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Autor: Sharma, Ram S.

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On Banded Gneisses and Migmatites from Lavertezzo and Rozzera (Valle Verzasca, Canton Ticino)

By *Ram S. Sharma* (Basel) *)

With 26 figures in the text, 14 tables and 4 plates

Summary

Two representative outcrops in the same gneiss complex of the Verzasca Valley, Canton Ticino, developed as banded gneisses at Lavertezzo and as irregularly-veined migmatites at Rozzera, are described and discussed in detail. Both outcrops are situated in the migmatite-zone between the trondhjemitic core of leucocratic Verzasca-gneiss and the surrounding mantle of mesocratic paragneiss and amphibolite. Field and laboratory studies have shown that there is no fundamental difference regarding the origin of the rocks in both outcrops; they are the result of partial melting under the same PT-conditions during Tertiary regional metamorphism. The banded structure in the rocks of Lavertezzo is produced by differential movements belonging to the main phase of the Alpine metamorphism.

In the light of regional geological studies by E. Wenk (1943, 1962) the outcrops of Lavertezzo and Rozzera can be regarded as examples demonstrating partial anatectic mobilisation accompanying, and outlasting, the differential movements, respectively.

Riassunto

Due affioramenti caratteristici dello stesso ricoprimento della Valle Verzasca, Cantone Ticino, vi vengono descritti ed interpretati. Si tratta di gneiss a bande a Lavertezzo e di migmatiti dalle vene irregolari a Rozzera. Ambedue gli affioramenti si trovano nella zona migmatitica fra il nucleo trondhjemitico del gneiss leucocratico tipo Verzasca e la sua coltre composta di paragneiss mesocratico e anfibolite. Gli studi di campagna e laboratorio hanno indicato che non c'è nessuna differenza fondamentale nella genesi delle rocce d'ambedue gli affioramenti, sono il prodotto d'una rifusione parziale alle stesse condizioni di temperatura e di pressione, durante il metamorfismo regionale terziario. La struttura a bande delle rocce di Lavertezzo si è formata tramite movimenti differenziali durante la fase principale del metamorfismo alpino.

Secondo gli studi geologici regionali di E. Wenk (1943, 1962), codesti due affioramenti possono essere interpretati come esempi di mobilitazione anatectica parziale, la quale si è formata, a Lavertezzo, durante i movimenti differenziali e a Rozzera anche dopo.

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*) Mineralogisch-Petrographisches Institut der Universität Basel. Present address: Dept. of Geology, Banaras Hindu University, India.

Contents

Preface

The present work was carried out under the guidance of Professor Dr. E. Wenk.

The field-mapping was undertaken during the summer and autumn months of 1965 to 1967. Laboratory studies and data-compilations were made at the Institute of mine-

ralogy and petrography in the University of Basle. During the investigation I received help from many individuals who are mentioned below.

I wish to express my sincere gratitude to Professor E. Wenk for entrusting to me this problem and for his overall guidance and great help. For having introduced me to the regional geology during several excursions in the Alps, and for his personal contact, I offer him my cordial thanks.

I owe sincere thanks to Professor Dr. P. Bearth for his valuable criticism; to Professor Dr. H. Schwander and Dr. W. B. Stern for the chemical analyses of my rocks and minerals; to Dr. A. Steck and Dr. F. Keller for their suggestions on several text-figures and sketches and for stimulating discussions; to Dr. V. Trommsdorff, P.D., for help in the rotation of the petrofabric diagrams; and to Dr. R. Schmid for programming chemical analyses to test my calculations.

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I am deeply indebted to family Irene-Angelo Bisi (Brione) who afforded constant hospitality in their home during the course of my field work. I also gratefully acknowledge the kind cooperation and courtesy offered by the people of the Valley.

It is also with extreme pleasure that I record my happy association with Dr. A. Günthert, J. Hansen, J. Arnoth, M. Joos, P. Moticska, R. Wetzel, A. Vgenopoulos, and C. Wenk.

Finally, I express sincere appreciation to my wife whose inspiration stimulated the research work.

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INTRODUCTION

1. Regional Geology of the Verzasca Valley[1]

The Verzasca Valley in the Canton Ticino is one of the geologically best-known areas in the vast gneiss region of the Lepontine Alps. According to classical Alpine geology, the valley is mainly built up of the middle to lower tectonic units of the deeper Pennines.

The chief rock-type is a leucocratic mica-oligoclase-gneiss of quartz dioritic to trondhjemitic composition, known as Verzasca-gneiss. In the central part of the valley it forms one major, up to 1000 m thick, sub-horizontal sheet and several minor ones, which are well exposed over a distance of about 15 km in the sheer rock walls on both sides, and also in the summital region. South of

[1]) See Wenk, 1943, 1948, 1953, 1956, 1962, 1967.

Lavertezzo the main gneiss nappe dips to the SW and gradually shoots down to the so-called root-zone. The Verzasca core-gneiss is mantled by mesocratic biotite-plagioclase-gneiss. The contacts between the core and the mantle are rarely sharp; more often they are marked by a transitional zone of migmatites whose leucocratic part has the same chemical character as that of the Verzasca gneiss. The migmatite zone can attain a considerable thickness.

Remarkably, the light-coloured core which is gneissic in the frontal part, becomes rather schlieric or massive (granitic) towards its steeply-dipping southern part, where the paragneisses of the mantle grade into veined and banded gneisses and may hardly be distinguished from the core-material. Besides the nappe-structured gneisses with allochthonous character, there are also massive to gneissic rocks of quartz dioritic to granodioritic composition which occur as stocks and intrusions of autochthonous nature in the paragneiss-mantle. Here too the phenomena of injection, permeation etc., as found in the transitional zone mentioned above, can be seen with equal clarity.

On their external margin, the paragneisses are followed by thin bands of metamorphosed Mesozoic sediments, mainly calcareous schists, marbles and quartzites. They divide different tectonic units and are, in fact, the main proof for the existence of nappe-structures.

The planar and linear structures run N-S in the northern part of the valley. In accordance with the regional structural pattern, which converges to the SE, