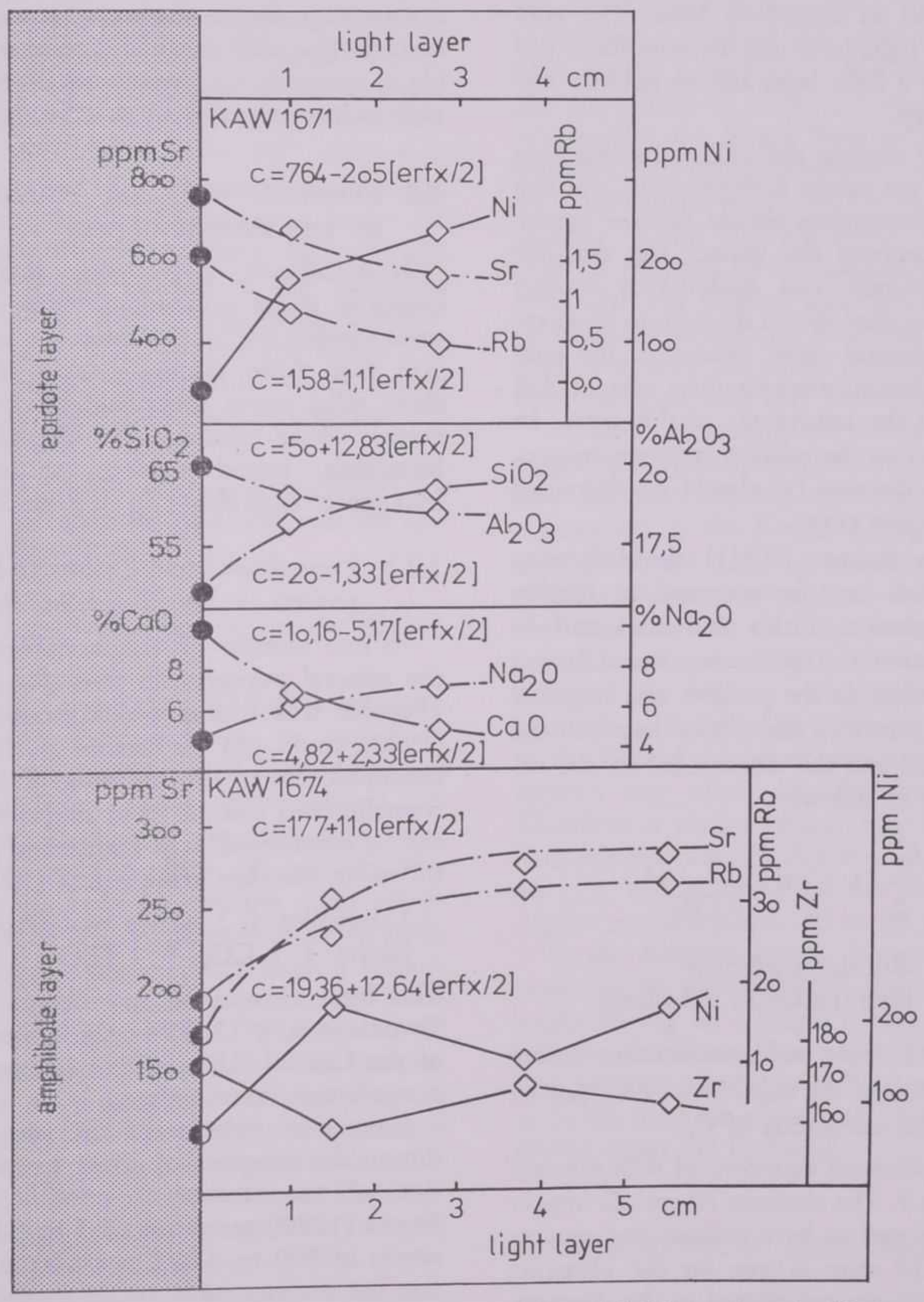


FIG. 3 - The movement of components between light and dark layers shown by diffusion curves.

Thus according to microscopic and macroscopic observations, the layering observable today could be considered as a metamorphic product. It is not possible to say whether a primary magmatic layering existed in the rock before metamorphism, the differentiation only being accentuated during the metamorphic events. It is possible that restites in the form of nodules and hardrocks at first swam in a leucosome and only during the polymetamorphic events were they deformed and stretched, with the resulting layering observable today.

Therefore it can only be said, that in the original material the acidic and basic portions have been inhomogeneously distributed in such a manner that during later deformations and metamorphic differentiations the banded-amphibolites could be developed.

3.1.2. *Analytical Evidence for Diffusion*

To demonstrate the migration of material during segregation processes, the chemical data for two non-adjacent successive bands (KAW 1671 and 1674) in a banded – amphibolite sequence are plotted in figure 3. Here the concentrations of analyzed elements contained in two light layers are shown to be related to the distance from an epidote layer and an amphibole layer. The contacts between a light layer and an amphibole layer, and between a light layer and an epidote layer are razor sharp.

In the case of element diffusion, assuming that the light layers are nearly homogeneous, the single element concentrations should become approximately homogeneous the greater the distance from the hornblende- and epidote-rich contact zones; this means they should describe in this range a nearly horizontal curve. Nearer to the contact zone the element-concentrations rise or fall dependent upon the mineralogy of this zone. In the case of diffusion the relation between concentration (C) and distance (x) should be described by an error-function curve.

According to BARRER (1941) the following physical condition must be proposed to resolve the diffusion-equation (Fick's 2nd law) and to derive the equation for this curve: the diffusion is running infinitely in the positive and negative x-direction and therefore the relation between the concentration (C) and the distance (x) to the extraction zone is as follows:

$$C = \frac{C_o}{2}\left[1 + \operatorname{erf}\left(\frac{x}{\sqrt{2\,Dt}}\right)\right]$$

where: D = diffusion coefficient
t = time (period of diffusion)

Supposing, that D and t had been constant during the time of diffusion the expression $\sqrt{Dt}$ can be neglected for the calculation of C.

The single calculated equations of diffusion are shown in figure 3. The elements Ni and Zr appear to be immobile and to have resisted the process of diffusion. The same is true for the elements Cr and Ti, which are not plotted in the diagram. The elements Rb and Sr follow this law in both investigated band successions.

During the formation of the epidote-layer (see section 2) the major elements SiO_2, Al_2O_3, Na_2O and CaO also must have shown conformity with Fick's law. According to the shown error-function curves it can be said that diffusion had an effect over a range of more than 3 centimeters.

3.1.3. *Conclusions*

Microscopic and macroscopic observations and the evidence of solid diffusion and solution reactions indicate that there was an influence of metamorphic differentiation on the development of banding. However the initial conditions of the layering very probably resulted from primary inhomogeneities in the original rocks. It is difficult to make a statement about the exact course of timing of metamorphic differentiation, and so it is not possible to estimate the influences of earlier metamorphic events revealed by microscopic observations.

3.2. EVIDENCE FOR THE POLYMETAMORPHISM OF THE AMPHIBOLITES

It is difficult to recognize relicts of previous events in these polymetamorphic and high grade metamorphic rocks. Microscopic observations reveal that three minerals seem to be relicts or show relict cores reflecting pre- to early- Alpine events. These minerals are diopside in the hornblendefels, zoned epidote, spotted and zoned blue-green amphibole in the amphibolites.

3.2.1. *Tremolite-Calcite-Dolomite-Diopside Paragenesis in the Hornblendefelses*

In one sample of the hornblendefelses (335) the mineral paragenesis tremolite-calcite-dolomite -diopside was found which, according to FRANK (1980), could not be formed during the last metamorphic event in this area. The formation of tremolite and calcite from diopside and dolomite can be considered as a retrograde product by the following reaction after METZ (1970):

1 tremolite + 3 calcite $\leftrightharpoons$ 4 diopside + 1 dolomite + 1 CO_2 + 1 H_2O

This kind of mineral assemblage was found by TROMMSDORFF (1972) only in the southern part of the Central Alps, where higher pressures and temperatures have existed.

From a knowledge of the pressure conditions during the progress of these reactions an estimation of temperature is possible. According to FRANK (1980) pressures of 5 to 6 kb and temperatures of 500 to 550°C must have existed during the last metamorphic event in this region.

On the assumption that such pressures of more than 5 kb had been operating on the tr-cc-di-dol--system, temperatures of more than 600°C can be established using the equilibrium curves of SLAUGHTER (1975). However phase-petrological investigations, especially those of FRANK (1980), indicate that temperatures of more than 550°C are too high. Therefore it is concluded that the observed paragenesis must be a relict one, pro-

bably representing the eo-Alpine high-pressure event.

3.2.2. *Zoned Epidote*

Frequently in the plagioclase- and garnet-amphibolites two generations of epidote minerals occur one following the other in a zoning (see section 2).

HOLDAWAY (1972) and LIOU (1973) could show experimentally that the Fe^{3+}-content is essentially controlled by the existing oxygen fugacity. The increase of temperature during metamorphic crystallization causes a decrease of the oxidation degree to such an extent that the Fe^{3+} -content in the epidote decreases. The ore minerals ilmenite, rutile and sphene in the investigated rocks are sensitive indicators for this process. Fe^{3+}-rich epidotes will be changed already in the transition zone of greenschist to amphibolite facies. Clinozoisite and zoisite remain stable into the higher P-T range of the low-grade amphibolite facies, beside muscovite, quartz and plagioclase (HOERMANN and RAITH, 1971, 1973).

The transformation of epidote into clinozoisite and zoisite can be observed particulary in the epidote-rich amphibolites.

3.2.3. *Polymetamorphism shown by the Amphiboles*

In the Simplon area, during the Lepontine phase of metamorphism, temperatures in excess of 500°C were obtained, and the P-T conditions of almandine amphibolite facies were reached. Several phases of amphibole crystallization were destroyed and a reconstruction of crystallization history is only possible by making comparisons with basic rocks of the neighbouring lower grade Alpine metamorphic regions. For such a comparison the Monte Rosa nappe is particulary suitable: lying in the southwestern Pennine area of the Central Alps, west of the Ticino culmination, about 15 km south-west of the Simplon. For the Monte Rosa region BEARTH (1967), using mineral paragenetic criteria, assumed temperatures between 450 and 500°C. In confirmation, HUNZIKER (1970), with the help of biotite and phengite ages, demonstrated that the south-western part of Monte Rosa remained for only a short time under conditions of elevated temperatures of metamorphism. Such a lower P-T regime permitted the preservation of all crystallized amphiboles. Therefore it was possible for WETZEL (1974) during his detailed work in the Monte Rosa nappe region to define several phases of amphibole crystallization during Alpine metamorphism. Glaucophanes are the oldest amphiboles in the Monte Rosa nappe, originating from an early Alpine high-pressure metamorphic event. The glaucophanes give K-Ar ages of 80 m.y. (HUNZIKER, 1974). By analogy the penninic basic and ultrabasic rocks of the Berisal crystalline complex must have supported higher-pressure metamorphic events similar to Monte Rosa 80 m.y. ago. During this high pressure event the basic rocks of the Berisal complex were probably transformed into eclogites and pyroxenefelses, the diopside in the hornblendefels perhaps representing a relict of this early Alpine metamorphic event. According to WETZEL (1974), with the appearance of albite and oligoclase, the glaucophane of the Monte Rosa starts to disappear, gradually becoming colourless and being covered by a blue-green barroisitic (= tschermakitic) amphibole. Later, the blue-green amphibole itself may be replaced by a Mg-hornblende, or actinolite, with the original glaucophane also changed to a nearly colourless, actinolitic amphibole. By such a process the often observed zoning (light core and dark rim) may be explained.

In later Alpine phases similar successions of amphibole crystallization following the glaucophane may be assumed, but the higher temperatures maintained in the Berisal during longer periods than at Monte Rosa, have destroyed several amphibole phases. Nevertheless the appearance of the amphiboles in the basic rocks of the Berisal crystalline complex is quite similar to the amphiboles of the highest metamorphic zones in the Monte Rosa described by WETZEL (1974). Similarly in the Berisal the zoned tschermakitic amphibole appears very often, also described by WETZEL. Therefore a similar history may be assumed for both regions: an early Alpine high pressure phase, 80 m.y. ago, followed by the Tertiary phase of Alpine metamorphism, 40 to 20 m.y. ago.

In the Simplon region the second phase was more intense than at Monte Rosa, higher temperatures lasting for a longer period of time. Therefore, in the Monte Rosa region the early Alpine high pressure mineral assemblage survived, whereas in the Simplon region only traces of this early Alpine event can be found.

4. GEOCHEMICAL ANALYSES

4.1. MAJOR AND TRACE ELEMENT ANALYSIS - METHODS AND RESULTS

30 kg samples of hornblendefelses, garnet-amphibolites and plagioclase-amphibolites were collected, petrographically examined, and prepared for geochemical analysis. When sampling the banded-amphibolites specimens of about 5-8 kg were obtained from undeformed rocks with parallel planar bands; the light and dark layers were se-

TABLE 1 - Chemical compositions and NIGGLI-values of the hornblendefelses

Sample	76	77	333	334	335	455	457	1657	1675	1818
SiO_2	53.0	52.0	52.5	47.3	51.8	49.5	50.5	51.5	53.5	50.4
Al_2O_3	5.3	9.2	10.0	9.9	4.0	8.0	8.5	5.5	4.7	10.1
Fe_2O_3	2.0	2.7	2.3	1.7	1.8	3.2	3.4	1.8	1.8	2.4
FeO	6.2	6.3	5.7	5.4	5.4	8.1	7.1	5.5	4.6	6.0
MnO	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
MgO	23.5	18.4	16.2	16.5	20.4	18.3	18.4	18.4	20.3	13.9
CaO	13.1	10.2	11.9	12.8	12.5	13.0	12.5	13.0	13.5	12.0
Na_2O	—	1.5	1.8	1.1	0.8	0.9	1.0	0.6	0.7	1.4
K_2O	0.1	0.3	0.3	0.1	0.1	0.3	0.3	0.1	0.2	0.2
TiO_2	0.1	0.4	0.3	0.1	0.1	0.5	0.3	0.2	0.1	0.2
P_2O_5	n.d.	n.d.	n.d.	0.1	0.1	n.d.	n.d.	0.1	0.1	0.2
H_2O	n.d.	n.d.	n.d.	2.5	2.9	n.d.	n.d.	2.2	1.3	2.4
CO_2	n.d.	n.d.	n.d.	1.6	1.2	n.d.	n.d.	1.4	0.1	1.4
Total	103.5	101.1	101.2	99.3	101.3	102.0	102.2	100.5	101.1	100.8
si	89.7	98.7	102.3	92.2	97.8	88.0	90.9	100.6	99.7	105.0
al	5.3	10.3	11.5	11.4	4.4	8.4	9.0	6.3	5.2	12.4
fm	70.8	65.9	60.1	59.5	68.8	65.1	64.8	65.3	66.3	57.7
c	23.7	20.7	24.7	26.8	25.3	24.6	24.0	27.1	27.0	26.8
alk	0.1	3.1	3.7	2.3	1.6	1.9	2.2	1.3	1.5	3.1
k	1.0	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
mg	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.9	0.8
Q	22.9	24.8	25.9	23.8	24.1	21.4	22.5	26.1	25.1	27.7
L	8.3	18.9	20.9	20.0	8.8	15.5	16.6	11.0	9.7	21.1
M	68.8	56.3	53.2	56.2	67.1	63.1	60.9	63.0	65.2	51.2
Cr	1830	1020	420	1100	1300	590	515	1300	1300	820
Ni	310	145	95	293	364	75	75	316	368	150
Ti	600	2200	1500	540	660	2700	2000	900	600	1380
Zr	10	40	30	40	35	50	60	75	70	75
Y	—	50	—	<10	<10	—	20	25	—	15
Nb	—	—	—	10	20	—	—	7	—	15
Rb	—	—	—	20	—	—	—	0.6	1.8	1.6
Sr	10	150	170	90	10	80	250	28	17	59
Ba	n.d.	n.d.	n.d.	—	—	n.d.	n.d.	—	—	—

TABLE 1 - (continued)

Sample	1820	1821	1822	1823	1824	1825	1826	1827	1819 A	1819 B
SiO_2	50.5	50.9	53.2	50.8	51.9	47.3	50.9	50.3	42.7	44.6
Al_2O_3	10.9	5.1	5.7	7.4	5.6	11.4	8.8	10.4	10.2	10.7
Fe_2O_3	3.1	1.7	1.9	2.9	1.7	1.8	2.3	1.8	2.4	2.8
FeO	6.5	5.9	5.9	5.9	5.5	5.0	5.8	5.5	7.8	7.4
MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
MgO	13.6	18.1	18.4	17.7	17.1	15.2	16.2	15.0	11.8	12.7
CaO	10.5	12.1	12.6	11.1	13.2	13.7	12.2	12.5	14.2	13.7
Na_2O	1.4	1.3	0.9	2.4	0.7	1.3	1.1	1.5	1.3	1.9
K_2O	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.8	0.3
TiO_2	0.5	0.1	0.1	0.5	0.2	0.1	0.1	0.1	2.2	2.2
P_2O_5	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.4	0.4
H_2O	2.3	2.5	2.5	2.8	2.5	2.7	2.4	2.3	2.2	2.3
CO_2	0.2	1.0	1.0	0.2	1.4	2.4	0.2	1.7	4.3	2.5
Total	100.1	99.1	102.7	102.1	100.2	101.4	100.5	101.6	100.5	101.7
si	106.7	100.5	103.1	97.1	104.6	92.6	101.0	101.8	86.9	88.9
al	13.6	6.0	6.6	8.4	6.7	13.1	10.3	12.4	12.2	12.5
fm	59.5	65.8	65.5	64.4	63.4	55.5	61.3	57.6	53.0	54.3
c	23.8	25.6	26.2	22.7	28.5	28.7	26.0	27.0	31.1	29.2
alk	3.2	2.7	1.8	4.5	1.4	2.8	2.4	3.1	3.7	4.0
k	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.3	0.1
mg	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7
Q	28.6	24.5	26.6	22.1	27.5	24.1	26.5	26.7	20.4	21.0
L	22.4	12.4	11.8	18.3	11.9	22.8	17.9	21.2	23.1	23.6
M	49.1	63.2	61.6	59.6	61.1	53.1	55.7	52.0	56.5	55.4
Cr	855	1300	1265	1745	1300	855	890	820	1160	1030
Ni	230	210	240	242	286	267	195	250	385	250
Ti	3000	780	720	2700	900	480	780	840	13430	13310
Zr	65	70	70	70	60	55	75	80	205	210
Y	—	20	—	10	<10	—	<10	—	—	—
Nb	<10	10	15	20	18	13	10	10	20	25
Rb	2.8	1.2	0.7	1.7	0.5	1.4	1.5	1.7	23	2.7
Sr	42	19	17	18	51	126	53	113	228	224
Ba	—	—	—	—	—	—	—	—	—	—

TABLE 2 - Chemical compositions and NIGGLI-values of the garnet-amphibolites

Sample	60	199	278	345	347	348	349	350	4139	4311
SiO_2	50.0	48.7	47.9	49.5	52.5	50.0	49.5	48.5	51.5	48.0
Al_2O_3	13.2	13.7	14.8	11.1	9.7	13.3	10.7	10.1	10.8	8.0
Fe_2O_3	2.1	2.1	2.9	1.7	2.3	1.6	1.7	2.1	2.9	3.6
FeO	10.9	9.5	10.5	10.7	10.4	9.2	12.1	10.6	12.4	14.4
MnO	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
MgO	7.6	6.2	7.3	7.0	11.5	7.8	10.9	12.3	9.6	9.1
CaO	10.5	14.3	10.0	12.6	11.6	9.7	10.5	11.4	9.7	12.0
Na_2O	1.1	2.1	2.7	2.4	0.6	2.9	1.8	1.8	1.3	2.3
K_2O	0.2	0.3	0.3	0.5	0.3	1.1	1.0	1.6	0.5	0.2
TiO_2	2.3	0.9	1.0	3.4	2.5	2.8	3.2	2.9	2.1	3.4
P_2O_5	0.5	0.4	0.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	98.6	98.4	98.1	99.1	101.6	98.6	101.6	101.5	101.0	101.2
si	117.8	109.1	108.3	113.9	112.6	118.2	103.6	97.4	113.6	99.2
al	18.3	18.2	19.7	15.1	12.3	18.5	13.2	12.0	14.0	9.7
fm	52.3	42.5	50.0	47.8	59.5	48.8	58.3	58.0	59.6	58.9
c	26.5	34.4	24.1	31.1	26.7	24.4	23.5	24.5	22.8	26.5
alk	2.9	5.0	6.3	6.1	1.6	8.3	5.0	5.6	3.5	4.9
k	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.2	0.1
mg	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.5	0.5
Q	33.2	29.0	27.9	27.7	31.1	28.1	25.1	22.0	30.1	22.5
L	26.1	29.6	32.9	26.4	18.0	32.1	24.1	24.0	22.5	20.0
M	40.7	41.5	39.2	46.0	50.9	39.8	50.9	54.1	47.4	57.5
Cr	185	325	190	220	490	180	460	440	290	265
Ni	25	35	15	60	200	65	160	165	55	25
Ti	18400	10700	14700	20500	15000	16600	19300	17500	12300	20600
Zr	170	120	130	170	200	280	170	190	60	30
Y	80	70	50	70	—	20	30	65	60	20
Nb	—	—	—	30	35	40	30	35	—	—
Rb	30	10	20	20	—	75	75	90	10	20
Sr	125	305	170	240	70	400	95	215	10	70

TABLE 3 - Chemical compositions and NIGGLI-values of the plagioclase-amphibolites

Sample	36	38	207	283	332	419	6045	322
SiO_2	52.0	52.5	51.5	53.5	57	50.0	57.0	56.0
Al_2O_3	11.9	12.1	12.2	12.9	14.4	12.9	12.2	13.3
Fe_2O_3	2.8	4.2	3.4	4.2	3.2	3.1	3.8	2.8
FeO	9.0	9.1	8.4	7.7	5.6	6.1	8.6	7.3
MnO	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.2
MgO	9.1	8.3	6.6	6.1	5.6	11.9	4.8	7.8
CaO	10.8	9.3	9.3	8.3	8.9	12.4	7.5	8.6
Na_2O	2.1	3.8	3.1	3.2	3.9	2.8	3.2	3.2
K_2O	0.2	0.2	0.5	1.0	0.7	0.2	0.9	0.7
TiO_2	1.2	1.9	1.7	1.8	1.1	1.2	1.9	0.6
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.3	101.6	96.8	98.9	100.5	100.7	100.1	100.3
si	118.1	118.8	128.8	136.6	150.7	102.1	157.4	138.8
al	15.9	16.1	18.0	19.4	22.4	15.5	19.8	19.4
fm	53.0	52.7	49.0	48.3	41.3	51.7	48.1	49.2
c	26.1	22.4	24.8	22.7	25.2	27.0	22.0	22.7
alk	4.9	8.7	8.3	9.6	11.1	5.7	10.0	8.7
k	0.1	0.0	0.1	0.2	0.1	0.1	0.2	0.1
mg	0.6	0.5	0.5	0.5	0.5	0.7	0.4	0.6
Q	30.8	27.4	31.1	32.3	35.3	25.0	36.8	33.9
L	25.9	30.2	30.5	32.3	35.1	28.3	30.8	31.4
M	43.3	42.4	38.4	35.4	29.6	46.8	32.4	34.7
Cr	340	265	225	280	200	380	190	1360
Ni	55	30	30	45	10	180	20	55
Ti	7400	11200	10000	10800	6500	7300	11500	3800
Zr	60	120	125	120	140	70	220	70
Y	50	30	60	30	100	30	70	30
Nb	—	—	—	—	—	—	—	—
Rb	20	—	20	30	30	25	40	40
Sr	95	105	290	140	495	180	160	275
Ba	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

TABLE 3 - (continued)

Sample	1596	1654	1676	1816	1817	1849	1850
SiO_2	51.5	53.0	56.7	49.6	53.8	49.2	49.9
Al_2O_3	14.5	17.2	14.7	13.8	16.9	14.4	13.9
Fe_2O_3	4.2	3.1	3.3	4.2	2.3	3.3	3.7
FeO	6.9	5.0	5.3	6.6	5.0	7.1	6.9
MnO	0.2	0.1	0.1	0.4	0.1	0.2	0.2
MgO	6.7	4.9	5.1	7.5	4.9	6.1	6.0
CaO	7.9	8.4	7.4	11.2	7.3	11.3	10.1
Na_2O	4.3	4.3	3.8	3.0	3.5	3.6	4.5
K_2O	0.3	0.8	0.6	0.2	1.2	0.4	0.4
TiO_2	1.6	1.3	1.1	1.4	1.0	1.4	1.4
P_2O_5	0.2	0.4	0.2	0.4	0.3	0.2	0.2
H_2O	1.5	1.4	1.5	2.0	1.6	2.5	2.7
CO_2	0.2	<0.1	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.0	100.0	99.8	100.3	97.9	99.7	99.9
si	127.3	140.3	160.6	114.3	152.3	116.9	121.0
al	21.2	26.8	24.5	18.7	28.1	20.2	19.9
fm	47.3	36.9	41.6	46.7	37.8	42.2	42.8
c	20.9	23.9	22.3	27.6	22.2	28.8	26.1
alk	10.6	12.3	11.6	7.0	11.9	8.8	11.2
k	0.0	0.1	0.1	0.0	0.2	0.1	0.1
mg	0.5	0.5	0.5	0.6	0.6	0.5	0.5
Q	29.6	32.9	37.5	28.6	36.3	28.1	27.0
L	36.4	41.5	36.2	31.7	40.7	35.0	36.6
M	34.1	25.6	26.3	39.7	23.0	37.0	36.5
Cr	170	137	137	170	103	340	205
Ni	10	127	136	100	116	—	—
Ti	9410	7490	6350	8150	5750	8450	8210
Zr	175	190	200	115	178	n.d.	190
Y	15	—	20	40	—	n.d.	<10
Nb	20	15	10	<10	—	n.d.	20
Rb	4.2	11.6	11.8	1.9	28.2	5.8	5.6
Sr	232	566	155	239	424	235	267
Ba	—	150	—	—	220	n.d.	320

TABLE 4 - Chemical compositions and NIGGLI-values of the banded-amphibolites

Sample	1655* A	1655 B	1655* C	1656 A	1656 B	1656* C	1669* A	1669 B	1669* C	1669* D
SiO_2	65.2	51.3	63.3	52.1	50.5	70.9	67.4	52.0	65.6	67.3
Al_2O_3	15.5	14.9	15.9	18.3	15.1	15.0	16.0	15.0	16.7	16.1
Fe_2O_3	2.5	5.1	2.7	2.7	3.8	0.6	1.4	4.1	1.6	1.4
FeO	1.7	5.4	2.0	4.5	6.7	0.9	1.6	6.2	1.7	1.9
MnO	0.1	0.2	0.1	0.1	0.2	0.0	0.1	0.2	0.1	0.1
MgO	1.1	7.0	1.3	6.5	7.9	0.5	1.2	5.7	1.3	1.4
CaO	4.6	9.4	4.7	6.4	8.8	3.5	3.4	8.2	4.3	3.5
Na_2O	4.3	1.6	4.5	5.5	3.2	5.9	6.5	4.1	6.4	6.4
K_2O	1.0	0.6	1.0	0.3	0.3	0.1	0.2	0.2	0.1	0.1
TiO_2	0.7	0.4	0.7	0.8	1.8	0.2	0.2	1.4	0.2	0.3
P_2O_5	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1
H_2O	1.0	2.6	1.1	2.0	1.6	0.4	0.9	1.7	0.8	0.7
CO_2	0.1	0.1	0.1	0.1	0.2	<0.1	n.d.	n.d.	n.d.	n.d.
Total	97.0	99.8	97.6	99.5	100.3	98.2	99.0	99.0	98.9	99.3
si	274.2	129.1	251.8	134.8	120.2	349.0	284.7	132.5	258.7	276.7
al	38.3	22.1	37.3	27.9	21.2	43.6	39.9	24.0	38.7	39.1
fm	20.7	47.8	22.7	40.1	48.6	9.7	17.6	43.4	18.4	19.8
c	20.9	25.2	20.2	17.8	22.4	18.6	15.5	22.4	18.3	15.3
alk	20.1	4.9	19.8	14.2	7.8	28.2	27.0	10.4	24.6	25.9
k	0.1	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
mg	0.3	0.6	0.3	0.6	0.6	0.4	0.4	0.5	0.4	0.4
Q	51.2	35.4	48.6	30.3	30.1	54.9	48.8	31.8	47.0	48.4
L	40.2	31.2	41.7	45.3	34.4	41.3	44.3	38.2	44.9	44.0
M	8.6	33.4	9.8	24.4	35.5	3.9	6.9	30.0	8.2	7.6
Cr	70	205	—	137	205	70	70	205	70	70
Ni	224	40	215	169	58	300	262	112	223	194
Ti	3900	8330	4260	4920	10550	1020	1140	8273	1320	1620
Zr	265	143	260	152	185	175	140	125	155	135
Y	35	15	10	10	10	—	—	—	—	—
Nb	20	10	20	—	18	25	15	10	20	20
Rb	30	14.8	31	5	4.8	1	11.2	2.4	1.5	2.4
Sr	335	234	326	563	255	688	387	315	431	322
Ba	380	—	150	20	—	70	340	—	80	—

* light layers

TABLE 4 - (continued)

Sample	1670* A	1670 B	1671* A	1671 B	1671* C	1671 D	1671* E	1671** F	1671* G	1671* H
SiO_2	66.4	52.1	79.1	53.8	71.4	52.2	71.1	50.0	58.3	62.9
Al_2O_3	18.1	18.9	11.9	17.3	12.4	17.4	15.2	20.0	19.0	18.7
Fe_2O_3	0.8	1.7	0.4	4.0	1.8	3.9	1.1	5.1	3.2	2.0
FeO	1.1	4.5	0.3	4.9	1.9	5.6	1.0	4.1	1.9	1.5
MnO	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.0
MgO	0.7	7.2	0.0	4.2	1.7	4.8	0.4	2.8	1.2	0.5
CaO	4.2	5.3	2.1	7.5	4.2	8.2	3.5	10.2	6.8	5.0
Na_2O	7.2	5.6	4.7	5.1	4.8	5.0	6.3	4.8	6.4	7.2
K_2O	0.3	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.1
TiO_2	0.2	0.9	0.1	0.8	0.2	0.9	0.2	1.0	0.4	0.3
P_2O_5	0.1	0.2	0.0	0.2	0.1	0.2	0.1	0.2	0.1	0.1
H_2O	0.5	2.9	0.2	1.7	0.6	1.2	0.4	1.3	0.7	0.5
CO_2	n.d.	n.d.	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total	99.6	99.6	99.0	99.9	99.4	99.8	99.4	99.9	98.3	98.9
si	268.1	136.2	549.6	146.2	324.3	134.4	336.9	128.4	191.0	233.9
al	43.0	29.1	48.6	27.7	33.2	26.4	42.5	30.2	36.6	40.9
fm	10.1	41.6	3.8	36.5	24.8	38.3	10.8	29.6	19.0	13.2
c	18.0	14.9	15.7	21.8	20.5	22.5	17.7	27.9	23.7	19.9
alk	29.0	14.4	31.9	14.0	21.5	12.8	29.1	12.3	20.7	26.0
k	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mg	0.4	0.7	0.0	0.5	0.5	0.5	0.3	0.4	0.3	0.2
Q	46.1	30.9	66.3	33.2	55.2	31.0	53.3	30.9	39.1	43.1
L	48.9	46.3	32.6	43.2	34.2	42.6	42.1	46.7	49.2	50.0
M	5.0	22.9	1.1	23.6	10.7	26.4	4.6	22.5	11.7	7.0
Cr	—	205	—	70	70	70	70	170	70	70
Ni	294	235	304	122	236	110	231	40	182	235
Ti	1200	5520	359	4620	1080	5220	1080	6175	2100	1680
Zr	180	188	162	150	160	135	160	129	180	180
Y	—	—	—	10	10	7	—	—	—	<10
Nb	20	—	30	15	20	18	20	—	—	10
Rb	8.8	3.4	3	1.4	0.6	1.7	0.4	1.6	0.8	0.5
Sr	840	617	348	395	353	358	393	764	680	559
Ba	140	—	180	—	—	—	50	—	—	60

* light layer ** epidote-layer

TABLE 4 - (continued)

Sample	1672* A	1672 B	1672* D	1672 E	1673* A	1673 B	1674* A	1674 B	1674* C	1674* D	1674* E
SiO_2	76.8	51.5	74.9	57.8	71.1	49.8	67.9	52.9	72.3	66.2	72.8
Al_2O_3	11.9	17.0	12.0	15.4	12.1	15.6	15.0	14.6	12.8	14.0	13.7
Fe_2O_3	1.8	5.5	1.9	4.3	1.1	2.1	1.2	3.5	0.6	2.0	1.0
FeO	0.9	6.9	1.0	5.6	3.3	9.0	2.3	7.2	1.2	3.4	1.4
MnO	0.0	0.2	0.0	0.1	0.1	0.2	0.1	0.2	0.0	0.1	0.0
MgO	0.0	4.5	0.0	3.8	2.3	7.1	1.8	6.4	0.7	2.5	1.2
CaO	1.0	5.7	1.2	3.3	2.7	9.3	3.7	7.9	2.3	4.7	2.8
Na_2O	3.3	4.6	5.6	4.1	3.0	2.6	5.1	2.7	5.0	4.0	4.9
K_2O	1.6	0.8	0.4	1.4	1.5	0.7	0.7	0.8	0.8	0.9	1.0
TiO_2	0.2	2.0	0.2	1.7	0.7	1.8	0.3	1.6	0.2	0.7	0.2
P_2O_5	0.0	0.2	0.0	0.3	0.1	0.2	0.1	0.2	0.1	0.1	0.1
H_2O	0.9	1.1	0.6	1.7	1.0	1.8	0.8	1.7	0.7	1.0	0.9
CO_2	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	n.d.	<0.1	n.d.
Total	98.5	100.3	97.9	99.6	99.1	100.3	99.1	99.8	96.7	99.7	100.0
si	534.8	135.6	458.9	185.0	339.5	118.7	285,6	138.0	403.6	257.4	362.1
al	48.6	26.4	43.3	29.1	34.1	21.9	37.0	22.4	42.2	32.0	40.2
fm	14.7	44.3	13.9	43.9	33.4	47.5	23.6	47.7	14.1	31.3	18.4
c	7.5	16.2	7.9	11.3	13.9	23.6	16.8	21.9	13.8	19.4	14.9
alk	29.2	13.0	35.0	15.7	18.7	7.0	22.6	8.0	29.8	17.3	26.6
k	0.2	0.1	0.1	0.2	0.3	0.2	0.1	0.2	0.1	0.1	0.1
mg	0.0	0.4	0.0	0.4	0.5	0.5	0.5	0.5	0.4	0.5	0.5
Q	66.5	30.9	59.9	39.8	57.9	30.6	51.0	34.8	58.3	50.1	56.5
L	27.6	42.4	36.5	37.4	30.7	34.5	40.1	33.5	37.5	36.2	37.8
M	5.9	26.7	3.6	22.8	11.4	34.9	9.0	31.7	4.2	13.7	5.7
Cr	—	170	70	137	70	137	68	240	—	68	70
Ni	265	34	219	50	227	34	209	78	233	154	217
Ti	1320	11750	1260	10070	4320	10790	1858	9830	1140	4320	1440
Zr	595	318	465	280	320	185	150	176	160	170	165
Y	65	50	45	35	25	35	10	25	10	10	10
Nb	25	15	25	20	15	20	15	10	20	15	25
Rb	37.5	26.4	59	13	73.5	20	24.9	19.4	26	32	32
Sr	98	128	91	148	231	131	285	177	225	276	287
Ba	530	—	120	70	180	—	280	—	270	280	600

* light layer

parated using a diamond saw. Each hornblendefels and amphibolite sample was coarsely crushed and then pulverised for 15 hours in an agate mill to obtain a grain size smaller than 250 mesh.

Major element analyses and trace element analyses of Cr, Ni, Zr, Y, Nb, Rb, Sr, Ba have been performed for 20 hornblendefelses, 10 garnet-amphibolites, 15 plagioclase-amphibolites and 31 dark and light layers of banded-amphibolites from the Berisal complex. All major and trace element analyses were determined by X-ray fluorescence double determinations, with the exception of Fe^{2+} which was determined by colorimetric method and Ba by atomic absorption spectrometry. The resulting analytical data, together with the calculated Niggli-values are compiled in tables 1 - 4. The precise sample locations are provided in an appendix.

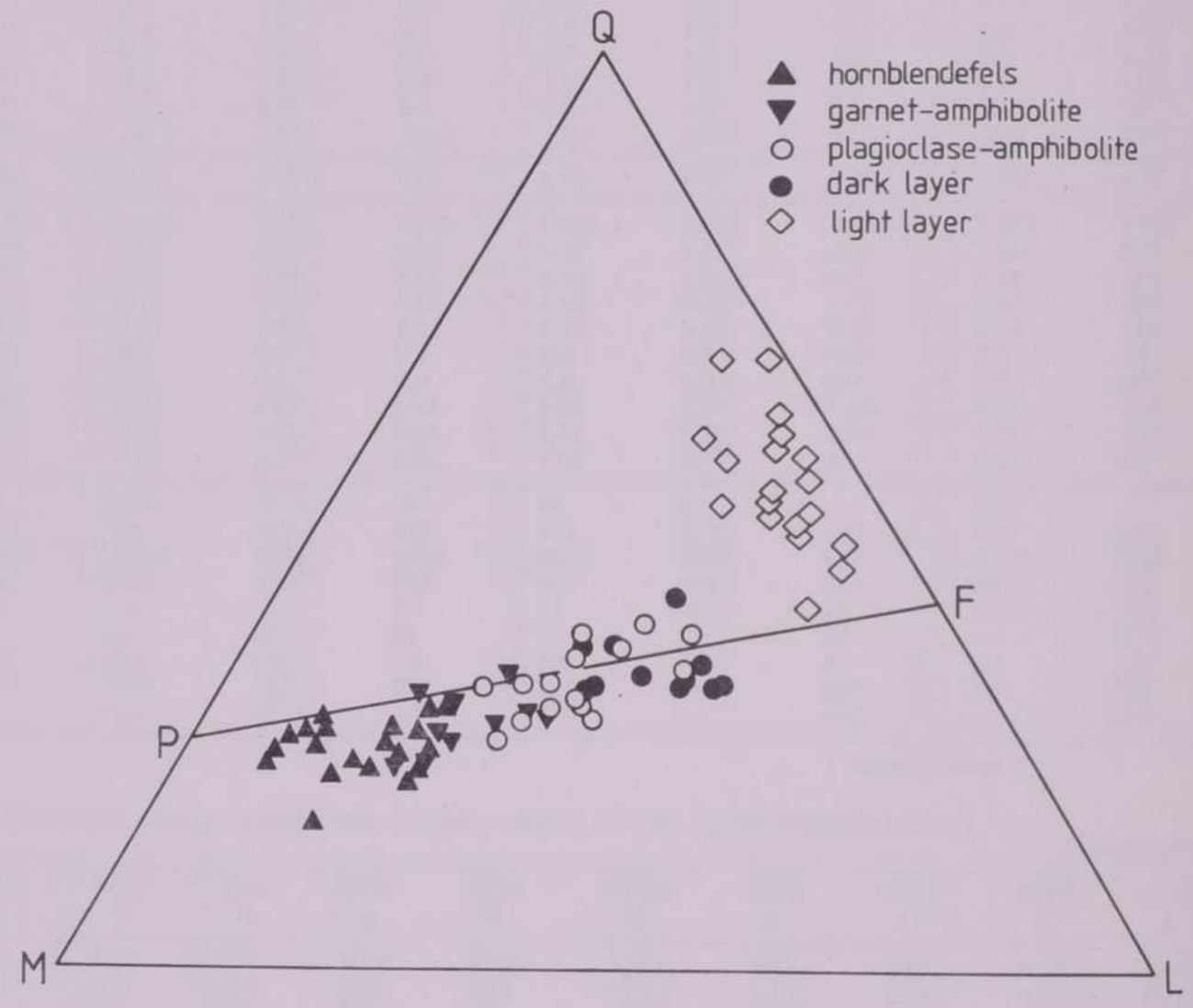


FIG. 4 - QLM-triangle showing the hornblendefelses, plagioclase-amphibolites, garnet-amphibolites and dark layers lying on and below the saturation line. The bimodal distribution of the light layers and the amphibolites is distinct.

4.2. Evaluation of Analytical Data to Elucidate Amphibolite Origin

In order to obtain information about the origin of the amphibolites, the 76 data points were plotted in various variation diagrams where possible magmatic variation trends can be differentiated from sedimentary trends. Characteristic element ratios of orthogenic and sedimentary material are compared with the data of the analysed samples. Finally discrimination analysis was used to distinguish between a magmatic and sedimentary origin.

4.2.1. *QLM and AFM Triangles*

A first survey of possible mineral contents is provided by a triangular plot of the QLM values calculated from different analyses (Fig. 4). The analytical data points of the plagioclase-amphibolites and of the dark layers of the banded-amphibolites lie on or below the saturation line PF, separating the quartz-rich from the quartz-free mineral assemblages. The data points of the hornblendefelses and the garnet-amphibolites lie below, and the points for the light layers above the saturation line. Thus most of the investigated amphibolites, together with the hornblendefelses describe a field where the mineral combination pyroxene, felspar/felspathoid, olivine exists. The field described by the light layers of the banded-amphibolites is typical of a quartz-felspar assemblage.

Na, K, Fe and Mg are important elements in characterizing igneous differentiation trends, and

are represented in the AFM-diagram (Fig. 5) by the parameters $A=Na_2O+K_2O$, $F=Fe_2O_3+FeO$ and $M=MgO$. The data appear to indicate a calc-alkaline differentiation trend. However, LEAKE (1975) has reported that a highly metamorphosed sedimentary series often resembles an igneous trend and that upon this evidence alone a definitive initial rock system cannot be concluded.

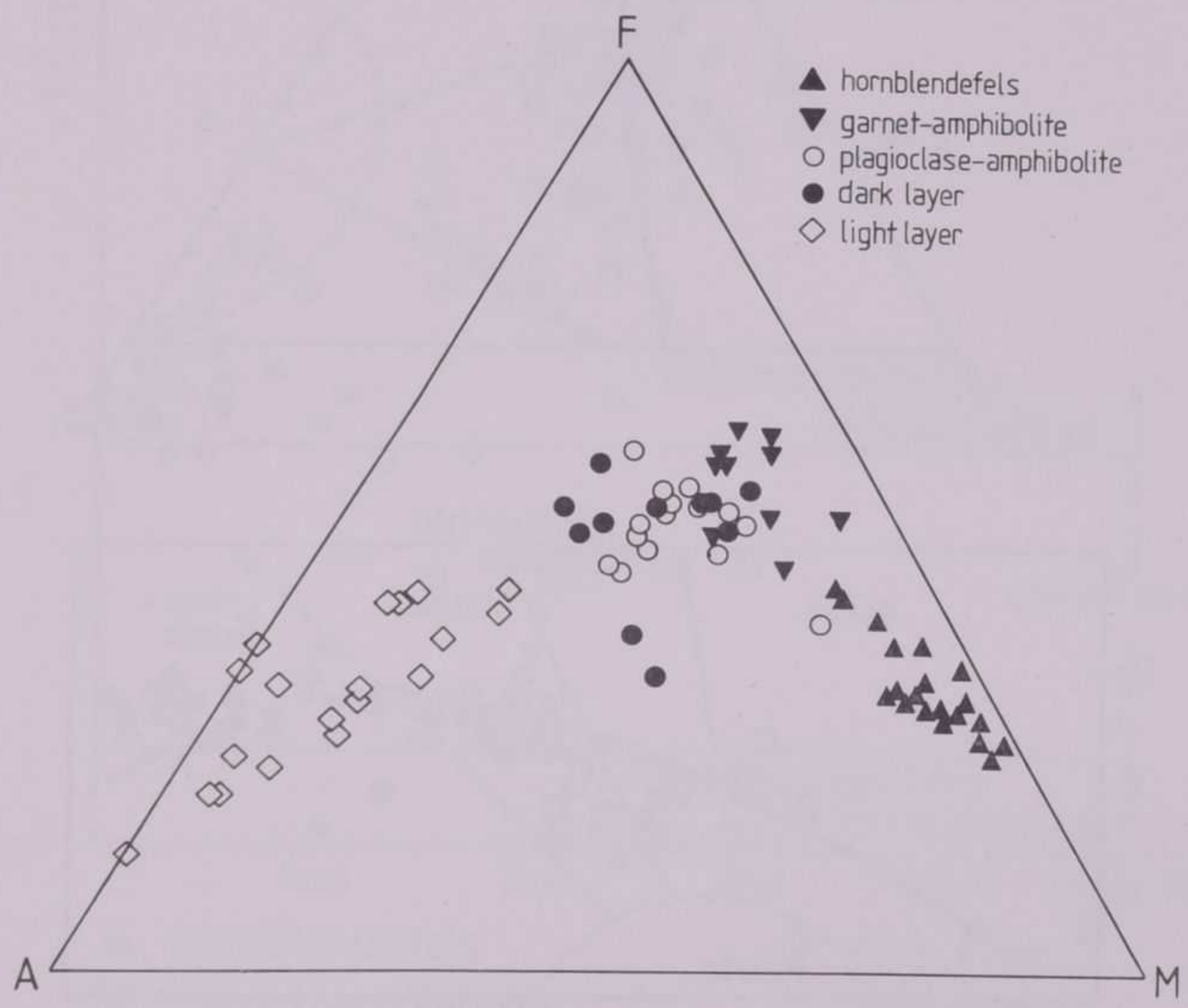


FIG. 5 - The data-points, plotted in the AFM-triangle, indicate a calc-alkaline trend.

4.2.2. *The c-mg Diagram and the c-mg-(al–alk) Triangle*

With the help of these two presentations (Figs. 6 and 7) LEAKE (1964) attempted to delineate the trends of igneous rocks mixed with sedimentary components e.g. tuffogenic amphibolites. In figure 6 Niggli c and mg are plotted with Niggli (al–alk) in a triangle, whilst in figure 7 the calculated Niggli-c values are plotted against Niggli-mg values. Two main sediment-magmatic mixture trends are possible: firstly mixtures of carbonate rocks (limestones and dolomites) with basic or acidic volcanic rocks; secondly, mixtures of clays and graywackes with basic or acidic volcanic rocks.

In both diagrams, hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and also the dark and light layers of the banded-amphibolites follow a more general igneous trend.

4.2.3. *Cr-Ni Diagram*

According to FROEHLICH (1960), amphibolites with Cr- contents of more than 150 ppm point to an orthogenic origin. In figure 8 the Cr- contents are plotted against the Ni- contents in a diagram particulary suitable for discerning igneous from sedimentary trends. The field between 20 and 150 ppm Cr is uncertain; Cr- contents lower than 20 ppm indicate a sedimentary origin. Cr- contents of the investigated samples are mainly greater than 100 ppm indicating an igneous origin.

The Cr/Ni-ratios of the plagioclase-amphibolites, garnet-amphibolites and hornblendefelses are without exception greater than 1 which, according to KUKLEY (1975), again indicates a magmatic origin for the amphibolites.

The Cr-Ni values of the plagioclase-amphibolites, garnet-amphibolites and hornblendefelses describe a clear positive correlation, which is strongly indicative of magmatic differentiation. The Cr-contents of the light and dark layers of the banded amphibolites are lower and show no positive correlation with Ni.

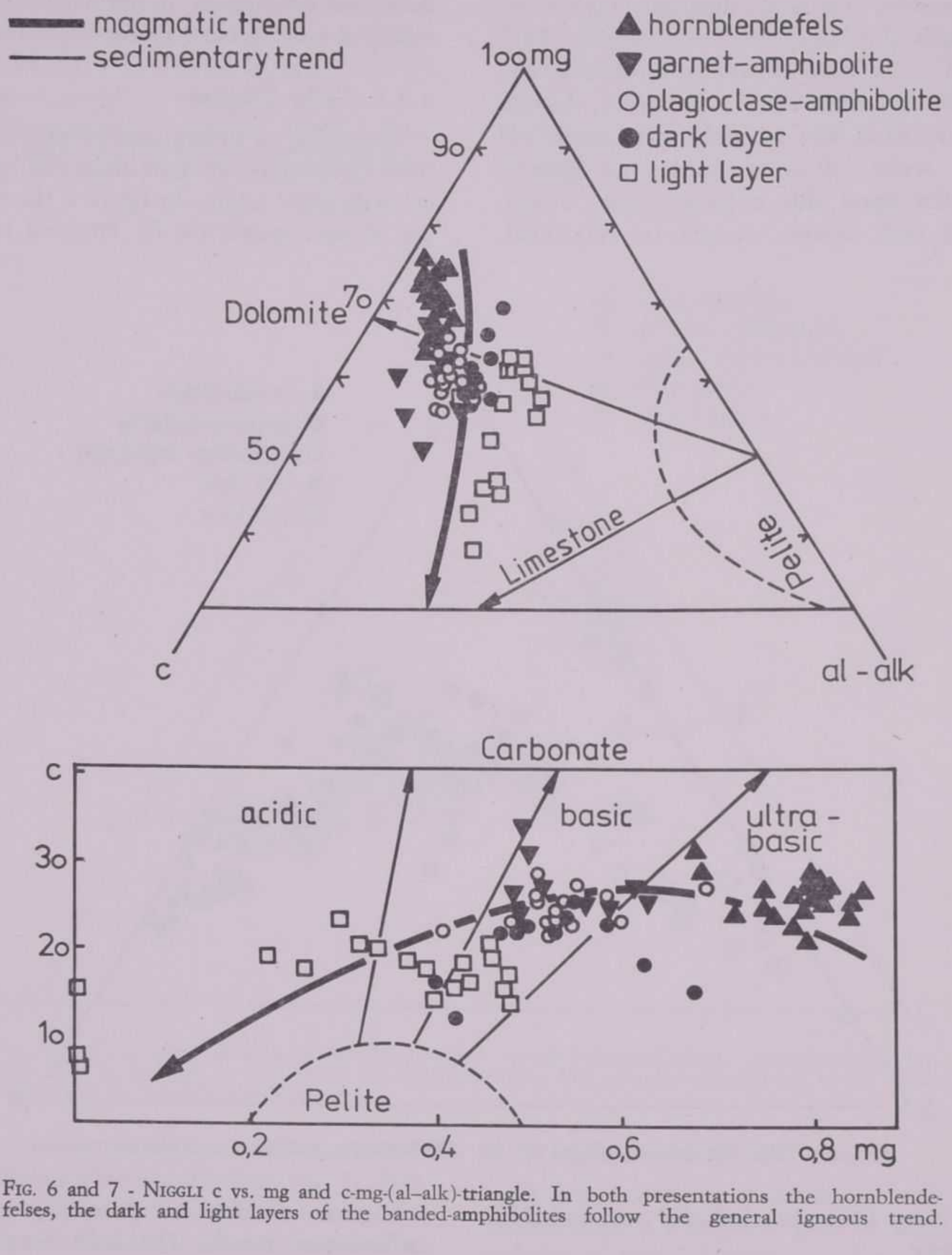


FIG. 6 and 7 - NIGGLI c vs. mg and c-mg-(al–alk)-triangle. In both presentations the hornblendefelses, the dark and light layers of the banded-amphibolites follow the general igneous trend.

4.2.4. *The K-M-N-Diagram (Fig. 9)*

MOINE and DE LA ROCHE (1966, 1968) proposed the following parameters:

$$K = \frac{K_2O}{MgO + K_2O + Na_2O} \quad \text{(weight-\%)}$$

$$M = \frac{MgO}{MgO + K_2O + Na_2O} \quad \text{(weight-\%)}$$

$$N = \frac{Na_2O}{MgO + K_2O + Na_2O} \quad \text{(weight-\%)}$$

Mg, Na and K are very important elements to characterize alumino-silicates and thus total rock chemistry. The main differentiation trend from basic to acid rock systems, and the fields of arkoses and graywackes are shown. The hornblendefelses are characterized by the highest Mg- and the lowest Na-K-contents, confirming their ultrabasic rock-character. The plagioclase-amphibolites, garnet-amphibolites and the dark layers show lower Mg-, but higher Na-contents than the hornblendefelses.

It is surprising that all the investigated samples possess very low K-contents causing a deviation from the general differentiation-trend.

The Mg-, Na- and K- contents of the light layers are typical of anorthositic rocks.

4.2.5. *The Al, Fe, Ti, K, Na - Distribution*

Because of the different behaviour of the elements Al, Fe, Ti, K and Na in sedimentary and volcanic formations MOINE and DE LA ROCHE (1968) proposed the parameters [(Al + Fe + Ti) /3–K] and [(Al + Fe + Ti)/3–Na] to discern between ortho- and paraamphibolites. These parameters are calculated in atom-% and plotted in the diagram of figure 10. Here, the amphibolites including the dark layers are in good agreement with the given basaltic field. The hornblendefelses show much lower Al- and Ti-contents and lie, according to their ultrabasic chemistry, out of the defined field. The light layers of the banded amphibolites are significantly distinguishable from the defined field of graywackes.

4.2.6. *The Al, Fe, Ti, Ca, Mg - Distribution*

Because of the much lower Mg- and Ca- contents in graywackes when compared with basaltic rocks MOINE and DE LA ROCHE (1968) proposed to distinguish further between ortho- and paraamphibolites using the following parameters: (Al + Fe + Ti) and (Ca + Mg). These parameters are calculated in atom-% and plotted in the diagram of figure 11. The diagram shows the behaviour of Al, Fe and Ti with increasing Ca and Mg. The light layers of the banded-amphibolites show the lowest Ca- and Mg- contents but also possess low amounts of Al, Fe and Ti. Ca and Mg are positively correlated to Al, Fe and Ti up to the field of the plagioclase-amphibolites. Here the trend direction changes. Rising values of Ca and Mg are accompanied by falling values of Al, Fe and Ti. The light layers lie in the field of the graywackes, while the plagioclase-amphibolites, garnet-amphibolites and the dark layers fall in the range of the defined basaltic field. The ultrabasic hornblendefelses lie outside of the basaltic field and show the highest Ca- and Mg- contents. The geochemical behaviour of the light layers together with the position of the other kinds of amphibo-

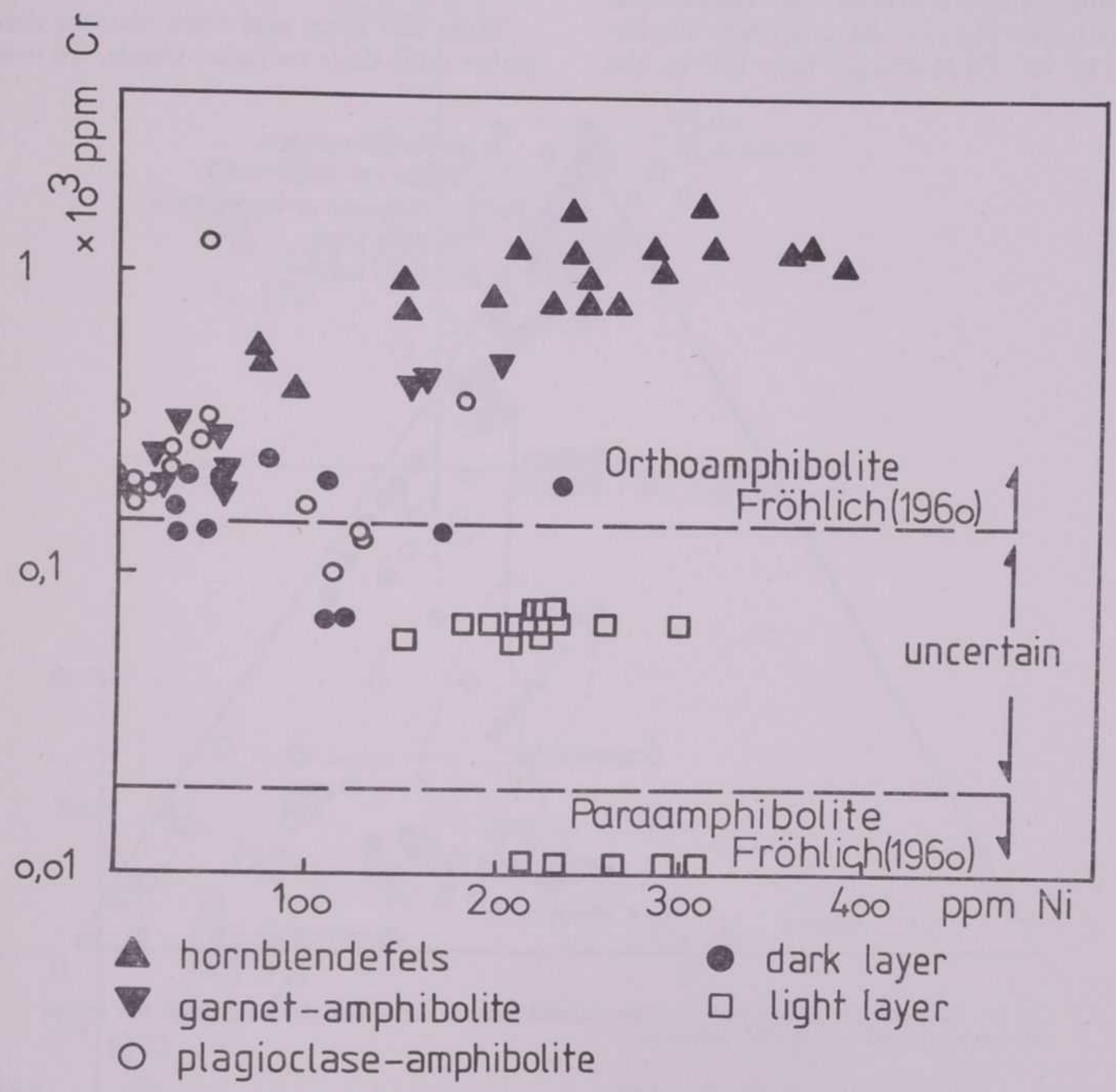


FIG. 8 - Cr vs. Ni. After FROEHLICH (1960), amphibolites with Cr-contents of more than 150 ppm are of orthogenic origin.

lites could be an expression of a magmatic differentiation.

4.2.7. *Conclusions*

In every variation diagram the difference in chemistry between the hornblendefelses and the other types of amphibolites is evident. The hornblendefelses have higher Mg-, Cr-, Ni- and lower Ti-, Zr-contents. In the QLM-triangle they fall in the field of hornblendites-pyroxenites. In the AFM-triangle the hornblendefelses agree, according to NOCKOLDS (1954), with the field of pyroxenites. The very low Ti-Zr-Ba- and higher Cr- contents are typical of an ultrabasic origin; similary the high Cr- contents of the garnet- and plagioclase-amphibolites are far from normal sedimentary rocks. The Cr/Ni- and the Sr/Ba- ratios of the garnet-amphibolites, plagioclase-amphibolites and the hornblendefelses are greater than 1, indicating, according to KUKLEY (1975) and SIDORENKO (1972), an igneous origin.

The trace-elements Cr and Ni show in combination with Niggli-mg a clearly positive correlation, a further indication of the igneous origin. Mixtures of clay and dolomite show a negative correlation (KALSBEEK and LEAKE, 1969). Neither the hornblendefelses nor the plagioclase-and garnet-amphibolites exhibit trends of sedimentary mixtures in the diagrams of LEAKE (1964). In the diagrams after MOINE and DE LA ROCHE (1966, 1968) the hornblendefelses lie in the range of ultrabasic, the garnet- and plagioclase-amphibolites in the range of basic rocks.

From the main and trace element contents together with their variation-trends, the overall indication is of a magmatic origin for the hornblendefelses, garnet-and plagioclase-amphibolites.

It is quite difficult to make a statement about the origin of the banded-amphibolites. In the c-mg-(al–alk)-diagram the light and the dark layers show no agreement with the defined trends of sedimentary mixtures, indicating rather a magmatic trend of differentiation or partial melting. The Cr/Ni- and the Sr/Ba- ratios of the dark layers, being greater than 1 speak for their igneous origin. Their Cr-contents partly support an orthogenic origin, but their relationship is uncertain. In the diagrams of MOINE and DE LA ROCHE the dark layers show a relatively good agreement with the defined basaltic fields; the light layers fall, with one exception, outside of the fields of arkoses and graywackes but also fail to agree with the fields of orthogenic rocks.

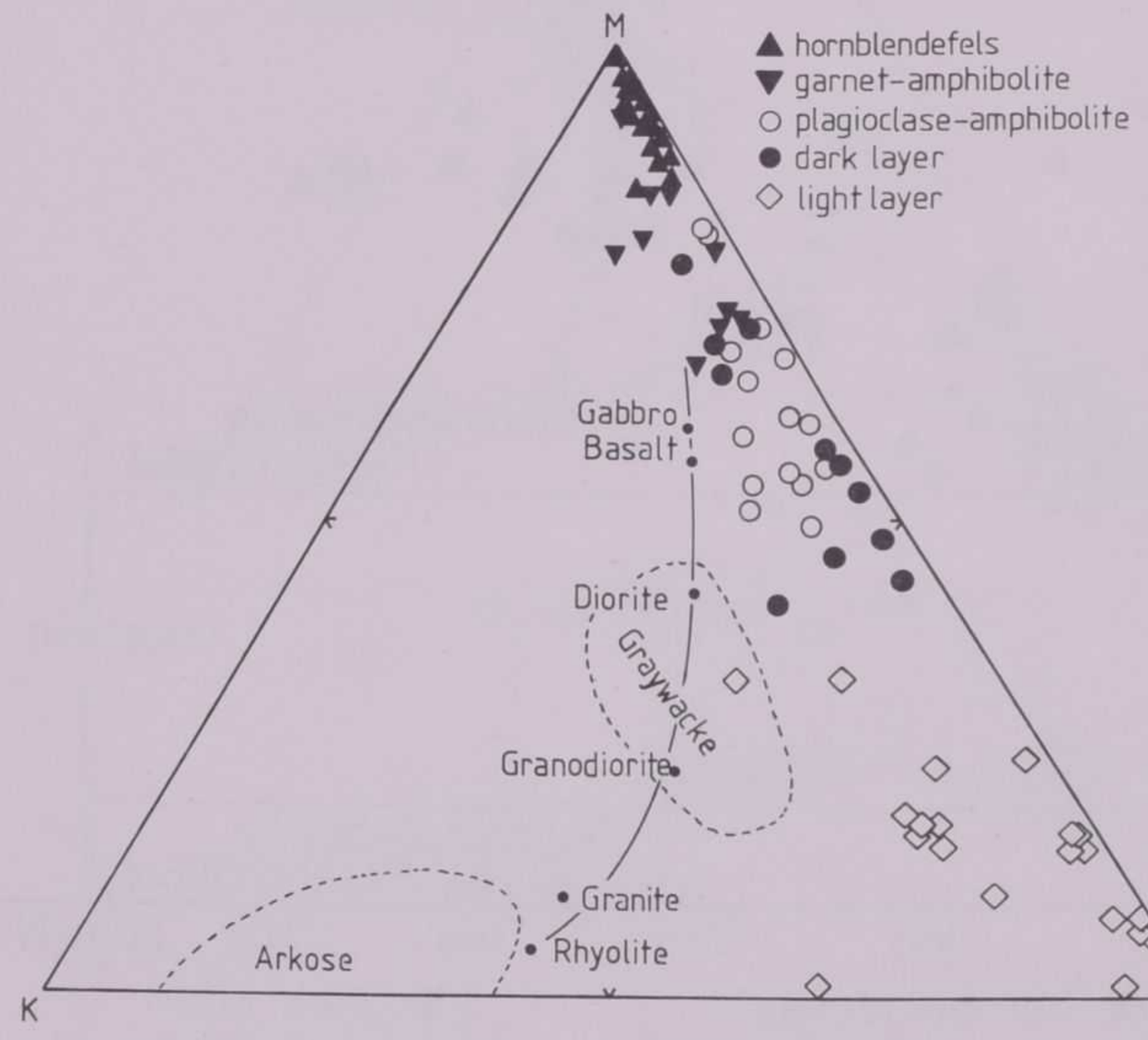
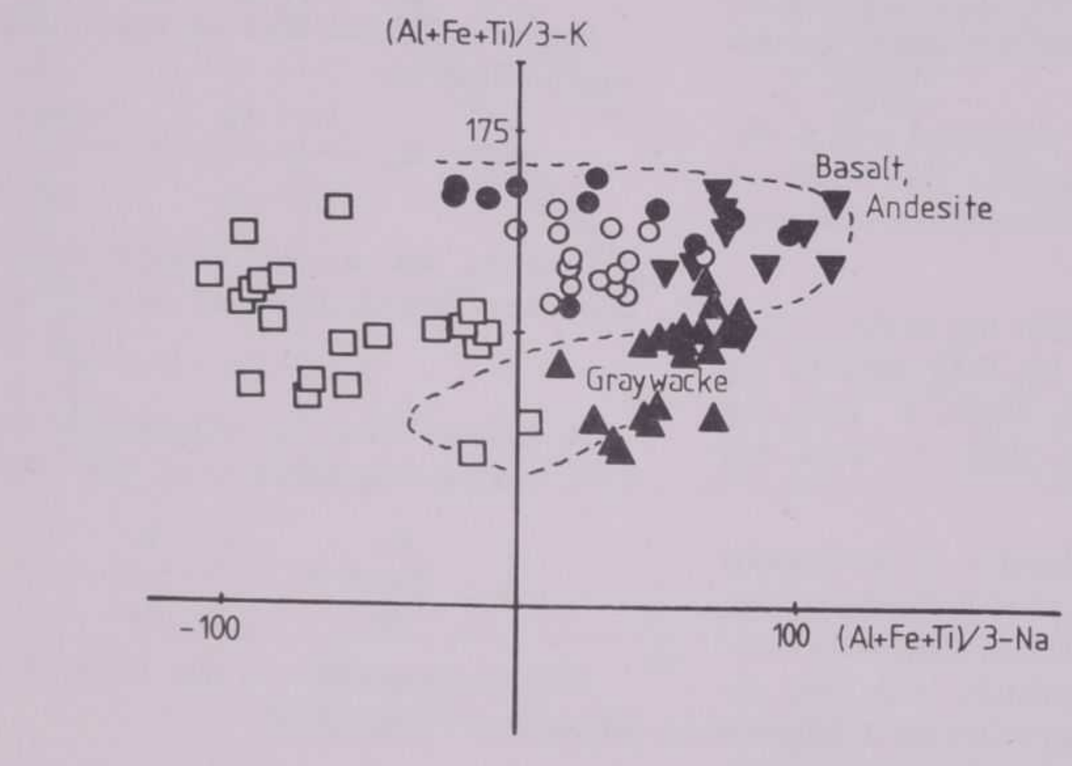


FIG. 9 - The very low K-contents of all investigated samples cause the deviation from the general differentiation-trend in the KMN-triangle.

The origin of the banded-amphibolites using both main- and trace-elements is not so clearly defined in comparison to the other amphibolites. However using their main- and trace- elements in combination with the variation diagrams of all is interpreted as implying a direct genetic relationship between the banded-amphibolites and the other types of amphibolites the indication is that the banded-amphibolites could be of orthogenic origin.



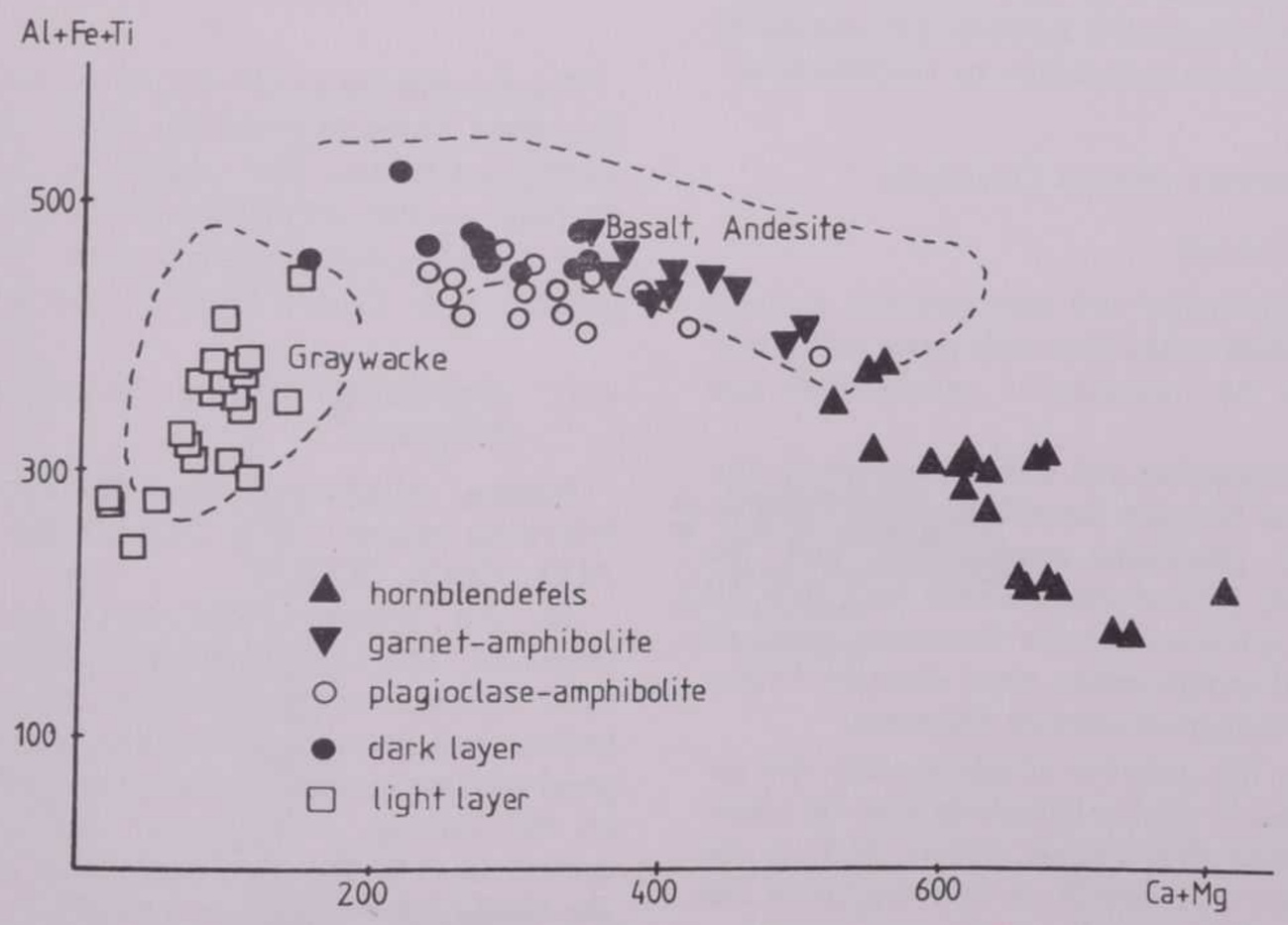


FIG. 10 and 11 - Presentations according to MOINE and DE LA ROCHE (1968) using the elements Al, Fe, Ti, K, Na, Ca and Mg to distinguish ortho- and para-amphibolites.

amphibolites and the hornblendefelses one statement can be made. If the hornblendefelses, plagioclase- and garnet-amphibolites reflect in all the variation diagrams the behaviour of differentiation or partial melting, the banded-amphibolites generally agree with these different trends; if this

4.3. APPLICATION OF DISCRIMINANT ANALYSIS TO THE GEOCHEMICAL DATA

The discriminant function is a powerful tool in multivariate statistical analysis, complementing qualitative graphical methods in distinguishing

between two different groups, such as ortho-amphibolites and para-amphibolites. If a number of geochemical variables are measured on samples of ortho-and para-amphibolites, the best linear combinations of these variables can be calculated to discriminate between these two groups. The calculated discriminant function (D.F.) permits the allocation of a sample of unknown origin to one of the original groups.

SHAW and KUDO (1965) calculated group discriminant functions to determine the origin of amphibolites. For the main elements the following equation was written:

$$\text{D.F.} = 7.07 \log TiO_2 + 1.91 \log Al_2O_3 - 3.29 \log Fe_2O_3 + 8.48 \log FeO + 2.97 \log MnO + 4.81 \log MgO + 7.80 \log CaO + 3.92 \log P_2O_5 + 0.15 \log CO_2 - 15.08$$

Positive D.F.-values are indicators of an igneous origin, negative D.F.-values of sedimentary rocks.

The 25 calculated D.F.-values of plagioclase- and garnet-amphibolites were positive, with two exceptions. The method indicates that an orthogenic origin for both types of amphibolites is very probable. The application of this method to hornblendefelses is not possible because their chemistry is quite different in comparison to amphibolites.

4.4. 2-COMPONENT MIXING DIAGRAMS

4.4.1. *The Concept*

Variations in major and trace element analyses may reveal whether the four rock types being examined could be mixtures of geochemical end members.

On the assumption that a direct genetical connection exists between hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and the whole pile of layered amphibolites and that all were closed systems since the formation time, all the measured sample-points must describe hyperbolas in 2 -component-mixture diagrams.

To answer the question of relationship the general equation of mixing hyperbola may be considered (modified after FAURE, 1977). If F is the mixing parameter, A and B are the weights of the components to be mixed

$$\text{Then} \qquad F = \frac{A}{A + B}$$

The concentration of an element x in the mixture, which is present in the components A and B, is therefore:

$$x_m = x_A \cdot F_A + x_B \cdot F_B$$

Because of the connection between F_A and F_B namely $F_B = 1 - F_A$ it can be written:

$$x_m = F_A (x_A - x_B) + x_B$$

For two elements (x and y) it can be written:

$$x_m = F_A (x_A - x_B) + x_B$$
$$y_m = F_A (y_A - y_B) + y_B$$

Hence it follows that the equation for a mixing straight line is:

$$y_m = x_m \frac{y_A - y_B}{x_A - x_B} + \frac{x_A y_B - x_B y_A}{x_A - x_B}$$

Only y_m and x_m are variable members of this equation. Therefore it can be simplified to:

$$y_m = x_m \cdot b + a$$

It follows that the equation of the 2-component mixing hyperbola is of the kind:

$$\frac{y_m}{x_m} = z = \frac{a}{x_m} + b$$

This corresponds to the form of the general equation of hyperbola:

$$y = \frac{A}{x} + B$$

The correlation-coefficient of the mixing straight line gives some information about the fit of the mixing conditions. The calculations have been carried out on the IBM-system/370-158 of the Bernese data-processing corporation (BEDAG). The program was written by SCHAFROTH (1978).

4.4.2. *Application of the 2-Component Mixing Diagrams*

Mixing calculations have been made for the following oxides: SiO_2, MgO, CaO, Na_2O, K_2O, Al_2O_3, Cr_2O_3, NiO.

In the systems SiO_2-MgO and CaO-MgO (Figs. 12, 13) banded-amphibolites (including the light layers), hornblendefelses, plagioclase-amphibolites and garnet-amphibolites together describe good mixing hyperbolas: the correlation-coefficient of the mixing straight line for the SiO_2-MgO system is 0.9976. The correlation coefficient for the CaO-MgO system is 0.9405.

In the Na_2O-K_2O mixing-system (Fig. 13) the dark and light layers of the banded-amphibolites are moderately correlated with the plagioclase-amphibolites and partly with the garnet-amphibolites. The correlation-coefficient of the calculated mixing straight line is 0.9655. The hornblendefelses and partly the garnet-amphibolites do not fulfil the conditions of the mixing hyperbola, showing very low Na-K contents.

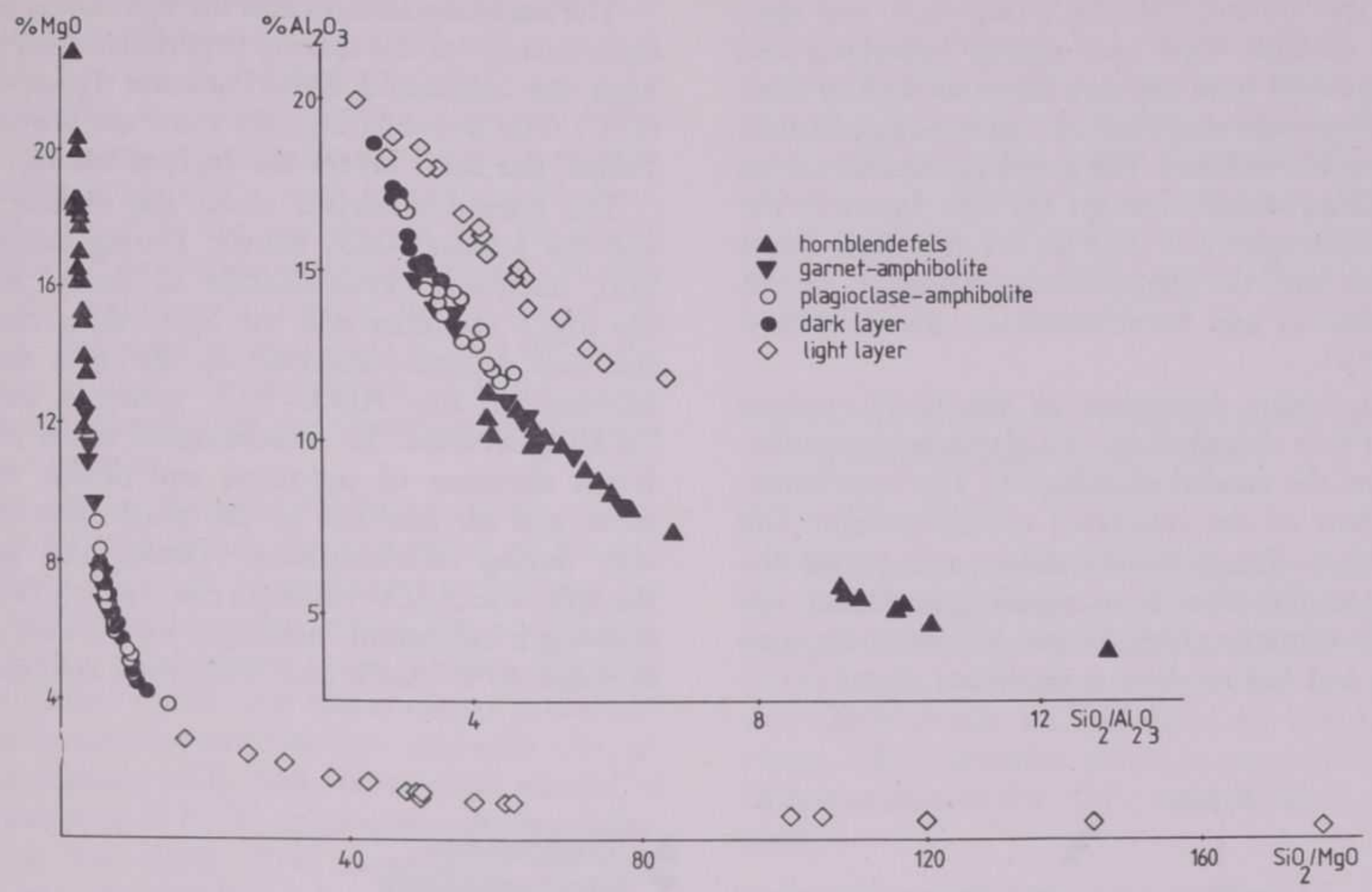


FIG. 12 - The MgO-SiO_2 and the Al_2O_3-SiO_2-mixing diagrams.

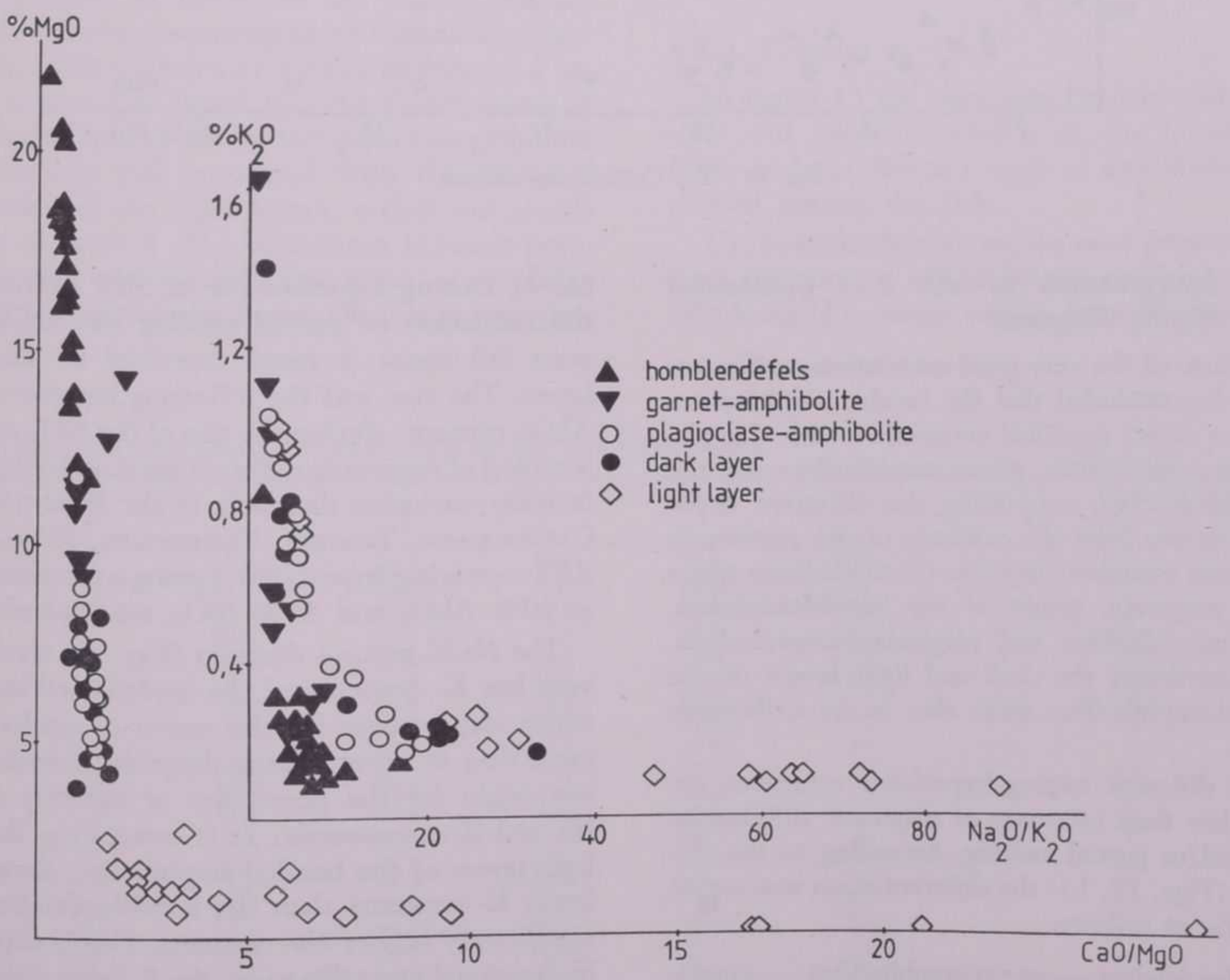


FIG. 13 - The MgO-CaO and the Na_2O-K_2O-mixing diagrams.

In the system Al_2O_3-SiO_2 (Fig. 12) the light layers describe their own mixing hyperbola and are separated from the dark layers as well as from the plagioclase-amphibolites, garnet-amphibolites and hornblendefelses. The correlation-coefficient of the mixing straight line for the light layers in the SiO_2-Al_2O_3 system is 0.9852; for the dark layers together with the plagioclase-amphibolites, garnet-amphibolites and hornblendefelses the coefficient is 0.9947.

The mixing hyperbola in the Cr-Ni system (Fig. 14) is described by the plagioclase-amphibolites and the banded-amphibolites. The correlation-coefficient of the calculated mixing straight line is 0.9665. The hornblendefelses and partly the garnet-amphibolites have significantly higher Cr- and Ni- contents. Their Cr and Ni values are scattered, and fail to show a significant trend.

The hornblendefelses and the light layers are the end-members of the mixing hyperbolas. This agrees with the calculated Differentiation Index values (D.I.). The hornblendefelses show the lowest D.I. values, the light layers the highest values.

The hornblendefelses show the highest MgO and the lowest Al_2O_3 values. During differentiation, fractional crystallization or partial melting the MgO- contents and the SiO_2/Al_2O_3- ratios in the melt decrease successively during a constant increase of the Al_2O_3 - SiO_2 contents and the CaO/MgO-ratios. In mineralogical terms this infers a decrease of pyroxene and olivine components and an increase of the plagioclase component during differentiation. During this process the SiO_2- and Al_2O_3- contents rise strongly (Fig. 12) reaching a maximum, described by the dark layers at about 20% Al_2O_3 and 53% SiO_2 (see also Table 4). During a further rise of SiO_2 with further differentiation or partial melting the Al_2O_3- contents fall again, a trend described by the light layers. The rise and the following decrease of the Al_2O_3- contents during the rise of the SiO_2- content is typical of magmatic differentiation and observable in many variation diagrams in the literature (e.g. Carmichael, Turner, Verhoogen, 1974). Thus the two mixing hyperbolas, having a common point at 20% Al_2O_3 and 53% SiO_2, are explicable.

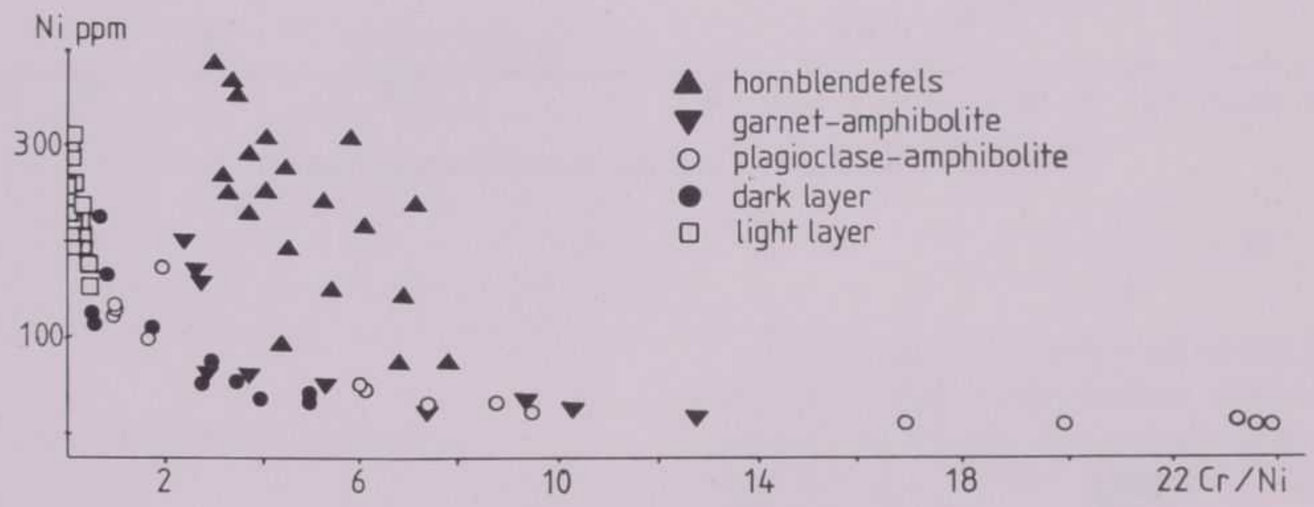


Fig. 14 - The Cr-Ni-mixing diagram.

4.4.3. *Interpretation of the 2 - Component Mixing Diagrams*

Because of the very good correlation-coefficients it can be concluded that the banded-amphibolites are in a direct genetical connection with the plagioclase-amphibolites, garnet-amphibolites and the hornblendefelses, supporting the tentative hypothesis drawn from the evidence of the previously presented variation diagrams. Good evidence exists for a magmatic origin of the hornblendefelses, garnet-amphibolites and plagioclase-amphibolites, and accordingly the dark and light layers of the banded-amphibolites must also be of orthogenic origin.

The different mixing hyperbolas represent nothing less than processes of magmatic differentiation and/or partial melting. According to the diagrams (Figs. 12, 13) the differentiation succession must be as follows:

hornblendefelses — garnet-amphibolites — plagioclase-amphibolites — banded-amphibolites.

The Na-K mixing diagram (Fig. 13) shows the very low K- contents of the investigated samples, which may account for the scatter of results much more than in other mixing diagrams. Another reason might be the possibility of mobility of the Na and K compounds. It is interesting that the light layers of the banded-amphibolites show even lower K- contents than the hornblendefelses, but significantly higher Na- contents. This is explained by fractional crystallization, the K being controlled by the mafic minerals, the Na by the plagioclase.

The plagioclase-amphibolites and garnet-amphibolites are only moderately correlated with the dark and light layers of the banded-amphibolites and the differentiation succession is not completely fulfilled. Light layers are mixed on the hyperbola with plagioclase-amphibolites and garnet-amphibolites, possibly caused by the mobility of the Na and K compounds. The samples showing higher K contents have also significantly higher Rb- contents. In some K- rich samples very little K and Rb contamination or migration can not be excluded, a supposition emphasized by the observation of biotite in these samples.

According to the general differentiation succession, postulated above, the behaviour of Na and K in figure 13 might be explained as follows: the hornblendefelses have the lowest Na- and K- contents, typical of ultrabasic rocks. During magmatic differentiation the K- and Na- contents in the garnet-and plagioclase-amphibolites normally rise, giving an increase of K- and Na- content parallel to the increasing D.I.. K enrichment during differentiation was slight. The material of the light layers must be developed from the lowest differentiated plagioclase-amphibolites, that means from the amphibolites with the lowest K- contents.

The behaviour of Cr and Ni in all the investigated samples, as shown in the mixing diagram (Fig. 14), is also an expression of fractional crystallization, differentiation or partial melting of a basaltic magma (see figure 8). The Cr-Ni values of the plagioclase-and partly the garnet-amphibolites are relatively well correlated with the values of the dark and the light layers, a fact not clearly visible in figure 8. The connection between hornblendefelses and the different types of amphibolites is not apparent in figure 14, but is more readily seen in figure 8. Thus with the help of immobile trace elements in a combination of figures 8 and 13 it is possible to say that a direct genetic relationship must exist between the hornblendefelses and the other types of amphibolites. The behaviour of Cr and Ni in both these diagrams is an especially good indicator of the igneous origin of the dark and light layers of the banded-amphibolites.

4.5. Norm-Minerals, Normative An-contents and Differentiation-Index

4.5.1. *Calculations*

The Norm-minerals are calculated according to the Barth-Niggli-Kation-Norm, a molecular-norm proposed by Niggli (1936) and modified by Barth (1952) such that standard minerals, present in the CIPW-Norm, are calculated by the Kation-Norm. The normative anorthite-content and the Differentiation-Index (D.I.) are calculated as follows:

$$\text{normative anorthite content} = An/(Ab + An)$$

$$D.I. = Q + Or + Ab + Ne + Lc + Kp$$

The main norm-minerals, normative anorthite contents and D.I. values are compiled in Table 5.

4.5.2. *Results*

In figure 15 the normative hypersthene-, diopside- and anorthite-contents of the hornblendefelses and the different types of amphibolites are plotted against the D.I..

The hornblendefelses are the most primitive and least fractionated of the investigated rocks, their calculated D.I. values varying between 5 and 20.

Table 5A - Barth-Niggli-Kation-Norms of the hornblendefelses

Sample	Or	Ab	An	Di	Hy	01	Q	Diff' index	Norm. An-content
76	0.8	0.0	13.1	38.1	35.1	10.8	—	0.8	100
77	1.4	13.3	16.8	25.6	28.8	10.9	—	15	56
333	1.4	15.5	17.9	31.1	21.6	9.8	—	17	54
334	0.8	10.4	22.1	33.8	12.0	18.9	—	11	68
335	0.7	6.9	7.0	43.4	33.4	6.4	—	8	50
455	1.4	8.1	16.3	36.6	14.6	19.2	—	10	67
457	1.9	9.0	16.8	33.9	18.8	15.8	—	11	65
1657	0.7	5.6	12.0	41.7	37.2	0.5	—	6	68
1675	1.0	6.5	8.8	44.7	33.6	3.4	—	7	58
1818	1.2	13.0	21.0	30.9	29.4	1.4	—	14	62
1820	1.4	12.9	23.1	22.6	34.3	—	1.2	15	64
1821	0.7	12.0	7.9	41.8	26.8	8.5	—	13	40
1822	0.6	7.8	11.3	39.6	38.3	—	0.2	9	59
1823	0.8	20.7	9.1	35.1	10.9	19.6	—	21	31
1824	0.5	6.1	12.4	42.9	34.2	—	1.6	8	67
1825	1.3	12.0	24.7	34.5	5.0	20.2	—	13	67
1826	1.0	10.2	18.5	33.1	30.2	4.1	—	11	64
1827	1.0	13.1	21.3	32.0	22.3	7.9	—	14	62
1819A	5.2	4.6	20.5	41.7	—	16.3	—	15	82
1819B	1.9	12.5	20.4	37.5	—	18.1	—	17	62

TABLE 5B - BARTH-NIGGLI-KATION-NORMS of the garnet-amphibolites

Sample	Or	Ab	An	Di	Hy	01	Q	Diff' index	Norm. An-content
60	1.4	10.6	31.6	15.2	27.3	—	7.2	19	75
199	1.8	19.4	28.1	34.0	8.9	3.4	—	21	59
278	1.9	24.7	28.3	16.1	15.3	8.3	—	27	53
345	3.3	22.2	18.5	36.8	12.0	0.6	—	25	45
347	1.7	5.2	23.1	27.8	29.4	—	6.9	14	82
348	6.7	26.3	20.6	22.7	11.3	6.9	—	33	44
349	6.0	16.0	18.1	27.1	16.9	9.8	—	22	53
350	9.5	15.4	14.5	33.1	—	20.9	—	25	49
4139	2.9	12.1	22.4	21.0	31.4	—	4.3	19	65
4311	1.3	20.9	11.1	39.4	9.6	9.0	—	22	35

TABLE 5C - BARTH-NIGGLI-KATION-NORMS of the plagioclase-amphibolites

Sample	Or	Ab	An	Di	Hy	01	Q	Diff' index	Norm. An-content
36	1.2	19.1	22.9	25.1	23.7	—	3.3	24	55
38	1.2	34.1	15.0	24.3	15.8	2.6	—	35	31
207	3.3	28.7	18.8	23.4	16.4	—	3.2	35	40
283	5.8	29.8	18.3	19.1	14.9	—	5.1	41	38
332	4.0	34.7	19.8	19.4	11.0	—	6.3	45	36
419	1.1	24.3	21.8	30.6	1.7	15.8	—	25	47
6045	5.6	29.0	16.8	16.8	13.7	—	11.4	46	37
322	4.2	28.2	20.0	17.9	21.2	—	4.8	37	41
1596	1.6	38.9	20.1	14.6	17.5	—	0.1	41	34
1654	4.7	39.0	25.6	11.6	12.0	—	1.4	45	40
1676	3.6	35.1	21.6	11.5	13.6	—	9.3	48	38
1816	1.0	27.7	24.1	24.3	15.3	—	0.3	29	47
1817	7.4	32.9	27.5	6.6	15.9	—	5.2	45	46
1849	2.4	33.0	23.0	26.5	1.7	7.3	—	35	41
1850	2.2	38.0	17.0	26.1	0.0	8.0	—	42	31

TABLE 5D - BARTH-NIGGLI-KATION-NORMS of the dark layers

Sample	Or	Ab	An	Di	Hy	01	Q	Diff' index	Norm. An-content
1655B	3.6	15.4	33.1	11.4	17.9	—	10.5	30	68
1656A	1.5	49.6	24.4	5.1	2.0	13.2	—	51	33
1656B	1.7	29.2	26.5	13.1	21.3	—	1.2	32	48
1669B	1.3	37.3	25.1	12.1	15.3	—	2.2	41	40
1670B	1.0	50.0	24.9	—	6.4	13.7	—	51	33
1671B	1.4	46.7	23.8	10.1	10.6	—	1.7	50	34
1671D	1.4	45.0	24.7	11.9	8.0	3.3	—	46	35
1672B	4.9	41.8	24.0	3.0	15.9	—	1.5	48	37
1672E	8.5	38.4	15.3	—	14.5	—	13.8	61	28
1673B	4.2	23.8	29.5	12.8	24.4	—	—	28	55
1674B	4.7	24.7	26.4	9.9	20.5	—	7.3	37	52

TABLE 5E - BARTH-NIGGLI-KATION-NORMS of the light layers

Sample	Or	Ab	An	Di	Hy	01	Q	Diff' index	Norm. An-content
1655A	5.9	40.3	20.9	1.5	2.4	—	25.0	71	34
1655C	6.3	41.9	21.3	1.6	3.4	—	21.3	69	34
1656C	0.5	53.6	14.7	1.9	1.3	—	27.0	81	22
1669A	1.3	58.4	14.3	1.7	3.7	—	18.7	78	20
1669C	0.6	57.5	16.7	3.3	3.3	—	16.3	74	23
1669D	0.7	57.9	14.8	1.3	4.9	—	18.3	77	20
1670A	1.6	64.1	15.8	3.1	1.0	—	12.9	79	20
1671A	0.6	43.1	10.5	—	—	—	44.7	88	20
1671C	0.5	44.4	12.2	7.0	2.7	—	30.9	76	21
1671E	0.4	56.7	13.2	3.0	0.2	—	25.0	82	19
1671G	0.6	58.5	22.9	7.3	—	—	6.2	65	28
1671H	0.6	64.2	18.5	3.9	—	—	9.8	75	22
1672A	9.9	31.1	5.0	—	—	—	48.3	89	14
1672D	2.6	52.3	6.0	—	—	—	36.6	91	10
1673A	9.5	28.2	13.4	—	10.0	—	35.6	73	32
1674A	4.4	46.2	16.2	1.4	6.8	—	23.0	74	26
1674C	4.7	47.0	10.8	0.6	2.9	—	32.9	85	19
1674D	5.6	36.6	18.0	3.9	8.3	—	24.2	66	33
1674E	5.7	44.5	12.8	0.6	4.3	—	30.6	81	22

The normative hypersthene content scatters between 5 and 35%, the normative diopside content between 20 and 45%, and the normative anorthite content amounts to about 60%.

between 0 and 30%, the normative diopside content between 15 and 40%. The normative anorthite contents are the same as observed in the hornblendefelses.

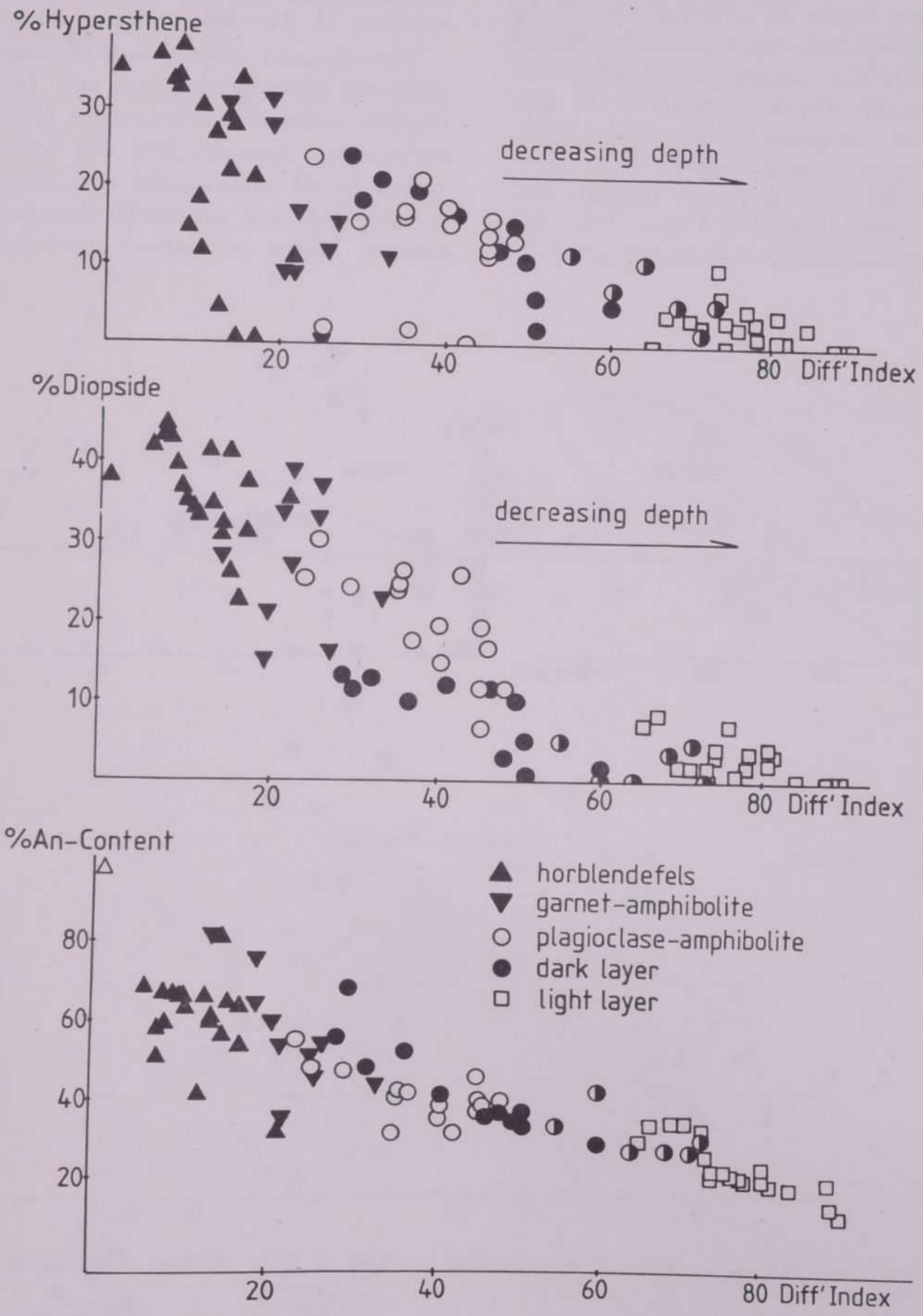


FIG. 15 - Differentiation Index vs. norm. An-content, norm. diopside-content and norm. hypersthene-content. Half filled circles represent calculated mixtures of dark and light layers.

The garnet-amphibolites are characterized, as are the hornblendefelses, by a low degree of fractional crystallization and are the next primitive. The calculated D.I. values vary between 15 and 35. The normative hypersthene contents scatter

The next differentiates are represented by the plagioclase-amphibolites, with D.I. values much higher than those of the hornblendefelses and garnet-amphibolites, scattering in a wider range between 20 and 50. The normative hypersthene con-

tents scatter between 0 and 25%, the normative diopside contents between 5 and 30%, and the normative anorthite contents vary between 30 and 55%.

The dark layers of the banded-amphibolites show the same degree of differentiation as the plagioclase-amphibolites, their normative hypersthene and anorthite contents being comparable. Only the normative diopside contents of the dark layers are lower, scattering between 0 and 15%.

The light layers show the highest D.I. values of more than 80, with normative diopside and hypersthene contents between 0 and 10%, and normative anorthite contents between 15 and 40%.

The differentiation succession must be as follows:

hornblendefelses — garnet-amphibolites — plagioclase-amphibolites — banded-amphibolites. The hornblendefelses and the light layers are the end-members of the differentiation succession.

The apparent substitution of diopside by hypersthene is interesting (see also Table 5). High diopside contents are very often parallel to lower hypersthene contents, and this behaviour is observed in all investigated rock types. With increasing D.I. and constantly decreasing anorthite content, higher normative hypersthene contents

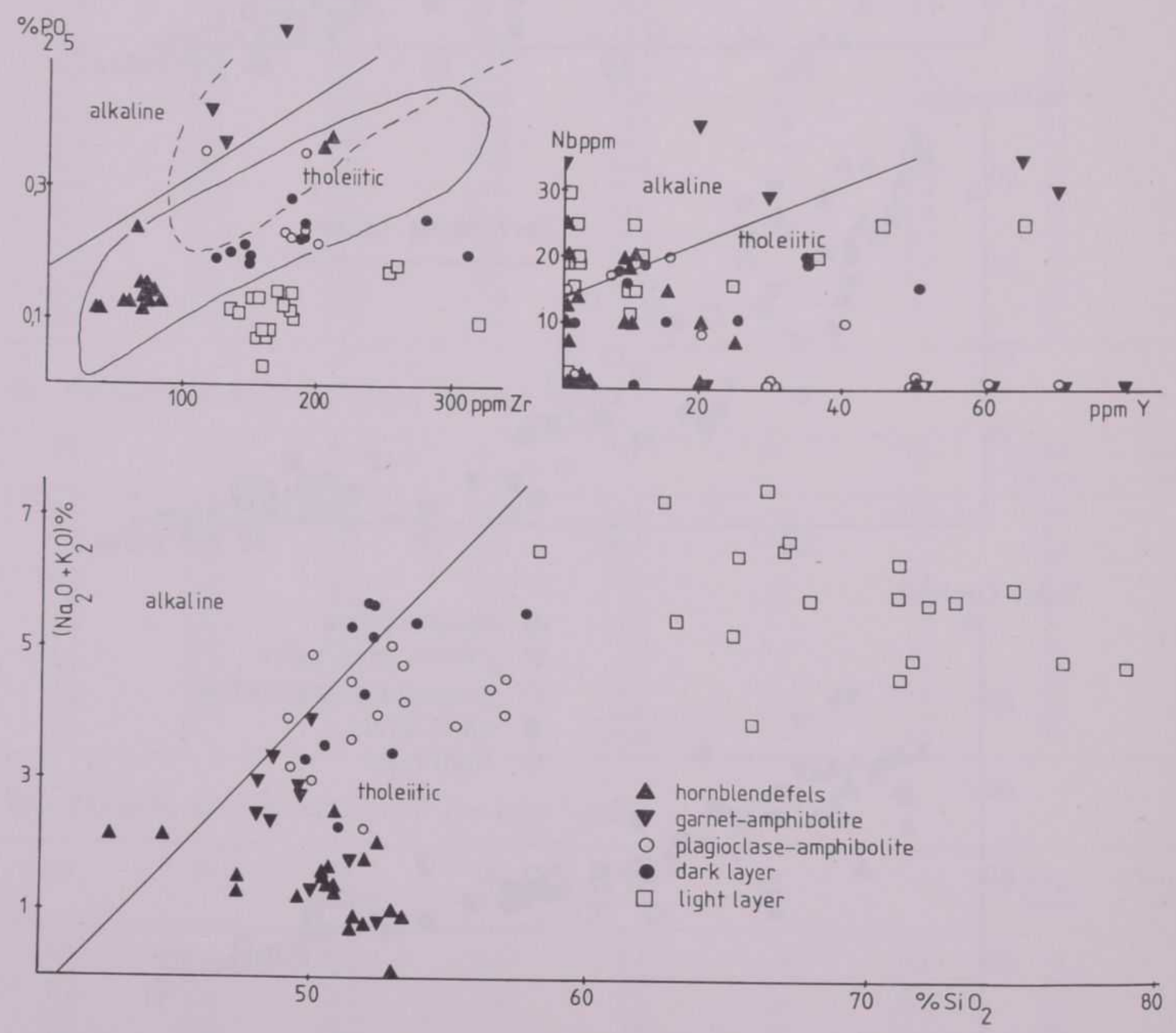
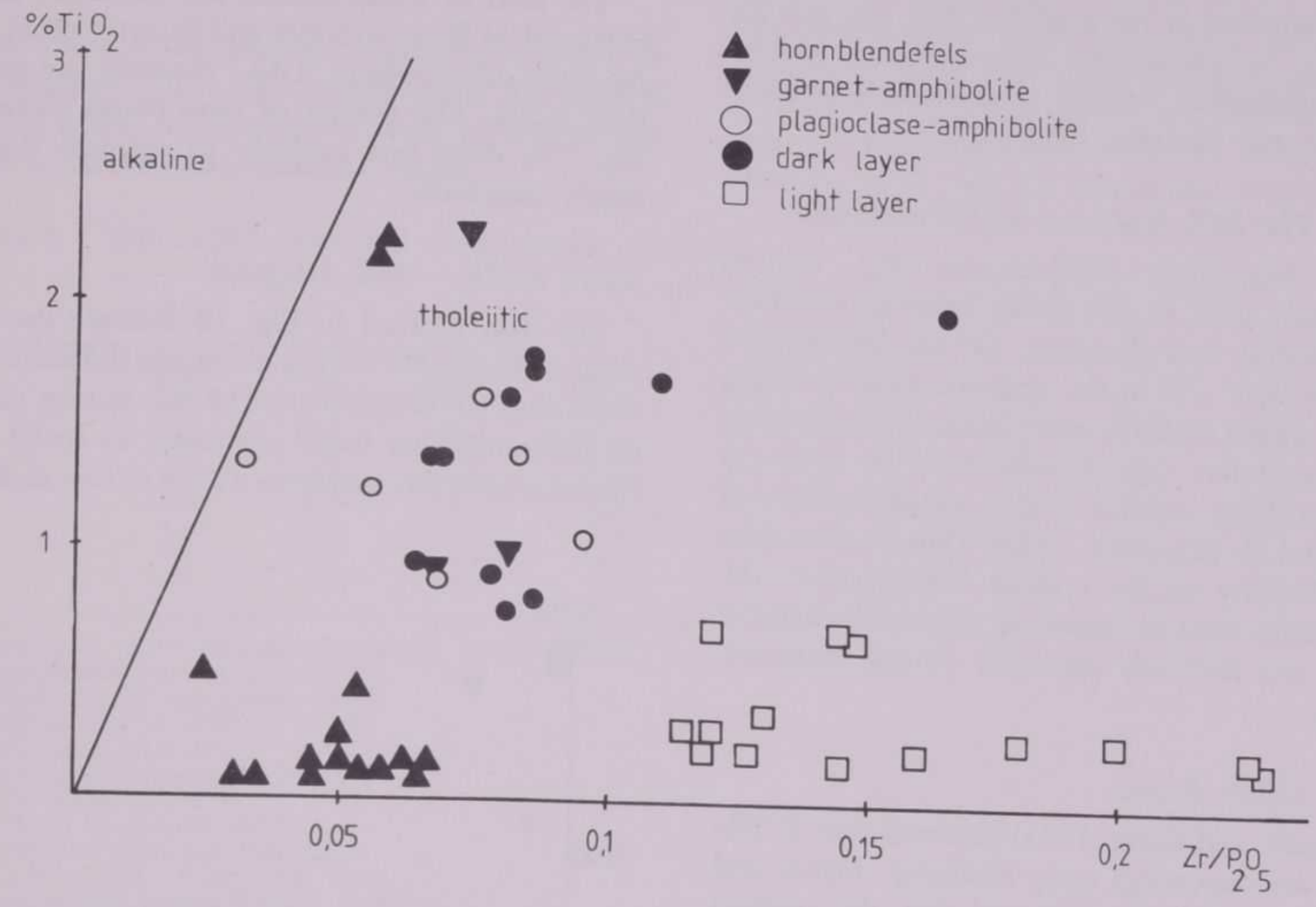


FIG. 16 a-c - The P_2O_5 vs. Zr-, Nb vs. Y- and the $(Na_2O + K_2O)$ vs SiO_2- diagrams distinguishing between alkali-basalts and tholeiites.

4.5.3. *Interpretation*

The three diagrams (Fig. 15) show the common differentiation behaviour of the hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites. During the decrease of normative diopside, hypersthene and anorthite content, the D.I. increases.

emerge in comparison to the normative diopside contents. This suggests that during magma generation a slow diapiric rise is accompanied by a constant crystallization of diopside and by an increase of albite content in the plagioclase. Thus the Ca-content decreases and the Na-content increases during fractional crystallization.



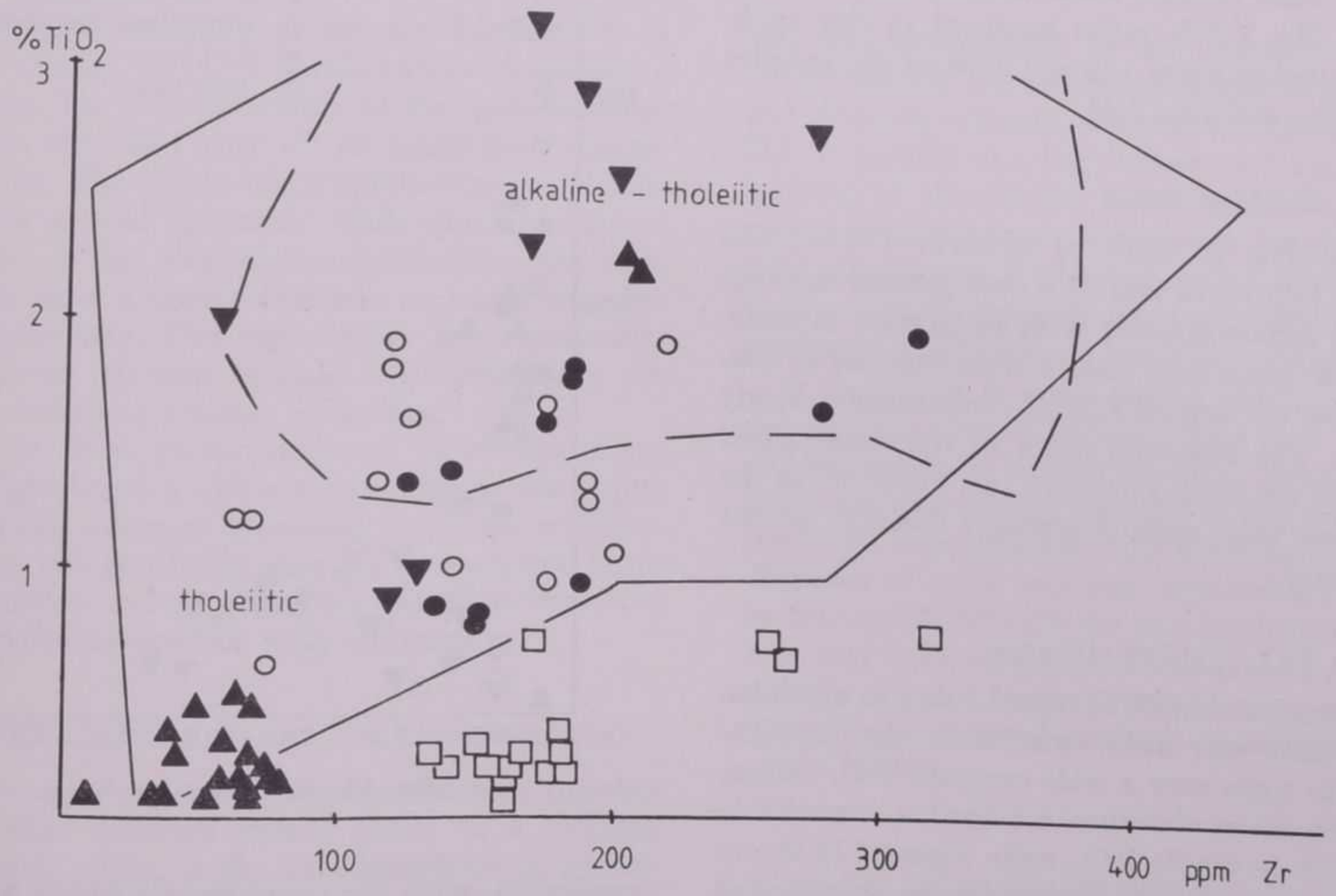


FIG. 17 a, b - TiO_2 vs. Zr/P_2O_5 and TiO_2 vs. Zr. Diagrams distinguishing between alkali-basalts and tholeiites.

4.6. Original Chemistry of the Amphibolites

Examination of the analytical data can provide evidence for the original composition of present day amphibolites, helping to distinguish between alkaline and tholeiitic chemistry.

4.6.1. *The SiO_2-,Na_2O-and K_2O-Distribution*

The SiO_2-(Na_2O+K_2O)-diagram (Fig. 16c) is commonly used to distinguish between tholeiitic and alkaline rock-chemistry. Of the investigated samples 90% fall in the tholeiitic field, pointing to an original tholeiitic rock-chemistry. In drawing this conclusion, consideration must be given to the increasing mobility during metamorphism of Si, K and Na (Elliott, 1973). Thus to determine the alkalinity of the original basalts other element-ratios must be examined, preferably elements which are relatively immobile during metamorphism.

4.6.2. *Y/Nb- Ratios*

Pearce and Cann (1973) observed that Y/Nb-ratios are dependent upon alkalinity. Field and Elliott (1974) demonstrated that the original Y/Nb- ratio remains stable in many metamorphic rocks. The Y/Nb- ratios measured in this study are plotted in figure 16b and 80% of the samples lie in the tholeiitic field.

4.6.3. *Zr/P_2O_5- Ratios*

According to work by Elliott (1973) and Engel (1962), Zr and P_2O_5 show limited mobility during metamorphism. With an increase in metamorphic grade both show a slight increase in content, but the original Zr/P_2O_5- ratio remains nearly stable. The measured ratios of the investigated samples are plotted in figure 16a; 90% fall in the tholeiitic field, again indicating a tholeiitic parent chemistry.

4.6.4. *TiO_2 - Zr/P_2O_5 Diagram*

Winchester (1976) reported that in alkali basalts there was little variation in the Zr/P_2O_5-ratio in rocks over a wide range of TiO_2 values; in comparison tholeiites exhibited a remarkable variation in the Zr/P_2O_5- ratio. Figure 17a shows the measured Zr/P_2O_5- values for the investigated samples plotted against TiO_2- values; data points lie entirely within the tholeiitic field, and exhibit a wide variation in Zr/P_2O_5- ratios. Such a plot is consistent with an original tholeiitic rock chemistry.

4.6.5. *TiO_2/Zr- Ratios*

The field of alkali-basalts and tholeiitic basalts proposed by Winchester and Floyd (1976) overlap each other where TiO_2- contents are greater than 1.2%. The scatter of data points plotted in Fig. 17b does not exclude an original tholeiite basalt chemistry.

4.6.6. *K/Rb - %K Diagram*

The data plotted in Fig. 18 indicate the behaviour of K and Rb during magmatic differentiation. According to Wedepohl (1978), during magmatic differentiation from ultrabasic to acidic rocks Rb concentration increases twice as fast as K concentration, with the consequently widely scattered K/Rb- ratio, having a near vertical trend for samples with very low K- contents. Such a near vertical field is described by the investigated samples, which, by comparison with the results of other workers, is typical of a tholeiitic rock chemistry.

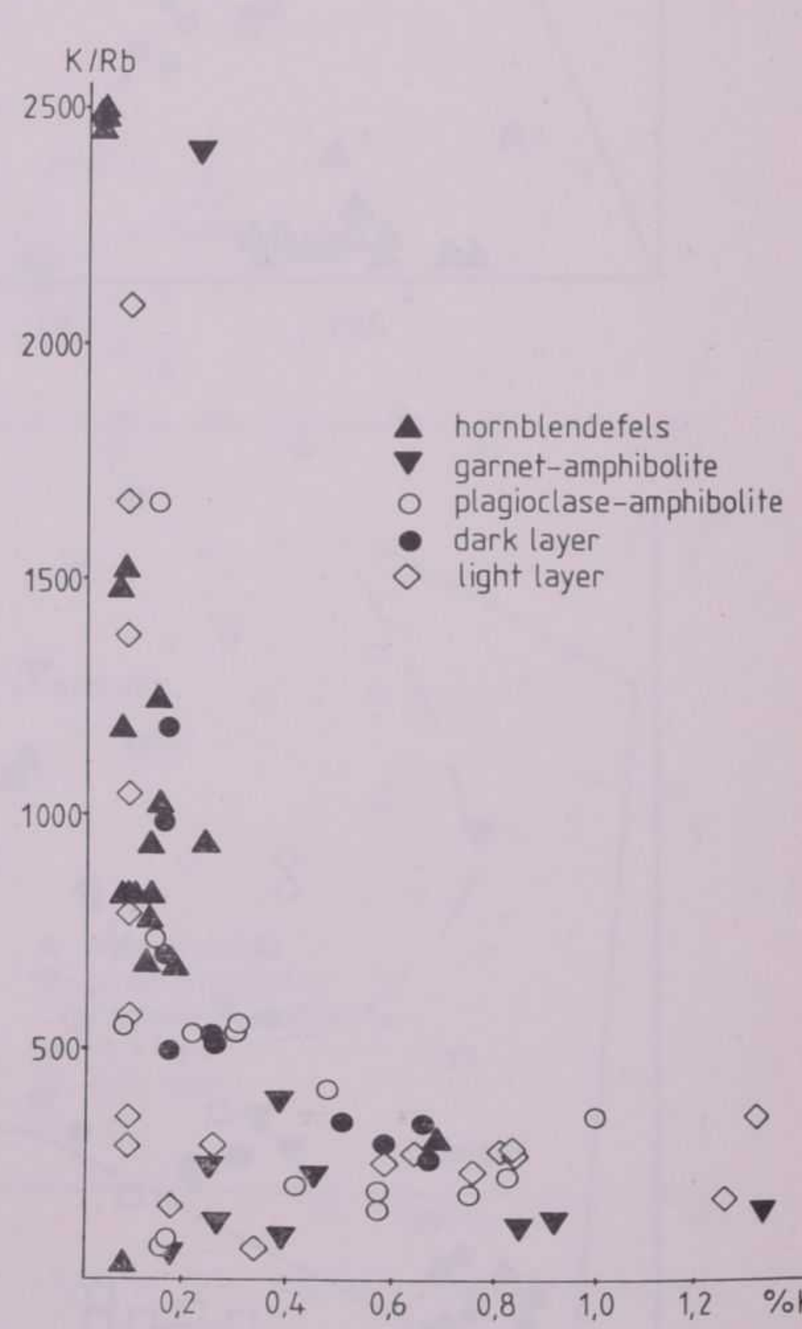


Fig. 18 - K/Rb-ratios vs. K.

4.7. The Calc-Alkaline Igneous Rock Association

In Table 6 the averaged chemical analyses of the different types of amphibolites, investigated in this study, are compared with published analyses of calc-alkaline basaltic rocks.

Table 6 - The amphibolites and their igneous equivalents

	1	2	3	4	5	6	7	8	9	10
SiO_2	49.9	49.6	52.2	52.9	52.4	69.6	69.0	62.7	60.4	56.4
Al_2O_3	13.9	11.5	14.6	13.8	16.3	14.7	14.8	16.5	15.6	16.6
Fe_{tot}	12.5	13.4	11.1	11.2	10.4	3.5	3.3	4	6.7	8.7
MnO	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1
MgO	8.5	8.9	7.4	6.8	6.0	1.0	1.0	3.2	3.7	4.3
CaO	10.8	11.2	9.4	9.2	7.0	2.5	3.6	6.2	5.8	8.5
Na_2O	1.8	1.9	2.7	3.5	4.0	3.4	5.3	4.1	4.6	3.0
K_2O	0.1	0.6	0.7	0.5	0.5	4.6	0.5	1.2	0.5	1.0
TiO_2	2.1	2.5	1.9	1.4	1.3	0.6	0.3	0.6	0.8	1.4

1 alkali-poor quartz tholeiite (Ringwood, 1975)
2 garnet-amphibolite (n = 10)
3 quartz tholeiite (Ringwood, 1975)
4 plagioclase-amphibolite (n = 15)
5 dark layers (n = 11)
6 rhyodacite (Ringwood, 1975)
7 light layers (n = 19)
8 andesite (Ringwood, 1975)
9 mixture of light and dark layers
10 basaltic andesite (Ringwood, 1975)
11 hornblenditic magma (Niggli, 1936)
12 hornblendefels (n = 20)

	11	12
si	90	99
al	7	9
fm	68	63
c	23	26
alk	2	2
k	—	0.1
mg	0.7	0.8

The rock-chemistry of the hornblendefelses is very similar to a « hornblenditic-pyroxenitic » magma. The rock-chemistry of the garnet-amphibolites resembles that of an alkali-poor quartz-tholeiite. The plagioclase-amphibolites are chemicaly in a good agreement with quartz-tholeiites. Similar to the plagioclase-amphibolites, the dark layers show a quartz-tholeiitic to basalt-andesitic rock-chemistry. The light layers are rhyodacitic. Calculated mixtures of light and dark layers are very similar to basaltic andesites.

Thus there exists between hornblendefelses and light layers a differentiation-series containing the whole range of ultrabasic to acidic rock-chemistry; it is concluded that the investigated hornblendefelses and amphibolites therefore represent a calc-alkaline igneous rock association.

4.8. Conclusions Based on Geochemistry

The major and trace element contents together with their variation trends point to a common magmatic origin of the hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites. Their variation trends reflect the development of a calc-alkaline basaltic magma. The following calc-alkaline magma series exists:
Pyroxenite (hornblendefels) — alkali-poor quartz-tholeiite (garnet-amphibolite) — quartz-tholeiite (plagioclase-amphibolite) — basaltic andesite (calculated mixture of light and dark layers). The magma generation from the pyroxenites (hornblendefelses) to alkali-poor quartz-tholeiite (garnet-amphibolite) is accompanied by a strong increase in the Fe/Mg- ratio, explained by the initial crystallization of the Mg-rich olivine and pyroxene phases, and subsequently by the crystallization of Fe-rich garnet. The decreasing normative anorthite and diopside contents observed during increasing D.I. is parallel to a Ca- decrease and a moderate increase of the alkaline elements. These fractionation mechanisms are responsible for the generally calc-alkaline FMA-trend in Fig. 5, displayed by the hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites.

It is difficult to say if partial melting, fractional crystallization or both processes have influenced the magmatic individualizations, because fractional melting may be regarded as the reverse of fractional crystallization. The different variation diagrams of major and trace elements are unable to distinguish between the two mechanisms, and it is only with the help of Rb-Sr isotope determinations that it becomes possible to say more about the processes of fractional crystallization and partial melting.

5. RB-SR ISOTOPE DETERMINATIONS

5.1. Method

Rock samples of 30 to 40 kg were collected for Rb-Sr determinations. For the hornblendefelses whole-rock isochron samples from only one outcrop

were obtained. Similary the plagioclase-amphibolites were sampled in a narrow range for the whole-rock isochron. The rock and sample preparation was carried out according to JÄGER (1960) and WÜTHRICH (1965).

The Rb- and Sr- contents of the samples were predetermined semiquantitatively by X-ray fluorescence. The Rb-contents lay mostly outside of the detection limit of this method, a fact which complicated the Rb-spike addition because the exact amount of spike could not be calculated in advance.

The chemical preparation of the samples was in accordance with the procedures of ALDRICH *et alii* (1956), JÄGER (1962) and WÜTHRICH (1965). After isotope dilution, using a strongly enriched Sr^{84} spike, the Rb-Sr measurements were made on a AVCO-mass spectrometer with a triple filament ion source.

The following constants were used for calculations:

Rb^{87} - decay constant	: 1.42×10^{-11} y^{-1}
Strontium 88/86	: 8.3752 (atoms)
Strontium 87/86	: 0.71014 (atoms)
Strontium 84/86	: 0.056584 (atoms)
Rubidium 85/87	: 2.5265 (atoms)

(STEIGER and JÄGER 1977)

The isotopic ratios, their means and the deviations were calculated using an on-line PDP-8 computer. The total rock isochrons were calculated on the same computer according to BROOKS *et alii* (1972) with an error in measurement for the Sr87/Sr86-ratio of 0.05% and for the Rb87/Sr86-ratio of 3%.

5.2. Rb-Sr Blank

Because of the very low Rb-contents in the samples the influence of the Rb-blank on the Rb-analysis warranted investigation. All the chemicals used were examined for Rb and Sr. The results are shown below:

	ngr Rb/gr sample	ngr Sr/gr sample
Total blank, including handling	0.57	3.0
20 gr HCL, 6 N, 3 × dist.	0.08	0.12
110 gr. 3 × dist. water	0.05	0.10
12 gr HF, Merck suprapure	0.16	0.08
17 gr $HCLO_4$, Merck suprapure	0.05	2.55
Overall Blank from chemicals	0.34	2.85

The overall Rb-blank from chemicals is 0.34 ngr/gr sample; the overall Sr-blank from chemicals is 2.85 ngr/gr sample. The total Rb-blank including total chemicals, «handling» and mass spectrometer blank is 0.57 ngr/gr sample and the total Sr-blank 3.0 ngr/gr sample. The difference between total measured blanks and overall chemical blanks is more critical for Rb than for Sr, indicating, Rb contamination by handling.

However, both, the Rb- and the Sr-blanks show that Rb- and Sr- contamination of the samples with chemicals and handling is very little, and thus no blank correction is necessary, even for the Rb-poor hornblendefels samples.

5.3. Results

Rb-Sr isotope determinations were performed on 9 hornblendefelses, 7 plagioclase-amphibolites and 32 layers of banded-amphibolites. The data are compiled in Tables 7-8.

TABLE 7A - Rb-Sr data of the hornblendefelses

KAW	Rb 87 ppm	Sr Common ppm	Sr 87/Sr 86	Rb 87/Sr 86	Rb/Sr
1657	0.2	28.2	0.704433	0.061328	0.022
1675	0.5	17.5	0.706238	0.295899	0.105
1818	0.5	59.3	0.704195	0.078309	0.030
1821	0.3	19.4	0.704680	0.168246	0.056
1822	0.2	16.8	0.704610	0.121671	0.043
1824	0.1	50.7	0.704132	0.027676	0.007
1825	0.4	126.1	0.704439	0.031563	0.011
1826	0.4	52.5	0.704390	0.082417	0.027
1827	0.5	113.0	0.704161	0.043930	0.016

TABLE 7B - Rb-Sr data of the plagioclase-amphibolites

KAW	Rb 87 ppm	Sr Common ppm	Sr 87/Sr 86	Rb 87/Sr 86	Rb/Sr
1676	3.3	155.4	0.707534	0.216619	0.076
1596	1.2	231.8	0.706322	0.051064	0.018
1654	3.2	566.2	0.704148	0.058383	0.020
1676	3.3	155.4	0.707534	0.216619	0.076
1816	0.5	238.9	0.705947	0.022537	0.008
1817	7.8	424,3	0.706935	0.188963	0.066
1849	1.6	235.2	0.705943	0.069555	0.024
1850	1.6	266.9	0.706120	0.060177	0.022

5.3.1. *Results of the Whole-Rock Analyses of the Hornblendefelses and Plagioclase-Amphibolites*

The whole-rock data of the hornblendefelses and the plagioclase-amphibolites are shown in figure 19, the results for each rock type describing a straight line. With the exception of one sample, the plagioclase-amphibolite data define a straight line such that the maximum deviation in the Sr87/Sr86- ratio from this line is only 0.05%. The exception (sample KAW 1654) originates from an outcrop far away from the other samples, in the southernmost part of the Berisal complex;

TABLE 8 - Rb-Sr data of the banded-amphibolites

KAW	Rb 87 ppm	Sr Common ppm	Sr 87/Sr 86	Rb 87/Sr 86	Rb/Sr	≠
x1655 A	8.3	335.3	0.708690	0.254274	0.089	3.5 cm
1655 B	4.1	233.7	0.708186	0.180029	0.063	2 cm
x1655 C	8.6	326.4	0.708628	0.270072	0.095	3.8 cm
1656 A	1.4	563.1	0.709533	0.025091	0.009	1 cm
1656 B	1.3	255.3	0.707373	0.053351	0.019	1 cm
x1656 C	0.3	688	0.708041	0.004181	0.001	1 cm
x1669 A	3.1	386.6	0.706731	0.082502	0.029	2.5 cm
1669 B	0.7	314.6	0.706750	0.021601	0.008	1.5 cm
x1669 C	0.4	430.6	0.706680	0.009731	0.003	0.8 cm
x1669 D	0.7	322.4	0.707471	0.020875	0.007	0.4 cm
x1670 A	2.5	839.6	0.707036	0.030006	0.011	2 cm
1670 B	0.9	616,6	0.707547	0.015523	0.005	2 cm
x1671 A	0.8	347.6	0.709561	0.024391	0.009	1.5 cm
1671 B	0.4	395.5	0.708763	0.009903	0.003	0.5 cm
x1671 C	0.2	353.2	0.708441	0.004821	0.002	0.7 cm
1671 D	0.5	358.1	0.708839	0.013362	0.005	0.8 cm
x1671 E	0.1	393.4	0.709313	0.003172	0.001	1.3 cm
*1671 F	0.4	764.3	0.712493	0.005893	0.002	0.5 cm
x1671 G	0.2	680.4	0.710345	0.003332	0.001	1.5 cm
x1671 H	0.1	558.5	0.709726	0.002378	0.001	2 cm
x1672 A	10.4	97.7	0.715522	1.091309	0.383	6 cm
1672 B	7.4	127.9	0.712096	0.588583	0.207	4 cm
x1672 D	16.5	91.4	0.713367	1.841316	0.647	2.5 cm
1672 E	3.6	148.4	0.712799	0.247915	0.087	3 cm
x1673 A	20.45	230.8	0.719284	0.905766	0.318	3 cm
1673 B	5.5	130.6	0.718911	0.431330	0.152	3.5 cm
+1673 C	0.4	1.2	0.717720	3.499752	1.197	0.5 cm
x1674 A	6.9	284.7	0.706413	0.248366	0.087	1.5 cm
1674 B	5.4	177.3	0.706565	0.310816	0.109	0.8 cm
x1674 C	7.3	255.4	0.706497	0.290200	0.102	2.4 cm
x1674 D	8.9	276.4	0.706456	0.329036	0.116	2 cm
x1674 E	8.9	286.7	0.706944	0.317855	0.112	1.5 cm

x: light layer
*: epidote-layer
+: quartz-layer

the deviating behaviour of this sample can be explained geochemically by the K/Rb- ratio and this is discussed later.

The two isochrons defined by the horblendefelses and plagioclase-amphibolites yield isochron ages, which within analytical error, are indistinguishable, the Sr-initial ratios however, are significantly different.

Both rock-types show very low Rb87/Sr86-ratios, the hornblendefelses a maximum of 0.2 and the plagioclase-amphibolites 0.3, implying for an age of 500 m.y. an increase of the Sr87/Sr86-ratio of only one percent. The averaged Rb/Sr-ratios of both rock-types are 0.035. The whole-rock isochron of the plagioclase-amphibolites gives an age of 530 ± 80 m.y. with Sr-initial ratio of 0.7057. (The sample KAW 1654 falling on the straight line of the hornblendefelses was omitted for age calculation). With the whole-rock isochron of the hornblendefelses an age of 500 ± 60 m.y. is obtained with a Sr- initial ratio of 0.7039.

The isochron ages of 500 m.y. indicate that both rock systems were unaffected by the Variscan and Alpine metamorphisms.

5.3.2. *Interpretation of the Whole-Rock Data*

The very low Sr-initial ratios of the hornblendefelses and the plagioclase-amphibolites point to a mantle origin. The significantly different Sr-initial ratios and the identical Rb/Sr-ratios of the hornblendefelses and plagioclase-amphibolites are the keys to revealing their formation-mechanisms.

Because of the identical Rb/Sr-ratios of both rock-types, there is no time relation between the Sr-initial ratios and thus the increase of the ratio from 0.7039 to 0.7059 cannot be explained by magmatic differentiation but rather by processes of disequilibrium partial melting.

If the diffusion rates of Sr were too low to effect isotopic homogenization at the time of the melting event, a magma could be formed with a Sr-isotope composition quite different from its source.

Therefore primary isotopic heterogeneities in the source material might have been of particular importance.

The acceptance of partial melting as the formation mechanism of the pyroxenites (hornblendefelses) and the quartz-tholeiites (plagioclase-amphi-

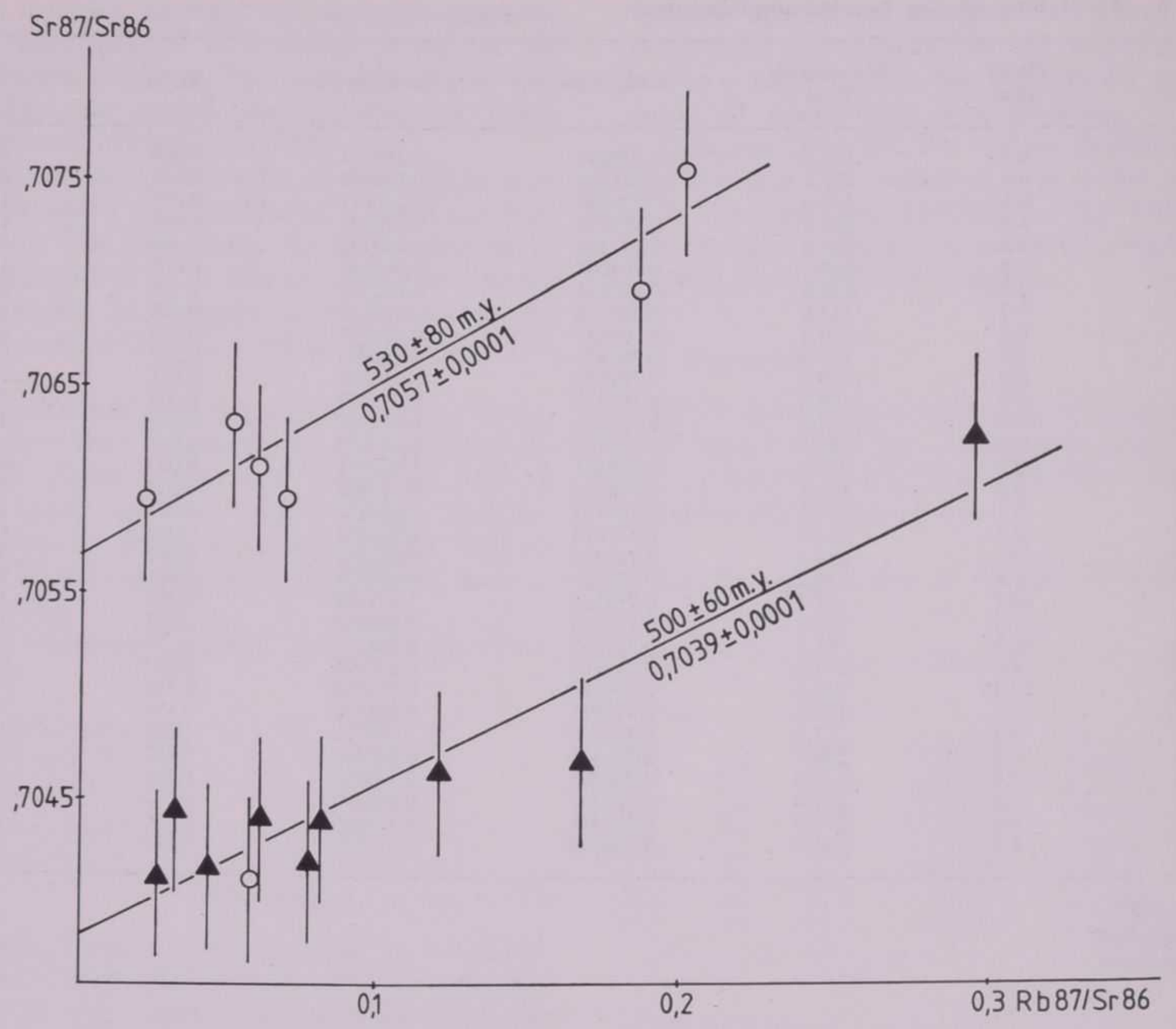


FIG. 19 - Rb-Sr total rock isochron of hornblendefelses (filled triangles) and plagioclase-amphibolites (circles).

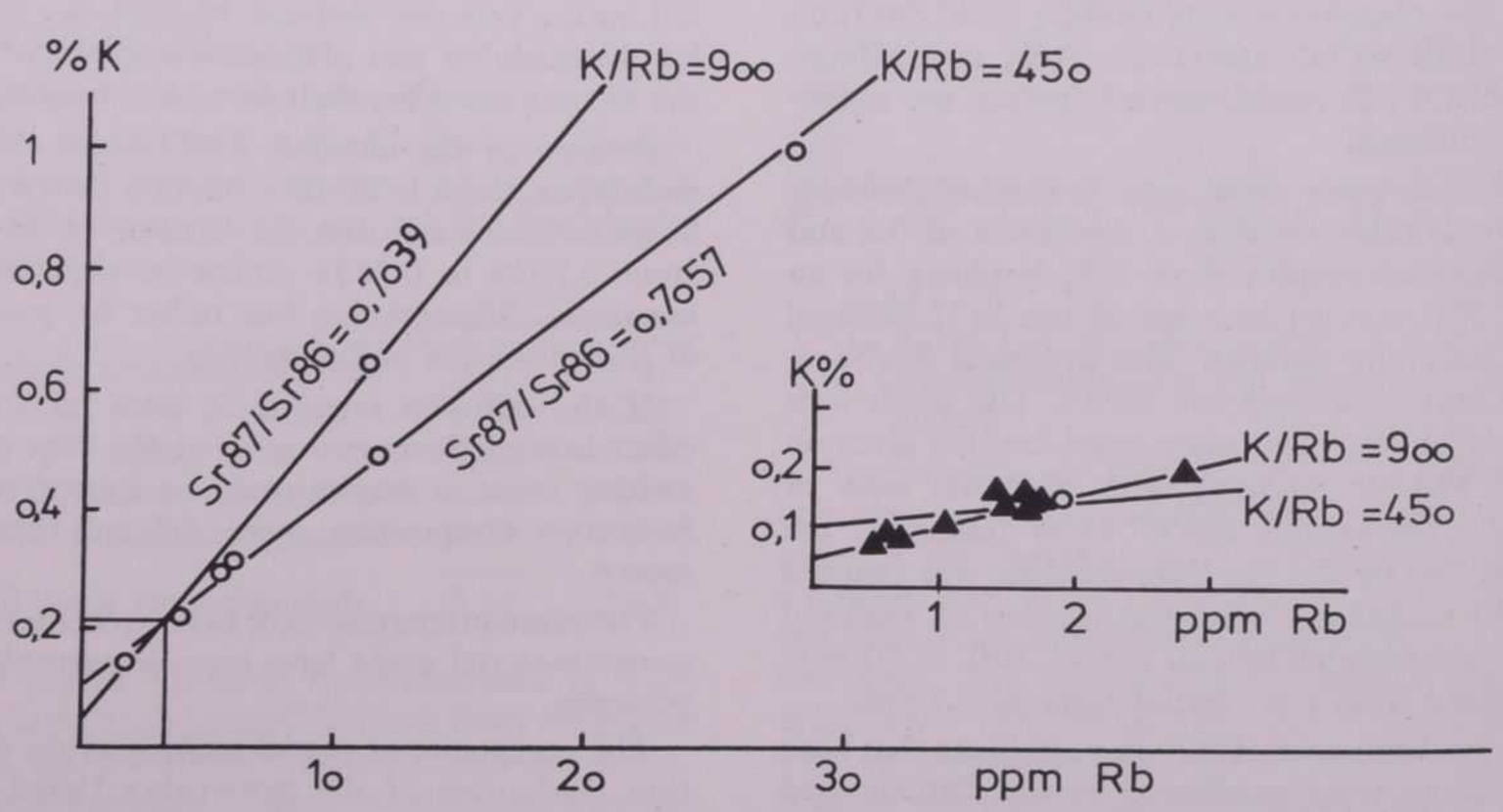


FIG. 20 - K-Rb-relations in the hornblendefelses (filled triangles) and plagioclase-amphibolites (circles).

bolites) agrees with the observations of GREEN and RINGWOOD (1968). They present considerable evidence which suggests that calc-alkaline magmas may be derived by partial melting in tholeiitic basalt piles. They have shown that by 20% partial melting of a pyroxenite, ascending as a diapir from the Benioff-zone at depths of 100 to 150 kilometers, magma segregation starts at 60 to 100 kilometers, forming magnesia-rich olivine-tholeiites to quartz-tholeiitic magmas. If the partial melting becomes sufficiently extensive, the liquid segregates from the residual refractory crystals and forms an independent magma body which may fractionate and differentiate by cooling and rising. The moment of magmatic individualization or formation of the pyroxenites (hornblendefelses) and the quartz-tholeiites (plagioclase-amphibolites) must have taken place around 500 m.y. ago.

5.3.3. *Geochemical Correlation of the Rb-Sr Data with K and Ca in the Hornblendefelses and Plagioclase-Amphibolites*

5.3.3.1. K-Rb Relations

Because of the very low Rb-contents in both rock-types only Rb determinations measured by mass spectrometry were used in figure 20.

The mean K/Rb-ratio of the hornblendefelses is 900, typical for ultrabasic rocks. The plagioclase-amphibolites describe a positive correlation as good as the hornblendefelses, with an average K/Rb-ratio of 450, typical of basic rocks. The sample KAW 1654 falling on the isochron of the hornblendefelses contains a much higher K/Rb-ratio and also falls on the correlation-line of the hornblendefelses. The lower Sr87/Sr86-ratio and the higher K/Rb-ratio of this sample points to its ultrabasic origin.

5.3.3.2. The Ca-Sr-Relations in the Hornblendefelses and the Plagioclase-Amphibolites

The Ca-Sr values of both rock-types are widely scattered (Fig. 21), although a weak negative correlation is observable. This agrees with observations of TUREKIAN (1956) who demonstrated that no distinct covariance in basic rocks exists between Ca and Sr despite the similarity of ionic radius and bond type of both elements. This covariant behaviour can be related to inhomogeneously distributed Sr-contents in the mantle, to disequilibrium partial melting (as discussed previously) and to fractional crystallization. The strong variation in the diopside content (Fig. 15) has as a consequence a strong scattering effect on the Ca- and the Sr-contents. The progressive crystallization of diopside and the increase of albite content in the plagioclase during magma generation (Fig. 15) must result in the decrease of the Ca-content in the remaining melt. In contrast the Sr-contents seem to increase (Fig. 21); this observation is in good agreement with TUREKIAN (1956), who could show, that Sr is preferentially enriched in the residual magma. Thus the Sr/Ca-ratios increase with progressive fractional crystallization, in contrast to rocks of sialic nature.

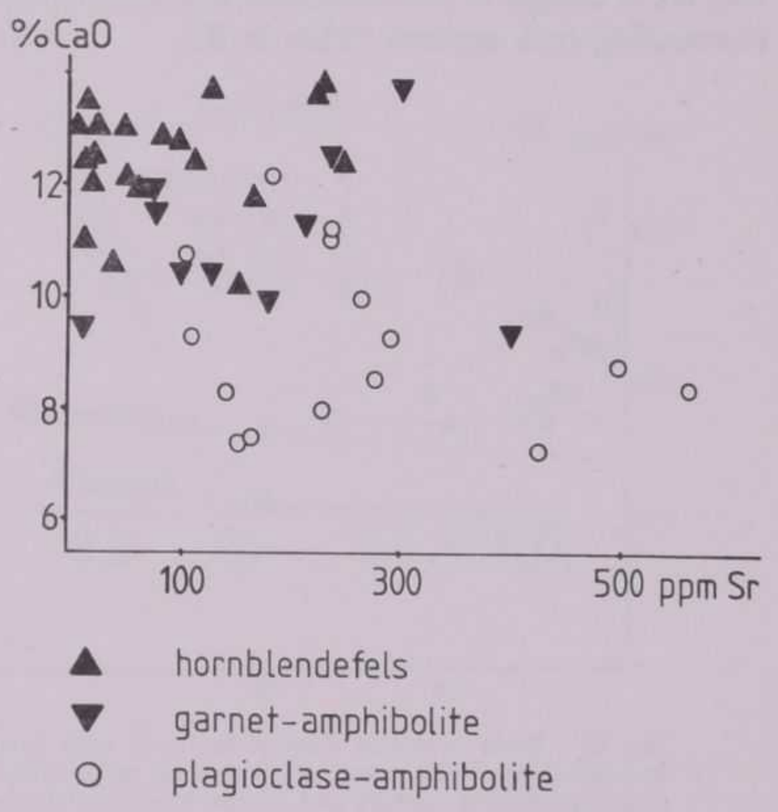


FIG. 21 - Ca-Sr relations in the hornblendefelses, plagioclase-amphibolites and garnet-amphibolites.

5.3.4. *Rb-Sr Isotope Analysis on Individual Layers of the Banded-Amphibolites*

The different Sr87/Sr86-ratios of the individual bands show values scattered between 0.706 and 0.712 (Fig. 22). Their Rb87/Sr86-ratios are very low, mostly between 0.001 and 0.03, with two band successions showing slightly higher ratios ranging between 0.06 and 0.1.

For each band succession the calculated mixtures are plotted because it may be assumed that the layering, observable today, is a product of magmatic and metamorphic processes. On the assumption that the original material of each band succession was isotopically homogeneous and uninfluenced during geological time by contamination, and since we deal with identical band successions, the trend described by the data points of the calculated mixtures in figure 22 must reflect the premetamorphic history, the genesis of the band material during magma generation.

With the exception of two band successions, which show slightly higher Rb/Sr-ratios, the other

bands describe a negative trend, indicating a decrease in the Rb/Sr-ratio with increasing Sr87/Sr86-ratio. Thus the bands do not define straight lines. Sr homogenization took place neither between the single bands nor between the band successions.

The deviation of the data points of single bands from their calculated mixture reflect the mobility of Rb and Sr within a band succession during metamorphism. The Rb- contents of the investigated samples are very low (see Table 8) and therefore they are in danger of Rb contamination from those surrounding rock systems richer in Rb.

In contrast to the samples following this negative trend, samples higher in Rb and K contain small amounts of biotite. It has been shown previously that these samples having higher K- and Rb- contents did not follow the general differentiation succession in the Na_2O-K_2O- mixing diagram (Fig. 13). There is no doubt that these two band successions had also been contaminated by very small amounts of alkaline elements, probably in Alpine time, because of the observed reactions between biotite and amphibole.

Correcting the Rb of these samples with the trend in figure 23a they also fall with the new

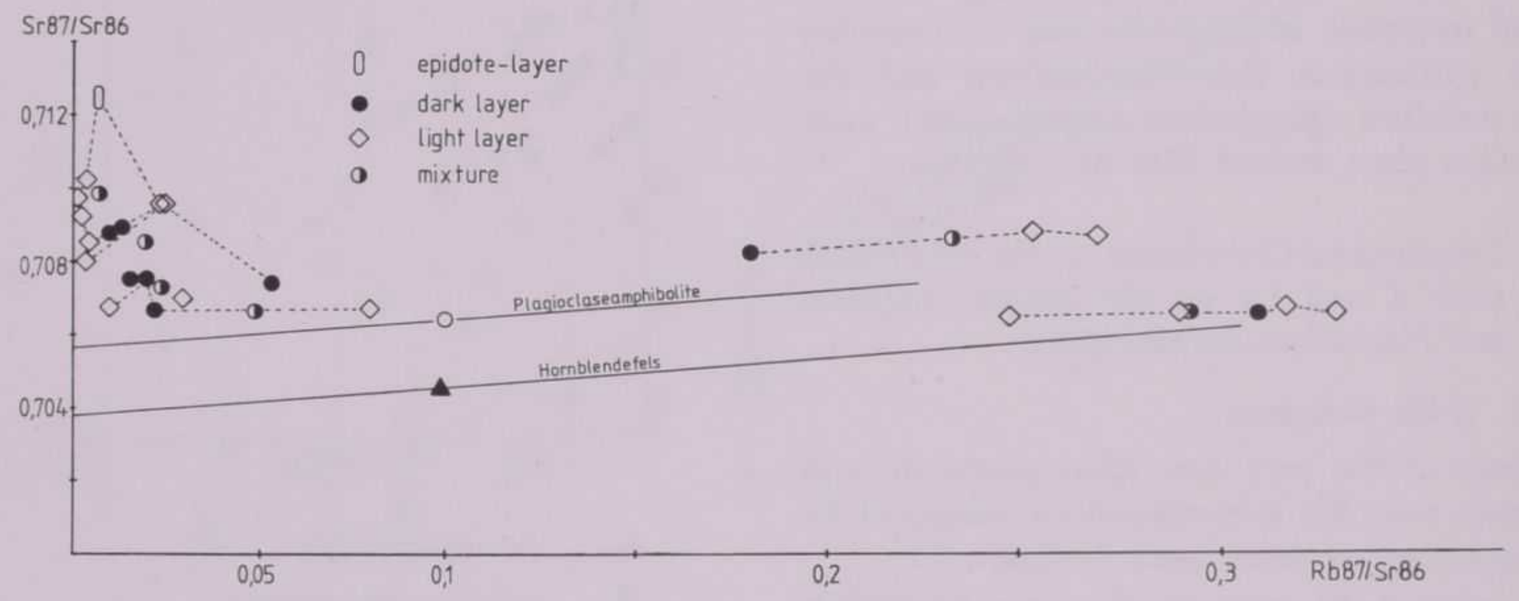


FIG. 22 - Rb-Sr evolution diagram for total rock samples of individual adjacent layers of banded-amphibolites. Individual band successions are connected with dotted lines. As comparison the average values of the plagioclase-amphibolites (circle) and of the hornblendefelses (filled triangle) are shown with their isochrons.

Only two of the investigated band successions (samples KAW 1672 and KAW 1673) are strongly contaminated and therefore are excluded from figure 22. Sample KAW 1672 was taken close to the contact of crystalline rock with the Mesozoic cover on the Alpe Veglia. It is very probable that this sample was contaminated by these Mesozoic sediments during the Alpine event. The light and dark layers of sample KAW 1673 are separated by a quartz-layer 0.5 cm in thickness, and here also it is assumed that Rb migrated from the quartz-layer. Both samples have significantly higher Sr87/Sr86- and Rb87/Sr86-ratios.

5.3.5. *Geochemical Correlation of the Rb-Sr Data with K and Differentiation Index Values in the Banded-Amphibolites*

The data points plotted in figure 23 represent the calculated mixtures of the different band successions (Table 9). Both elements K and Rb (Figs. 23a, b) show the same behaviour as the Rb87/Sr86-ratios plotted against the Sr87/Sr86-ratios (Fig. 23c), indicating a decrease of the K- and Rb- contents with increasing Sr87/Sr86-ratios.

TABLE 9 - The calculated mixtures of light and dark layers

	1671	1656	1655	1670	1669	1674
SiO_2	64.5	57.9	61.5	59.3	62.6	68.2
Al_2O_3	16.4	16.2	15.5	18.5	16.1	13.8
Fe_{tot}	4.5	6.8	6.1	4.4	5.5	4.2
MnO	0.1	0.1	0.1	0.1	0.1	0.1
MgO	1.3	5.0	2.4	3.9	2.5	2.0
CaO	5.2	6.3	5.7	4.8	4.9	3.8
Na_2O	5.9	4.9	3.8	6.4	5.8	4.5
K_2O	0.1	0.2	0.8	0.2	0.2	0.7
TiO_2	0.4	0.9	0.8	0.6	0.6	0.5
Rb	1.18	3.58	27.0	6.11	6.49	27.7
Rb (corr)	—	—	2.5	—	—	7.5
Sr	487	500	310	728	370	264
Sr 87/Sr 86	0.7099	0.7085	0.7086	0.7073	0.7068	0.7066
Rb 87/Sr 86	0.0068	0.0199	0.2469	0.023	0.049	0.2963
Rb (corr)	—	—	0.023	—	—	0.079
Or	0.6	1.2	1.1	1.3	1.1	1.4
Ab	53.2	44.4	36.0	57.1	52.2	42.1
An	18.4	21.8	25.9	20.6	17.8	17.2
Di	4.9	4.5	0.0	0.0	3.7	0.0
Hy	1.3	11.6	7.1	10.8	5.2	5.6
Q	17.6	9.5	23.3	5.5	14.8	29.4
Diff'Index	71	55	60	64	68	73
Norm. An-content	26	33	42	26	25	29

calculated Rb87/Sr86-ratios on the negative trend in the Nicolaysen-diagram (Fig. 23c) without changing the Sr-contents and the Sr87/Sr86-ratios.

The negative trend described by the data points of the calculated mixtures of the banded-amphibolites ends in figure 23c with the highest Rb/Sr-ratios and the lowest Sr87/Sr86-ratios close to the averaged ratios of the plagioclase-amphibolites.

banded-amphibolites, might be the key to their formation-mechanisms.

But can this behaviour of falling Rb/Sr-ratio with increasing Sr87/Sr86-ratio be explained?

A subsequent delivery of Rb to the surrounding rock-systems, much richer in alkaline elements is impossible. Also a subsequent Sr87 contamination

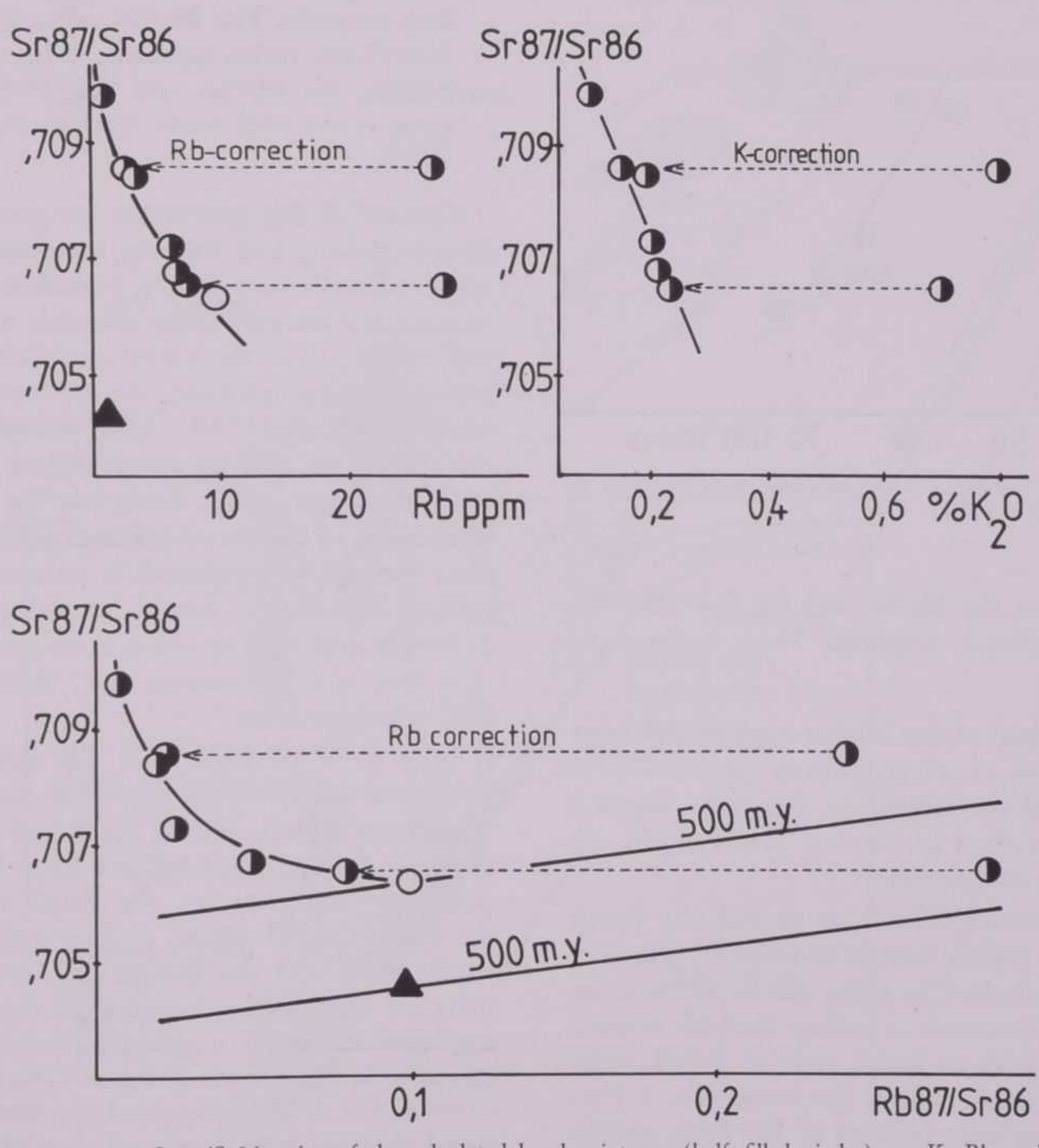


FIG. 23 a-c - Sr87/Sr86-ratios of the calculated band mixtures (half filled circles) vs. K, Rb and Rb87/Sr86. As comparison the average values of the plagioclase-amphibolites (circle) and of the hornblendefelses (filled triangle) are shown.

The same trend is observed in figure 24 where the D.I. values are plotted against the Sr87/Sr86-ratios, where a decreasing D.I. is accompanied by increasing Sr87/Sr86-ratios.

5.3.6. *Interpretation of the Rb-Sr Whole Rock Data on the Banded Amphibolites*

The negative trend, of decreasing Rb/Sr-ratios and decreasing D.I. values with increasing Sr87/Sr86-ratios, described by the data points of the

is improbable. The Sr-contents of the layers are so high, that unbelievably large amounts of Sr87 must have been supplied to augment the Sr initial ratios.

The Rb- contents of the single band successions are so low, that they also must have been augmented with the existence of fluids. Thus we can exclude every form of crustal contamination of the light and dark layers which describe this negative trend and conclude that the material of the

dark and light layers must also be of igneous origin. However, the discussed trend is in contrast to magmatic differentiation or fractional crystalli-

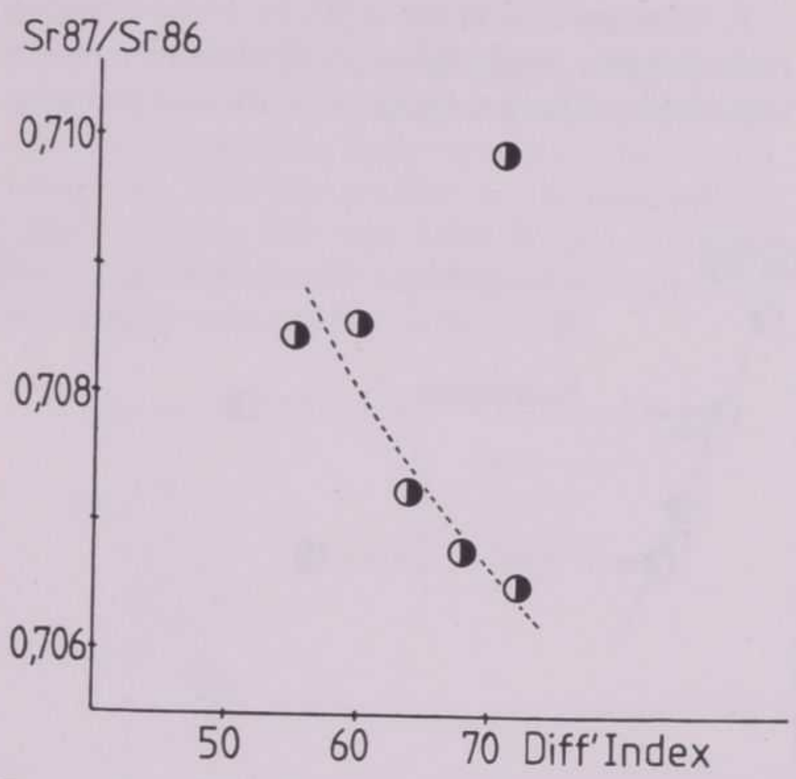


FIG. 24 - Sr87/Sr86-ratios of the calculated band mixtures vs. the Differentiation-Index.

zation, where the Rb/Sr- and the Sr87/Sr86-ratios are positively correlated. Three explanations are possible:

1. The material of the banded-amphibolites originated from an inhomogeneous mantle. This is improbable regarding the significant negative trend described by the data points of the calculated band mixtures.
2. It also seems difficult to explain the partly apparent higher Sr87/Sr86-ratios of the banded-amphibolites by aging effects; in these cases it is necessary to assume that the original material with an initial ratio of 0.704 maintained a closed system for more than 3 b.y.. This is unlikely because of the large masses of hornblendefelses and plagioclase-amphibolites showing formation ages of 500 m.y. adjacent to the banded-amphibolites.
3. The most probable process causing this inverted trend of the Rb/Sr- and the Sr87/Sr86-ratios, is the process of disequilibrium partial melting. According to O'NIONS *et alii* (1973) in disequilibrium partial melting the isotopic heterogeneities are reduced to the mineral scale. These isotopic inhomogeneities between the different minerals exist as long as phlogopite is a stable residual phase. Thus because phlogopite remains as a residual phase up to 10% melting the first formed partial melts must have much lower Rb/Sr-ratios than the bulk source (O'NIONS *et alii,* 1973); however their Sr87/Sr86-ratios must be much higher than the ratios of the source because during melting temperatures the still residual phlogopite must already be an open system for Sr, since it is the supplier of the radiogenic Sr87 for the melts. During increased melting the phlogopite itself starts to melt and brings the Rb and K into the melt. The Rb/Sr- ratios increase as the Sr87/Sr86- ratios decrease. With an increase in melting the Rb/Sr- and Sr87/Sr86- ratios become more and more similar to that of the source.

Because of the process of progressive disequilibrium melting low melting temperatures may be supposed, such that during partial melting of the source the least refractory minerals will melt first and separate from the partly unmolten portions of pyroxene and amphibole, the restites. This agrees with MEHNERT (1968) who demonstrated that the partial melting of amphibolites without the addition of granitizing fluids has the consequence of andesitic to dacitic mobilisates within the immediate vicinity of amphibolitic palaeosomes. With further melting the newly formed melts are increasingly enriched in alkaline elements and thus it is that with decreasing Sr87/Sr86- ratios the D.I. values increase.

It is quite possible that the quartz-tholeiitic plagioclase-amphibolites represent the source material from which, during fractional melting, the andesitic banded-amphibolites have been developed. This accounts for the trend described by the banded-amphibolites, ending with the highest Rb/Sr-ratios and the lowest Sr87/Sr86-ratios similar to the averaged ratios of the plagioclase-amphibolites. Such a genetical relationship also agrees with the observations of GREEN and RINGWOOD (1968, 1972) provided we accept that fractional melting may be regarded as the reverse of fractional crystallization. They found that in the presence of a substantial water vapour pressure, fractionation can continue from quartz-tholeiite through andesite into dacite and rhyodacite. The light rhyodacitic layers represent low melting portions and the dark quartz-tholeiitic to basalt-andesitic layers the restites. If the melting had been complete with subsequent fractional crystallization and homogenization unlayered andesitic rocks (calculated mixtures of dark and light layers) would exist, instead of the dark and light layers seen today. Thus the quartz-tholeiitic to basalt-andesitic dark layers and the rhyodacitic light layers may be re-

gard-d as complementary parts, originating during the fractional melting of a common source material, the quartz-tholeiitic plagioclase-amphibolites. It is difficult to estimate how far the layering itself is only a product of partial melting, since the influence of metamorphic differentiation and deformation on the development of the banding can also be demonstrated.

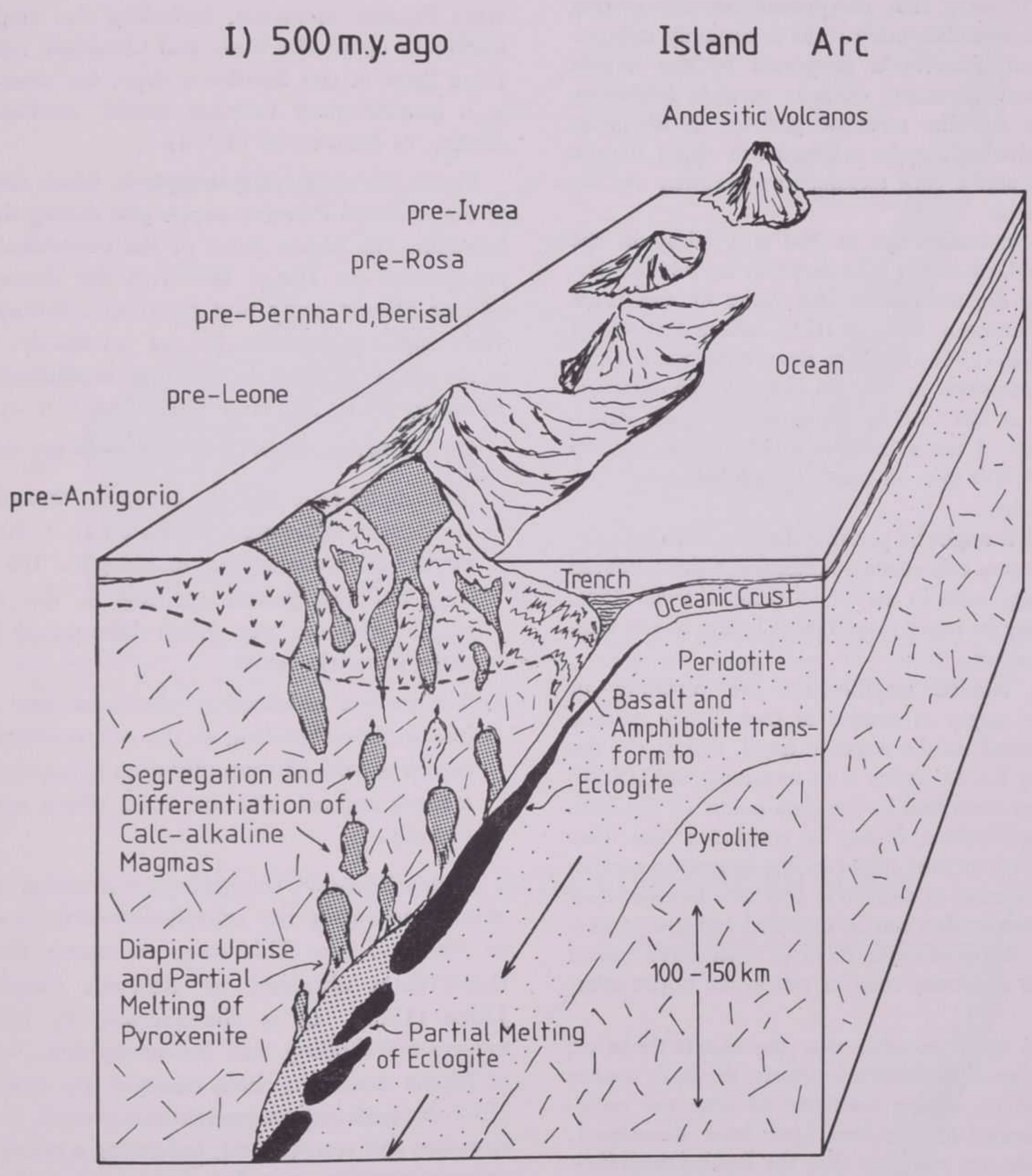


FIG. 25 - The magma generation in the subduction zone (according to RINGWOOD, 1974) forming the original material of the investigated amphibolites and hornblendefelses, in a palinspastic block diagram of the returned nappe pile during the Caledonian.

5.3.7. *Conclusions Based on Rb-Sr Isotope Data*

The Sr/Ca- K/Rb- ratios and the Rb-Sr isotope determinations clearly indicate a magmatic origin for the hornblendefelses and plagioclase-amphibolites. From their identical Rb/Sr- ratios, but significantly different initial Sr- ratios the process of partial melting may be inferred for the formation of these two rock types. Primary isotopic heterogeneities in the source material could have been particularly important. The magmatic individualization of the hornblendefelses and plagioclase-amphibolites must have taken place 500 m.y. ago, at which time the two magma-bodies must have been already totally separated and isotopically homogenized. Their Rb-Sr systems have not been

disturbed during a later event, there being no geochronological hint of a later metamorphism observed in many Pennine nappes.

The low Sr87/Sr86-ratios of less than 0.704 in the hornblendefelses as well as the Rb/Sr-ratio of 0.035 show that the present tectonic setting in the metasedimentary rocks is certainly not original, an observation supported by the largely sharp and discordant contacts between hornblendefelses and the schistose gneisses. Most likely these ultrabasic rocks originated in upper mantle regions and a cool tectonic emplacement can be considered.

The formation age of 500 m.y. lying on the Cambro-Ordovician boundary can be related perhaps to the ultramafics and mafics of the Ivrea zone (Southern Alps; N-Italy), where HUNZIKER and ZINGG (1980) fixed the time of basic and ultrabasic intrusions at 500 to 480 m.y.. In addition FRANK *et alii* (1976) found in the « Alt-Paläozoikum » of the « Ostalpin » (Austria) formation ages of 500 m.y. in banded-amphibolites of volcanic origin.

Thus it might be possible that in Cambro-Ordovician times calc-alkaline volcanic activities existed on a large scale in the whole Pennine area, reflected today by many amphibolitic bodies in the Pennine nappes.

The banded-amphibolites are certainly of igneous origin in respect of their Rb-Sr isotope data. Based on the negative trend, that is the decreasing Rb/Sr- ratios with increasing Sr87/Sr86-ratios as described by the data points of the banded-amphibolites, it may be concluded that disequilibrium melting might be the formation mechanism. Because of their very low Rb-contents crustal contamination can be excluded and the processes of disequilibrium melting must have taken place in the lower crust or just in the upper mantle.

It is quite possible that the quartz-tholeiitic plagioclase-amphibolites represent the bulk source from which, during fractional melting, the andesitic banded-amphibolites have been developed. Thus we can conclude that the banded-amphibolites must be of the same age as or younger than the plagioclase-amphibolites.

6. THE GENESIS OF THE AMPHIBOLITES AND HORNBLENDEFELSES IN THE LIGHT OF PLATE TECTONICS AND OROGENESIS

The described calc-alkaline rock association of pyroxenites, alkali-poor quartz-tholeiites, quartz-tholeiites, andesites and rhyodacites generated during partial melting of diapirically rising mantle material is typical of volcanic orogenic series in Island Arcs or Continental Margins. Therefore, the original volcanic igneous rock association of the Berisal crystalline complex, combined with other Pennine elements, including also amphibolitic rocks up to the basic and ultrabasic rocks of Ivrea Zone in the Southern Alps, are considered in a general plate tectonic model, modified according to RINGWOOD (1974).

Figure 25 shows a palinspastic block diagram of the returned Pennine nappe pile during the Caledonian. The oldest parts of the unravelled nappes formed an Island arc with the descending slab of oceanic crust and peridotitic lithosphere. The magma generation in the subduction zone, as discussed in previous sections, is schematically shown in figure 25, after RINGWOOD (1974).

The following stages of development are visible:

1. The amphibolite and the basalt on the subducted oceanic crust are dehydrated at 70-100 km depth and transformed to eclogite. The high P_{H_2O} initiates partial melting in the upper mantle. Magmas rise which differentiate in an early tholeiitic series.
2. The further subduction of the oceanic crust causes partial melting of the quartz-eclogite at depths of 100-150 km initiating pyroxenite-formations and calc-alkaline series which rise diapirically.

Figure 26 shows the geological situation of the same region after the calc-alkaline activities 400 to 300 m.y. ago. This stage represents the Variscan dates obtained on different nappes by JÄGER (1969). It is characterized by isostatic movements, folding and metamorphism. A kind of Alpine mountain chain emerges, the basic and ultrabasic bodies become metamorphosed, folded, stretched and transported, indicating a nearly cool tectonic emplacement for these basic and ultrabasic bodies, as discussed in earlier sections.

Figure 27 shows the same region after erosion in a geosynclinal stage in Mesozoic to Tertiary time. The Pennine crystalline basement, with the inclusions of basic and ultrabasic rocks, starts to be covered by new sediments, the « Bündnerschiefer ».

In the Alpine orogeny both elements, the sediments and the crystalline basement, become involved (Fig. 28).

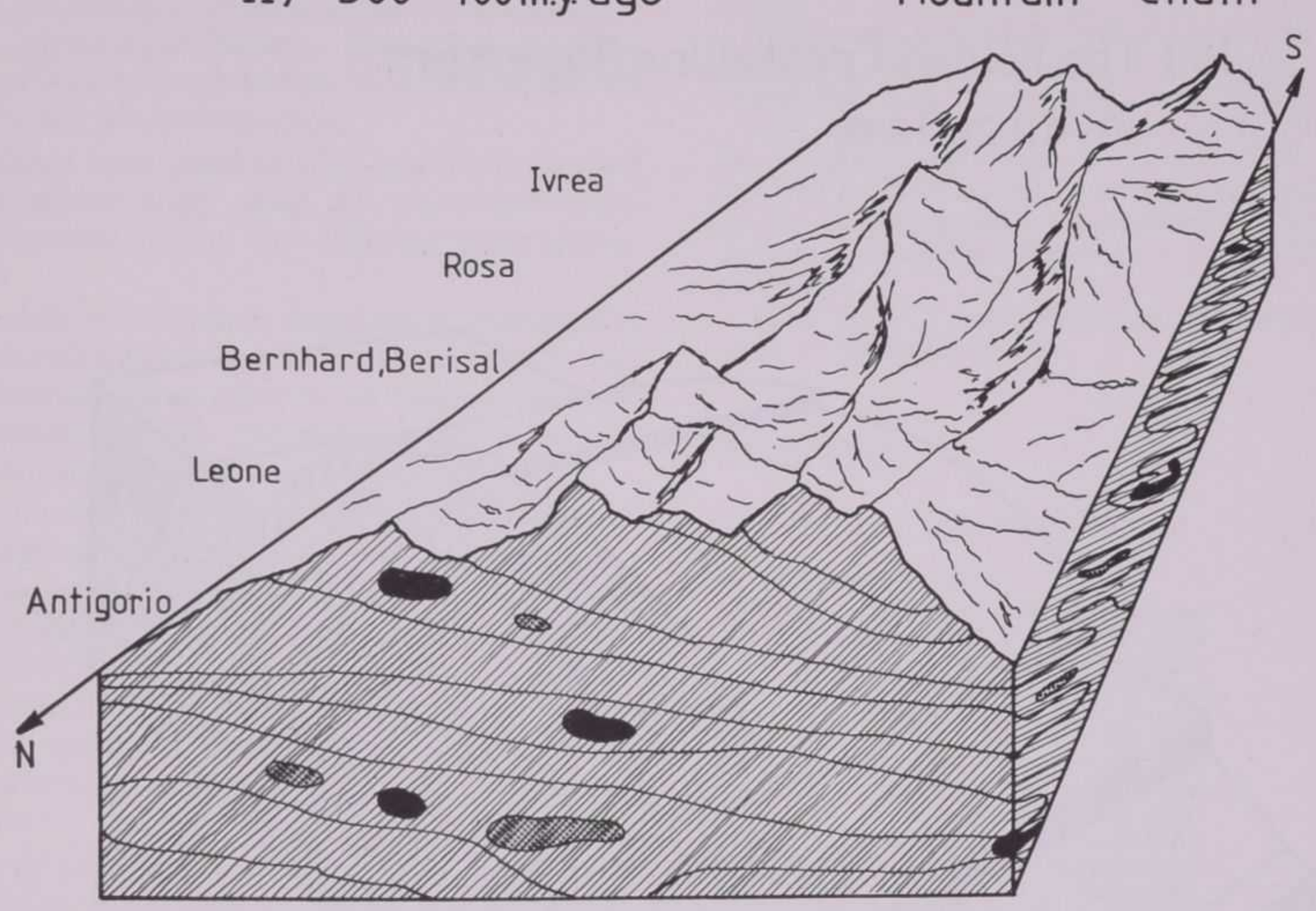


FIG. 26 - The palinspastic block diagram through the same region after the calc-alkaline activities 400 to 300 m.y. ago. This stage is characterized by isostatic movements, folding and metamorphism. The crystalline basement of the Pennine nappes is constructed. This is the earliest time during which the basic and ultrabasic rocks could have been metamorphosed into amphibolites and hornblendefelses.

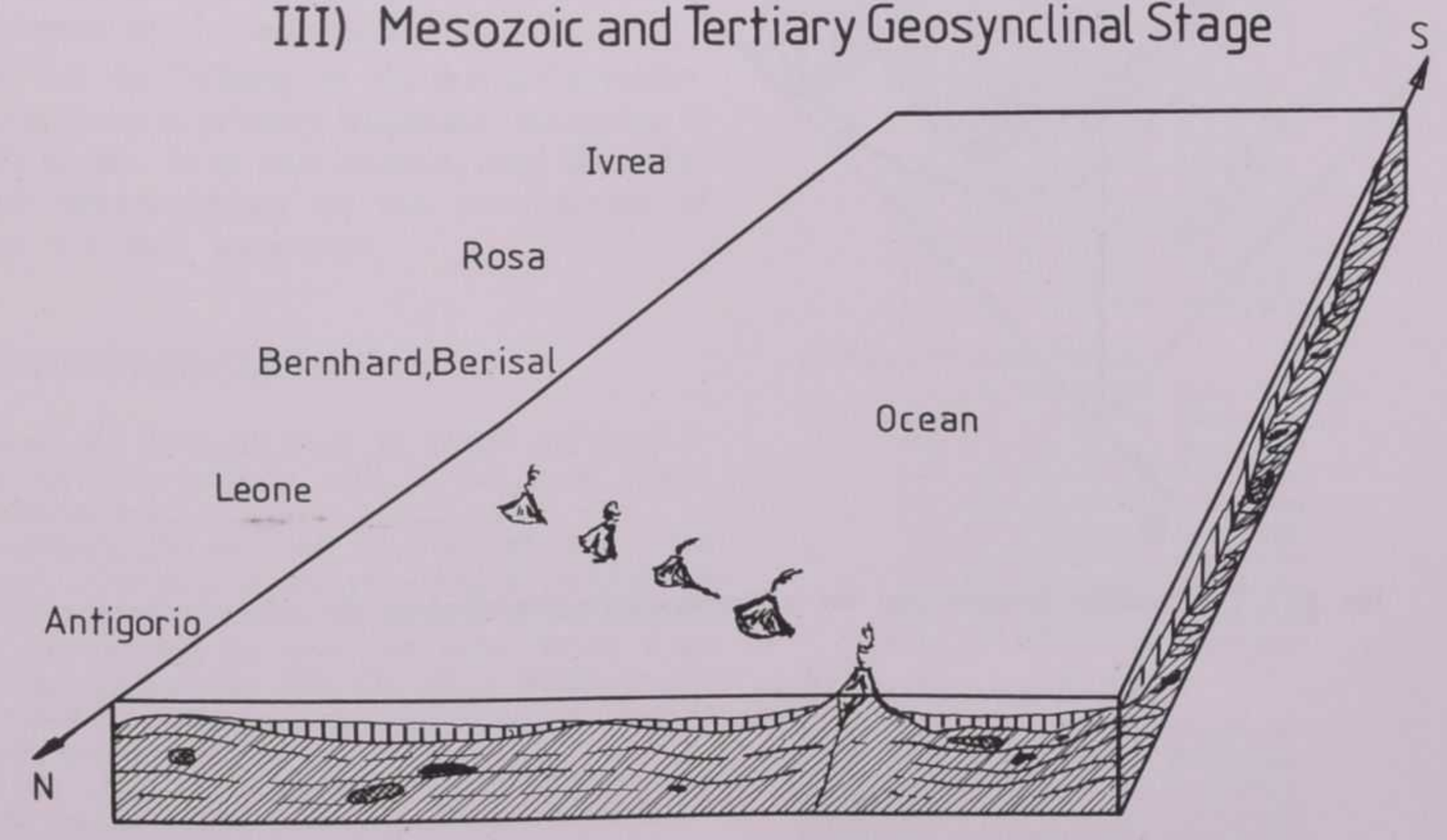


FIG. 27 - The palinspastic block diagram of the same region in Mesozoic to Tertiary time. After erosion the peneplain is recovered by the ocean. New geosynclines are formed. Sediments (« Bündnerschiefer ») start to cover the old basement.

IV) The Folded Crystalline Basement in Alpine Time

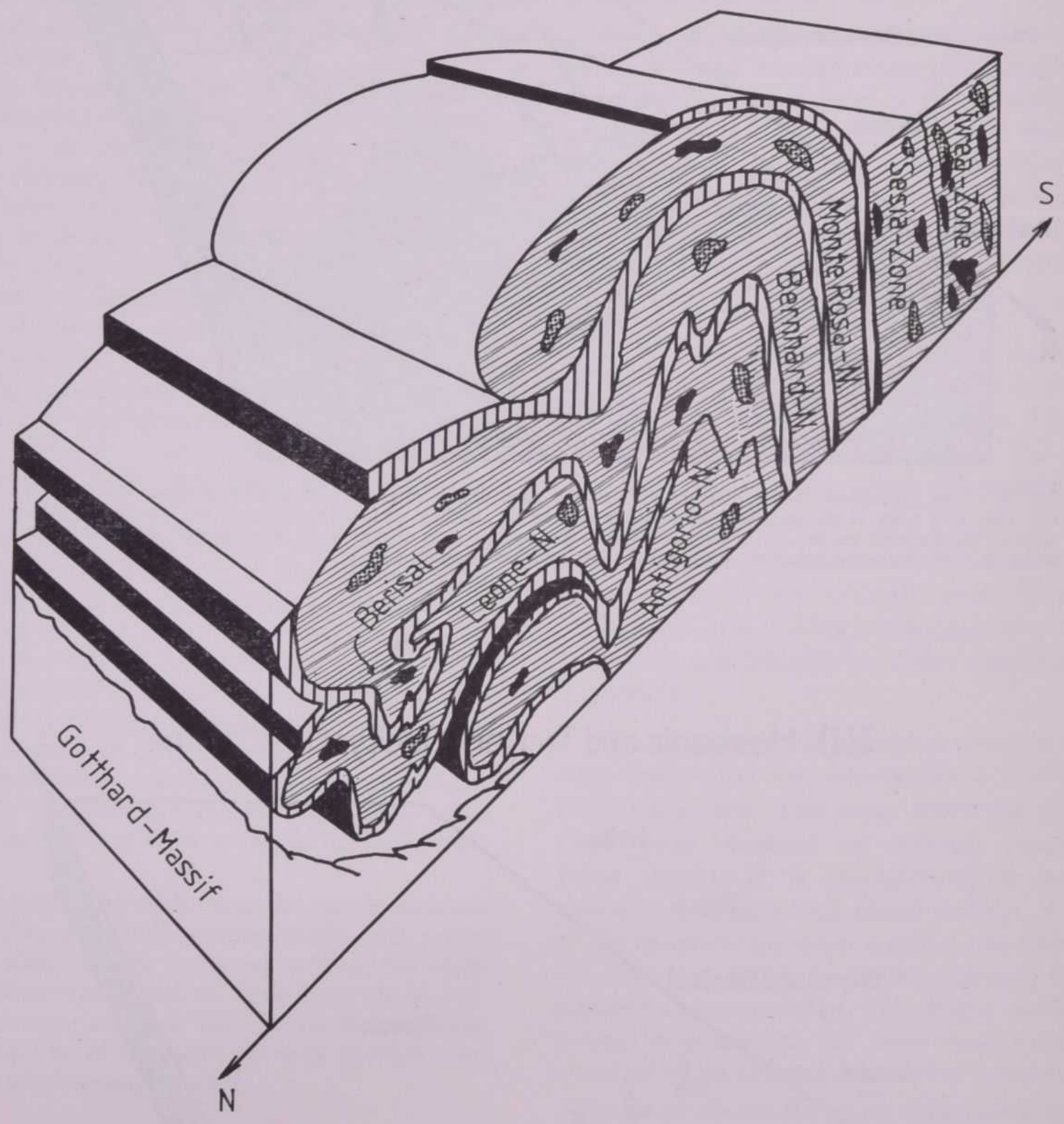


FIG. 28 - The crystalline basement and the « Bündnerschiefer » involved in the Alpine orogeny.

7. CONCLUSIONS

The microscopic investigations on hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites have shown that all of them are polymetamorphic.

Evidence from geochemistry and Rb-Sr isotope determinations show they all must have been closed systems during the different metamorphic events.

The different variation diagrams in combination with characteristic element ratios and Rb-Sr isotope determinations point to an igneous origin of the hornblendefelses, garnet-amphibolites, plagioclase-amphibolites and banded-amphibolites.

The investigations have shown that partial melting and fractional crystallization must have been very important mechanisms during the diapiric rise of the bulk source for the magma generation. The following calc-alkaline magma series exist: Pyroxenite (hornblendefels) — alkali-poor quartztholeiite (garnet-amphibolite) — quartz-tholeiite (plagioclase-amphibolite) — andesite (banded-amphibolite).

The moment of magmatic individualization must have taken place 500 m.y. ago.

The very low Sr87/Sr86-ratios of the hornblendefelses as well as the low Rb/Sr-ratios of all of the investigated rock-types and the generally sharp contacts between them and the surrounding schistose gneisses show that the present tectonic setting in the metasedimentary rocks is certainly not original. Most likely they originated in upper mantle to lower crustal regions and a cool tectonic emplacement can be considered.

How far the layering of the banded-amphibolites represents a primary magmatic formation is difficult to say. It is only certain, that the influence of metamorphism on the development of banding was very important.

8. ACKNOWLEDGMENTS

I would like to thank Prof. E. JÄGER and Prof. E. NIGGLI for their help as well as for many stimulating discussions.

The introduction of Prof. A. STRECKEISEN to the geological, mineralogical and petrological problems of the Simplon area cannot be estimated highly enough.

The introduction to and the help during x-ray fluorescence analysis by PD. Dr. W.B. STERN in the geochemical laboratory of the University of Basel is greatfully acknowledged.

PD. Dr. J.C. HUNZIKER helped to improve my ideas on the genesis of basic and ultrabasic rocks.

I would like to thank especially Dr. A. J. HURFORD correcting many English passages. Without his help the paper would not be written in English.

The introduction to and the help with computer problems by R. SIEGENTHALER is greatfully acknowledged.

With much gratitude I think of my friends Dr. J. ABRECHT, CH. BÜHLER, Dr. W. MORAUF, Dr. R. OBERHÄNSLI, H. STEINER and Dr. B. WIELAND.

The assistance in the laboratory of R. BRUNNER, Dr. K. HAMMERSCHMIDT, U. MISCHLER, K. RUFENER and L. RYTZ as well as the support of this work by the « Schweizerischer Nationalfond zur Förderung der wissenschaftlichen Forschung » is greatfully acknowledged.

Most of all I am indebted to my parents. This work is dedicated to them.

APPENDIX

SAMPLE AND LOCATION (COORD.)

a) Hornblendefelses:

KAW 1657, 652.400/127.050, Bortelgletscher
KAW 1675, 652.400/127.050, Bortelgletscher
KAW 1818, 652.400/127.050, Bortelgletscher
KAW 1820, 652.400/127.050, Bortelgletscher
KAW 1821, 652.400/127.050, Bortelgletscher
KAW 1822, 652.400/127.050, Bortelgletscher
KAW 1824, 652.400/127.050, Bortelgletscher
KAW 1825, 652.400/127.050, Bortelgletscher
KAW 1826, 652.400/127.050, Bortelgletscher
KAW 1827, 652.400/127.050, Bortelgletscher
KAW 1823, 652.260/127.120, Bortelgletscher
KAW 1819A, 648.620/123.710, Bodmertälli
KAW 1819B, 648.620/123.710, Bodmertälli
76, 652.220/126.800, Bortelhorn
77, 652.190/126.940, Bortelhorn
333, 652.260/126.920, Bortelgletscher
334, 652.260/126.920, Bortelgletscher
335, 652.260/126.920, Bortelgletscher
455, 652.890/126.120, Alpe Veglia
457, 652.890/126.120, Alpe Veglia

b) Plagioclase-amphibolites:

KAW 1654, 651.500/123.410, Monte Leone (north)
KAW 1676, 647.200/124.950, Jochtwald
KAW 1596, 648.790/126.010, Wasenalp
KAW 1816, 646.610/124.720, Chapfwald
KAW 1817, 647.200/124.670, Burst
KAW 1849, 648.860/125.980, Wasenalp
KAW 1850, 648.860/125.980, Wasenalp
36, 651.620/126.830, Bortelsee
38, 650.920/127.090, Bortelalp
207, 652.420/127.600, Pta. del Rebbio
283, 652.400/126.420, Bortellücke
332, 652.580/126.890, Pta. del Rebbio
419, 653.390/126.780, P. Taramona
322, 652.510/126.820, Bortellücke

c) Garnet-amphibolites:

60, 652.500/126.010, Cima Vallaperta
199, 127.380/127.250, Bortelgletscher
278, 652.400/126.420, Bortellücke
345, 652.350/126.600, Bortellücke
347, 652.350/126.600, Bortellücke
348, 652.350/126.600, Bortellücke
349, 652.350/126.600, Bortellücke
350, 652.350/126.600, Bortellücke
4139, 652.500/128.980, Blauseelücke
4311, 647.960/125.010, Chastelegga

d) Banded-amphibolites:

KAW 1655, 646.610/124.740, Chapfwald
KAW 1656, 648.090/123.810, Bodmertälli
KAW 1669, 648.090/123.810, Bodmertälli
KAW 1670, 648.090/123.810, Bodmertälli
KAW 1671, 648.090/123.810, Bodmertälli
KAW 1672, 653.480/125.590, Alpe Veglia
KAW 1673, 646.630/125.220, Jochtwald
KAW 1674, 647.180/124.780, Jochtwald

REFERENCES

Abraham N., Hoermann P.K., Raith M., 1974 - *Progressive metamorphism of basic rocks from the southern Hohe Tauern area. Tyrol.* N. Jb. Miner. Abh., v. 122, pp. 1-35, Stuttgart.

Barberi F., Borsi S., Ferrara G., Innocenti F., 1969 - *Strontium isotopic composition of some recent basic volcanites.* Contr. Mineral. Petrol., v. 23, pp. 157-172, Berlin.

Barker F., Petermann Z.E., 1974 - *Tholeiitic-dacitic magmatism and the early precambrian crust.* Precambian Research, v. 1, pp. 1-12, Amsterdam.

Barrer R.M., 1941 - *Oiffusion in and through solids.* Cambridge University Press, 464 p., Cambridge.

Bearth P., 1956 - *Geologische Beobachtungen im Grenzgebiet der lepontinischen und penninischen Alpen.* Ecl. Geol. Helv., v. 49, pp. 279-290, Basel.

Bearth P., 1956 - *Zur Geologie der Wurzelzone östlich des Ossolatales.* Ecl. Geol. Helv., v. 49, pp. 267-278, Basel.

Bearth P., 1958 - *Ueber einen Wechsel der Mineralfazies in der Wurzelzone des Penninikums.* SMPM, v. 38, pp. 363-373, Zürich.

Bearth P., Nabholz W., Streckeisen A., Wenk E., 1967 - *Simplonpass: Brig-Domodossola.* Geol. Führer der Schweiz. Exkursion Nr. 20. Wepf, Basel.

Bickle M., Pearce J., 1975 - *Oceanic mafic rocks in the Eastern Alps.* Contr. Mineral. Petrol., v. 49, pp. 177-189, Berlin.

Bowes D.R., Park R.G., 1966 - *Metamorphic segregation banding in the Loch Kerry Basite Sheet from the Lewisian of Gairloch Ross-shire, Scotland.* J. Petr., v. 7, pp. 306-330, Oxford.

Bowes D.R., Bhattacharjee C.C., 1967 - *The metamorphic and migmatitic history of the Lewisian rocks north-west of Loch Tollie, Ross-shire, Scotland.* Krystallinikum, v. 5, pp. 7-61, Prag.

Brooks C., Hart S.R., Wendt J., 1972 - *Realistic use of two-error regression treatments as applied to Rb-Sr-data.* Rev. of Geophys. a. Spac. Phys., v. 10/2, pp. 551-557, Washington.

Burri C., 1959 - *Petrochemische Berechnungsmethoden.* Birkhäuser Verlag, 334 p., Basel.

Cann J.R., 1970 - *Rb, Sr, Y, Zr and Nb in some ocean floor basaltic rocks.* Earth Plan. Sc. Lett., v. 10, pp. 7-11, Amsterdam.

Carmichael I.S.E., Turner F.J., Verhoogen J., 1974 - *Igneous petrology.* Mc Graw-Hill Book Comp., p. 739, New York.

Chatterjee N.D., 1961 *The alpine metamorphism in the Simplon area. Switzerland and Italy.* Geol. Rund., v. 51, pp. 1-72, Stuttgart.

Clark P., Jaeger E., 1969 - *Denudation rate in the alps from geochronologic- and heat flow data.* Am. J. Sc., v. 267, pp. 1143-1160, New Haven.

Colemann R.G., Lee D.E., Beatty L.B., Brannock W.W., 1965 - *Eclogites and eclogites, their differences and similarities.* Bull. Geol. Soc. Am., v. 76, pp. 483-508, Boulder.

Davis J.C., 1973 - *Statistics and data analysis in geology.* John Wiley & sons, Inc., 550 p., New York.

Degenhardt H., 1956 - *Untersuchungen zur geochemischen Verteilung des Zirkoniums in der Lithosphäre.* Geoch. Cosm. Acta, v. 2, pp. 279-309, London.

Dietrich R.V., 1960 - *Banded gneisses.* J. Petr., v. 1, pp. 99-120, Oxford.

Dougan Th. W., 1975 - *Origin of trondhjemitic biotite-quartz-oligoclase gneisses from the Venezuelan Guyana Shield.* Precambrian Res., v. 3, pp. 317-342, Amsterdam.

Duthou J.L., 1976 *Nouvelles données geochimiques relatives à quelques orthoamphibolites du Limousin.* C.R. Acad. Sc. Paris, v. 282, série D, p. 337, Paris.

Duthou J.L., 1977 - *Chronologie Rb-Sr et geochimie des granitoides d'un segment de la chaine varisque; relations avec le metamorphisme (Massif Central).* Ann. Sc. de l'université de Clermont, v. 63, p. 294, Clermont Ferrand.

Elliott R.B., 1972 - *The chemistry of gabbro/amphibolite transitions in South Norway.* Contr. Mineral. Petrol., v. 38, pp. 71-79, Berlin.

Engel A.E., Engel C.G., 1962 - *Hornblendes formed during progressive metamorphism of amphibolites, north-west Adirondack Mountains,* New York. Bull. Geol. Soc. Am., v. 73, pp. 1499-1514, Boulder.

Engel A.E., Engel C.G., Havens R.G., 1964 - *Mineralogy of amphibolite interlayers in the gneiss complex, northwest Adirondack Mountains,* New York. J. Geol., v. 72/2, pp. 131-156, Chicago.

Escher A., Watterson J., 1974 - *Stretching fabrics, folds and crustal shortening.* Tectonophysics, v. 22, pp. 223-231, Amsterdam.

Escher A., Escher J.C., Watterson J., 1975 - *The reorientation of the Kangâmiut Dike Swarm, West-Greenland.* Can. J. of Earth Sc., v. 12, pp. 158-173, Ottawa.

Eskola P., 1932 - *On the principles of metamorphic differentiation.* Bull. Comm. géol. Finl., v. 97, pp. 68-77, Helsinki.

Evans B.W., Leake B.E., 1960 - *The composition and origin of the striped amphibolites of Connemara, Ireland.* J. Petr., v. 1, pp. 337-362, Oxford.

Fabries J., 1966 - *The nature of hornblendes and metamorphic types.* Inter. Mineral. Assoc. Meeting, Cambridge, Abstr.

Faure G., 1977 - *Principles of isotope geology.* J. Wiley & sons, p. 464, New York.

Faure G., Hurley P.M., 1963 - *The isotopic composition of Sr in oceanic and continental basalts. Application to the origin of igneous rocks.* J. Petr., v. 4, pp. 31-50, Oxford.

Field D., Eliott R.B., 1974 - *The chemistry of gabbro/amphibolite transitions in South Norway. Trace elements.* Contr. Mineral. Petrol., v. 47, pp. 63-76, Berlin.

Floyd P.A., Winchester J.A., 1975 - *Magma type and tectonic setting discrimination using immobile elements.* Earth Plan. Sc. Lett., v. 27, pp. 211-218, Amsterdam.

Fluegel H., Schoenlaub H.P., 1972 - *Geleitworte zur stratigraphischen Tabelle des Paläozoikums von Oesterreich.* Verh. Geol. Bundesanst. Wien, pp. 197-198, Wien.

Forbes R.B., 1965 - *The comparative chemical composition of eclogite and basalt.* J. of Geophys. Res., v. 70/6, pp. 1515-1521, Richmond.

Francis G.H., 1958 - *The amphibolite of Doir'a Chatha (Durcha), Sutherland.* Geol. Mag., v. 95/1, pp. 25-40, London.

Frank E., 1979 - *Metamorphose mesozoischer Gesteine im Querprofil Bri-Verampio: Mineralogisch-petrographische und isotopengeologische Untersuchungen.* Unpubl, thesis, Bern.

Frank W., Klein P., Nowy W., Scharbert S., 1976 - *Die Datierung geologischer Ereignisse im Altkristallin der Gleinalpe (Steiermark) mit der Rb/Sr-Methode.* Tsch. Min. Petr. Mitt., v. 23, pp. 191-203, Wien.

Froehlich F., 1960 - *Ein Beitrag zur Geochemie des Chroms.* Geoch. Cosm. Acta, v. 20, pp. 215-240, Oxford.

Gale G.H., Roberts D., 1974 - *Trace elements geochemistry of Norwegian lower palaeozoic basic volcanics and its tectonic implications.* Earth Plan. Sc. Lett., v. 22, pp. 380-390, Amsterdam.

Gast P.W., 1968 - *Trace element fractionation and the origin of tholeiitic and alkaline magma types.* Geoch. Cosm. Acta, v. 32, pp. 1057-1086, Oxford.

Gerlach H., 1869 - *Die penninischen Alpen.* Neue Denkschr. d. Schweiz. Nat. Ges., v. 23, 132 p., Basel.

Gittins J., Hayatsu A., York D., 1969 - *A strontium isotope study of metamorphosed limestones.* Lithos, v. 3, pp. 51-59, Oslo.

Goldberg E.D., Arrhenius G.O., 1958 - *Chemistry of pacific pelagic sediments. Geoch.* Cosm. Acta, v. 13, pp. 153-212, London.

Gorbachev O.V., 1971 - *Ratios of pairs of similar elements in amphibolites are related to its origin.* Dok., v. 208, pp. 432-434, Silver Spring.

Green D.H., Ringwood A.E., 1967 - *The genesis of basaltic magmas.* Contr. Mineral. Petrol., v. 15, pp. 103-190, Berlin.

Green T.H., Ringwood A.E., 1968 - *Genesis of the calc-alkaline igneous rock suite.* Contr. Mineral. Petrol., v. 18, pp. 105-162, Berlin.

Green T.H., Ringood A.E., 1972 - *Crystallization of garnet-bearing rhyodacite under high pressure hydrous conditions.* J. Geol. Soc. Aust., v. 19, pp. 203-212.

Griffin W.L., Murthy V.R., Phimcy W.C., 1967 - *K/Rb in amphiboles and amphibolites from north-eastern Minnesota.* Earth Plan. Sc. Lett., v. 3, pp. 367-370, Amsterdam.

Günthert A., 1956 - *Ueber den Zusammenhang der Antigorio- und Monte Leone-Decke im Tessin. Eine tektonische Deutung.* Ecl. Geol. Helv., v. 49, pp. 151-156, Basel.

HARTE B., GRAHAM C.M., 1975 - *The graphical analysis of greenschist to amphibolite facies. Mineral-assemblages in metabasites.* J. Petr., v. 16, pp. 347-370, Oxford.

HASHIMOTO M., 1972 - *Reactions producing actionalite in basic metamorphic rocks.* Lithos, v. 5, pp. 19-31, Oslo.

HEZNER L., 1903 - *Ein Beitrag zur Kenntnis der Eklogite und Amphibolite.* Thesis, Zürich.

HIRST D.M., 1962 - *The geochemistry of modern sediments from the Gulf of Pavia-II; the location and distribution of trace elements.* Geoch. Cosm. Acta, v. 26, pp. 309-334, Oxford.

HOERMANN P., RAITH M., 1973 - *Bildungsbedingungen von Al-Fe (III) - Epidoten.* Contr. Mineral. Petrol., v. 38, pp. 307-320, Berlin.

HOLDAWAY M.J., 1972 - Thermal stability of Al-Fe-epidote as a function of fo_2 and Fe content. Contr. Mineral. Petrol., v. 37, pp. 307-340, Berlin.

HUNZIKER J.C., BEARTH P., 1969 - *Rb-Sr-Altersbestimmungen aus den Walliser Alpen. Biotitalterswerte und ihre Bedeutung für die Abkühlungsgeschichte der alpinen Metamorphose.* Ecl. Geol. Helv., v. 62/1, pp. 205-223, Basel.

HUNZIKER J.C., 1969 - *Rb-Sr-Altersbestimmungen aus den Walliser Alpen. Hellglimmer- und Gesamtgesteinsalterswerte.* Ecl. Geol. Helv., v. 62/2, pp. 527-542, Basel.

HUNZIKER J.C., 1970 - *Polymetamorphism in the Monte Rosa, Western Alps.* Ecl. Geol. Helv., v. 63/1, pp. 151-162, Basel.

HUNZIKER J.C., 1974 - *Rb-Sr and K-Ar age determinations and the alpine tectonic history of the Western Alps.* Mem. Ist. Geol. Min. Univ. Padova, v. 31, 54 pp., Padova.

HURLEY P.M., 1968 - *Absolute abundance and distribution of Rb, K, and Sr in the earth.* Geoch. Cosm. Acta, v. 32, pp. 273-283, Oxford.

JÄGER E., 1969 - *Colloquium on the geochronology of phanerozoic orogenic belts, guide book, Bern and Zürich.*

JÄGER E., 1969 - *Radiometrische Altersbestimmung in der Erforschung metamorpher Prozesse.* Fortschr. Min., v. 47, pp. 77-83, Stuttgart.

JÄGER E., 1971 - *Die Geschichte des alpinen Raumes, erarbeitet mit radiometrischen Altersbestimmungen.* Verh. Geol. B.-A., v. 2, pp. 250-254, Wien.

JÄGER E., 1973 - *Die alpine Orogenese im Lichte der radiometrischen Altersbestimmung.* Ecl. Geol. Helv., v. 66/1, pp. 11-21, Basel.

JÄGER E., HUNZIKER J.C., 1979 - *Isotope Geology.* Springer Verlag, 329 p., Berlin.

JANDA J., SCHROLL E., SEDLAZEK M., 1965 - *Zum Problem der geochemischen Unterscheidung von Para- und Orthoamphiboliten am Beispiel einiger Vorkommen des Waldviertels und der Ostalpen.* Tsch. Min. Petr. Mitt. v. 10, pp. 552-572, Wien.

KALSBEEK F., 1965 - *On the origin of some banded amphibolites and gneisses in the Belledonne massif.* N. Jb. Mineral. Abh., v. 102/2, pp. 177-188, Stuttgart.

KALSBEEK F., LEAKE B., 1970 - *The chemistry and origin of some basement amphibolites between Ivigtut and Frederikshab,* South-West Greenland. Grønlands Geologiske Undersøgelse, v. 90, pp. 5-23, Kopenhagen.

KATZ M.B., 1970 - *Banded gneisses.* Lithos, v. 3, pp. 1-13, Oslo.

KÖPPEL V., GRÜNENFELDER M., 1969 - *Colloquium on the geochronology of phanerozoic belts,* guide book, Bern and Zürich.

KRETZ R., 1966 - *Metamorphic differentiation at Einasleigh, Northern Queensland.* J. Geol. Soc. Aust., v. 13/2, pp. 561-582.

KUKLEY L.N., 1975 - *Origin of amphibolites of the precambrian Ol'khonsk series (Northwestern Baykal region).* Trans. from. Geokhimiya, v. 1, pp. 26-35, Moscow.

LA ROCHE H. DE, 1963 - *Sur l'expression graphique des relations entre la composition chimique et la composition minéralogique quantitative des roches cristallins.* Sci. de la terre, v. 9, p. 293, Nancy.

LA ROCHE H. DE, 1966 - *Sur l'existence de plusieurs facies geochimiques dans les schistes paleozoiques des Pyrenées Luchonnaises.* Geol. Rund., v. 55/2, pp. 274-300, Stuttgart.

LA ROCHE H. DE, 1972 - *Revue sommaire de quelques diagrammes chimico-minéralogiques pour l'étude des associations ignées ou sedimentaires et de leurs dérivés métamorphiques.* Sci. de la terre, v. 17, pp. 31-46, Nancy.

LEAKE B.E., 1958 - *Composition of pelites from Connemara, Co. Galway, Ireland.* Geol. Mag., v. 9, pp. 281-296, Hertford.

LEAKE B.E., 1964 - *The chemical distinction between ortho- and para-amphibolites.* J. Petr., v. 5, pp. 238-254, Oxford.

LEAKE B.E., 1968 - *The chemical analysis of rock powders by automatic X-ray fluorescence.* Chem. Geol., v. 5, pp. 7-86, Amsterdam.

LEAKE B.E., 1969 - *The discrimination of ortho- and paracharnockitic rocks, anorthosites and amphibolites.* The Indian Mineral., v. 10, pp. 89-104.

LIOU J.G., 1973 - *Synthesis and stability relations of epidote.* J. Petr., v. 14, pp. 381-413, Oxford.

MAARTEN J. DE WIT, STRONG D.F., 1975 - *Eclogite-bearing amphibolites from the appalachian mobile belt, Northwest-Newfoundland: dry versus wet metamorphism.* J. Geol., v. 83, pp. 609-627, Chicago.

METZ P., 1970 - *Experimentelle Untersuchung der Metamorphose von kieselig dolomitischen Sedimenten.* Contr. Mineral. Petrol., v. 28, pp. 221-250, Berlin.

MEHNERT K.R., 1968 - *Migmatites and the origin of granitic rocks.* Elsevier publishing comp., 393 p., Amsterdam.

MILNES A.G., 1969 - *On the orogenic history of the Central Alps.* J. Geol., v. 77, pp. 108-112, Chicago.

MILNES A.G., 1968 - *Strain analysis of the basement nappes in the Simplon region, Northern Italy.* XXIII international geol. Congr. 3.

MILNES A.G., 1973 - *Structural reinterpretation of the classic Simplon tunnel section of the Central Alps.* Bull. Geol. Soc. Am., v. 84, pp. 269-274, Boulder.

MILNES A.G., 1974 - *Post-nappe-folding in the western lepontine Alps.* Ecl. Geol. Helv., v. 67/2, pp. 333-348, Basel.

MYASHIRO A., 1975 - *Classification and origin of ophiolithes.* J. Geol., v. 83, pp. 249-281, Chicago.

MOINE B., LA ROCHE H. DE, 1968 - *Nouvelle approche du problème de l'origine des amphibolites à partir de leur composition chimique.* C.R. Acad. Sc. Paris, v. 267, pp. 2084-2087, Paris.

MOTTANA A., EDGAR A.D., 1969 - *The significance of amphibole compositions in the genesis of eclogites.* Lithos, v. 3, pp. 37-49, Oslo.

MORGAN B.A., 1970 - *Petrology and mineralogy of eclogite and garnet-amphibolite from Puerto Cabello, Venezuela.* J. Petr., v. 2, pp. 101-115, Oxford.

NIGGLI E., 1969 - *Alpine Metamorphose und alpine Gebirgsbildung.* Fortschr. Mineral., v. 47, pp. 16-26, Stuttgart.

NIGGLI P., 1936 - *Die Magmentypen.* SMPM, v. 16, pp. 335-399, Zürich.

NOCKOLDS S.R., 1954 - *Average chemical composition of some igneous rocks.* Bull. Geol. Soc. Am., v. 65, pp. 1007-1032, Boulder.

NOCKOLDS S.R., 1956 - *Geochemistry of some igneous rocks series.* Geoch. Cosm. Acta, v. 9, pp. 34-77, Oxford.

O'NIONS R.K., PANKHURST R.J., 1974 - *Petrogenetic significance of isotope and trace element variations in volcanic rocks from the Mid-Atlantic.* J. Petr., v. 15, pp. 603-634, Oxford.

O'NIONS R.K., EVENSEN N.M., HAMILTON P.J., CARTER S.R., 1978 - *Melting of the mantle past and present: isotope and trace element evidence.* Phil. Trans. R. Soc. Lond. A. 258, pp. 547-559, London.

ORVILLE PH. M., 1969 - *A model for metamorphic differentiation origin of thin-layered amphibolites.* Am. J. Sci., v. 267, pp. 64-87, New Haven.

PAYNE J.G., SHAW D.M., 1967 - *K-Rb-relations in the Blue Mountain nepheline-syenite.* Earth Plan. Sc. Lett., v. 2, pp. 290-292, Amsterdam.

PEARCE J.A., CANN J.R., 1973 - *Tectonic setting of basic volcanic rocks determined using trace element analyses.* Earth Plan. Sc. Lett., v. 19, pp. 290-300, Amsterdam.

PEARCE J.A., 1974 - *Statistical analysis of major element patterns in basalts.* J. Petr., v. 17, pp. 15-43, Oxford.

PETERMAN Z.E., HEDGE C.E., 1971 - *Related Sr-isotopic and chemical variations in oceanic basalts.* Bull. Geol. Soc. Am., v. 82, pp. 493-500, Boulder.

Plimer I.R., 1975 - *The geochemistry of amphibolite retrogression at Broken Hill, Australia.* N. Jb. Miner. Mh., v. 10, pp. 471-481, Stuttgart.

Poldervaart A., Walker F., 1949 - *Karroo Dolerites of the Union of South Africa.* Bull. Geol. Soc. Am., v. 60, pp. 591-706, Boulder.

Poldervaart A., 1953 - *Metamorphism of basaltic rocks: a review.* Bull. Geol. Soc. Am., v. 64, pp. 259-274, Boulder.

Potter P.E., Shimp N.F., Witters J., 1963 - *Trace elements in marine and fresh-water argillaceous sediments.* Geoch. Cosm. Acta, v. 27, pp. 669 - 694, Oxford.

Ragni M., 1960 - *Studio geologico-petrografico dei complessi metamorfici della zona di Alpe Veglia.* Thesis, unpubl..

Ringwood A.E., 1955 - *The principles governing trace element distribution during magmatic crystallization.* Geoch. Cosm. Acta, v. 7, pp. 189-202, Oxford.

Ringwood A.E., 1973 - *Composition and petrology of the Earth's Mantle.* Mc Graw-hill book comp., p. 618, New York.

Rivalenti G., Rossi A., 1975 - *Geochemistry of precambrian amphibolites in an area near Fiskenaesset, South-West-Greenland.* Boll. Soc. Geol. It., v. 94, pp. 27-49, Roma.

Rivalenti G., Sighinolfi G.P., 1969 - *Geochemical study of graywackes as a possible starting material of para-amphibolites.* Contr. Mineral. Petrol., v. 23, pp. 173-188, Berlin.

Robinson D., Leake B.E., 1975 - *Sedimentary and igneous trends on AFM-diagrams.* Geol. Mag., v. 112, pp. 305-307, London.

Roubault M., La Roche H. De, 1966 - *Parallele entre la géochimie des schistes paléozoiques et celle des formations granitiques dans le massif du Lys-Caillaouas (Pyrenées centrales).* Geol. Rund., v. 55, pp. 301-315, Stuttgart.

Sander B., 1912 - *Ueber einige Gesteinsgruppen des Tauernwestendes.* Jb. K. K. Geol. R.-A., v. 62/2, pp. 219-288, Wien.

Schafroth M., 1978 - *Statplot.* Thesis, Bern.

Schardt H., 1903 - *Note sur le profil géologique et la tectonique du massif du Simplon.* Ecl. Geol. Helv., v. 8, pp. 173-200, Basel.

Schmidt C., 1908 - *Die Geologie des Simplongebirges und des Simplontunnels.* Rektorats-Programm der Univ. Basel.

Schmidt C., Preiswerk H., 1908 - *Erläuterungen zur geologischen Karte der Simplongruppe.* Geol. Karte d. Schweiz.

Schroll E., Grohmann H., 1966 - *Ein Beitrag zur Kenntnis des K/Rb-Verhältnisses in magmatischen Gesteinen.* Geol. Rund., v. 55/2, pp. 261-264, Stuttgart.

Shaw D.M., 1954 - *Trace elements in pelitic rocks.* Bull. Geol. Soc. Am., v. 65, pp. 1167-1182, Boulder.

Shaw D.M., 1954 - *Trace elements in pelitic rocks. Variations during metamorphism.* Bull. Geol. Soc. Am., v. 65, pp. 1151-1166, Bouder.

Shaw D.M., 1956 - *Geochemistry of pelitic rocks. Major elements and general geochemistry.* Bull. Geol. Soc. Am., v. 67, pp. 919-934, Boulder.

Shaw D.M., Kudo A.M., 1965 - *A test of the discriminant function in the amphibolite problem.* Min. Mag., v. 34, pp. 423-435, London.

Shaw D.M., 1972 - *The origin of the Apsley Gneiss, Ontario.* Can. J. of Earth Sciences, v. 9, pp. 18-36, Ottawa.

Sigvaldason G.E., 1974 - *Basalts from the centre of the assumed icelandic mantle plume.* J. Petr., v. 15, pp. 497-524, Oxford.

Slaughter J., Kerrick D.M., Wall V.J., 1975 - *Experimental and thermodynamic study of equilibria in the system CaO-MgO-SiO_2-H_2O-CO_2.* Am. J. Sc., v. 275, pp. 143-162, New Haven.

Spry A., 1974 - *Metamorphic textures.* Pergamon Press Ltd., p. 571, Oxford.

Steiger R.H., Jäger E., 1977 - *Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology.* Earth Plan. Sc. Lett., v. 36, pp. 359-362, Amsterdam.

Stern W.B., 1972 - *Zur röntgenspektrometrischen Analyse von silikatischen Gesteinen und Mineralien.* SMPM, v. 52, pp. 1-25, Zürich.

Streckeisen A., 1974 - *On steep isogradic surfaces in the Simplon Area.* Contr. Mineral. Petrol., v. 47, pp. 81-95, Berlin.

Strong D.F., 1974 - *Plateau lavas and diabase dikes of northwestern Newfoundland.* Geol. Mag., v. 3, pp. 501-514, London.

Taylor S.R., 1955 - *The origin of some New Zealand metamorphic rocks as shown by their major and trace element composition.* Geoch. Cosm. Acta, v. 8, pp. 182-197, Oxford.

Thornton C.P., Tuttle O.F., 1960 - *Chemistry of igneous rocks.* Am. J. Sc., v. 258, pp. 664-684, New Haven.

Trommsdorff V., 1972 - *Change in T-X during metamorphism of siliceous dolomitic rocks of the Central Alps.* SMPM, v. 52/3, pp. 567-571, Zürich.

Turekian K.K., Kulp P., 1956 - *The geochemistry of Sr.* Geoch. Cosm. Acta, v. 10, pp. 245-296, Oxford.

Turekian K.K., 1963 - *The chromium and nickel distribution in basaltic rocks and eclogites.* Geoch. Cosm. Acta, v. 27, pp. 835-836, Oxford.

Van De Kamp P.C., 1968 - *Geochemistry and origin of metasediments in the Haliburton-Madoc area, southeastern Ontario.* Can. J. of Earth Sciences, v. 5, pp. 1337-1371, Ottawa.

Van De Kamp P.C., 1969 - *Origin of amphibolites in the Beartooth Mountains, Wyoming and Montana: New data and interpretation.* Bull. Geol. Soc. Am., v. 80, pp. 1127-1136, Boulder.

Van De Kamp P.C., Leake B.E., Senior A., 1976 - *The petrography and geochemistry of some californian arkoses with application to identifying gneisses of metasedimentary origin.* J. Geol., v. 84, pp. 195-212, Chicago.

Vidale R., 1973 - *Metamorphic differentiation layering in pelitic rocks of Dutchess County, New York.* In: Geochemical transport and kinetics, edited by Hofmann, Giletti, Yoder and Yund, pp. 273-286, Washington.

Von Raumer J.F., 1974 - *Zur Metamorphose amphibolitischer Gesteine im Altkristallin des Mont Blanc- und Aiguilles Rouges-Massivs.* SMPM, v. 54, pp. 471-488, Zürich..

Wager L.R., Mitschell R.L., 1953 - *Trace elements in a suite of Hawaiian lavas.* Geoch. Cosm. Acta, v. 3, pp. 217-223, Oxford.

Weber-Diefenbach K., 1976 - *Zur Geochemie und Metamorphose von Amphiboliten der Greiner Schiefer-Serie.* Tsch. Min. Petr. Mitt., v. 23, pp. 1-22, Wien.

Wedepohl K.H., 1959 - *Spurenanalytische Untersuchungen an Tiefseetonen aus dem Atlantik.* Geoch. Cosm. Acta, v. 18, pp. 200-231, Oxford.

Wedepohl K.H., 1969 - *Handbook of Geochemistry.* Springer, Berlin.

Weisbrod A., 1969 - *Caractères géochimiques et origine des schistes amygdalaires des Cévennes.* C.R. Acad. Sc. Paris, v. 268, pp. 3018-3020, Paris

Wenk E., 1936 - *Zur Genese der Bändergneise von Ornö Huvud.* Bull. Geol. Inst. Univ. Uppsala, v. 26, pp. 53-89, Uppsala.

Wenk E., Keller F., 1969 - *Isograde in Amphibolitserien der Zentralalpen.* SMPM, v. 49, pp. 157-198, Zürich.

Wenk E., Schwander H., Stern W., 1974 - *On calcic amphiboles and amphibolites from the lepontine Alps.* SMPM, v. 54, pp. 97-149, Zürich.

Wenk E., 1975 - *Zur alpinen Metamorphose.* SMPM, v. 55, pp. 116-125, Zürich.

Wetzel R., 1974 - *Hornblenden aus der Albit- bis Oligoklas-Zone zwischen Zermatt und Domodossola.* SMPM, v. 54, pp. 151-207, Zürich.

Winchester J.A., Floyd P.A., 1976 - *Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks.* Earth Plan. Sc. Lett., v. 28, pp. 459-469, Amsterdam.

Winchester J.A., 1976 - *Different Moinian amphibolite suites in northern Ross-shire.* Scott. J. Geol. v. 12, pp. 187-204, Edinburgh.

Windley B.F., 1976 - *The evolving continents.* J. Wiley & sons.

Wüthrich H., 1965 - *Rb-Sr Altersbestimmungen am alpin metamorph überprägten Aarmassiv.* SMPM, v. 45, pp. 875-971, Zürich.

Zakrutkin V.V., Trufanov V.N., Dudakov V.K., 1973 - *New method for determining the primary nature of mafic metamorphic rocks.* Dok., v. 217, pp. 446-448, Silver Spring.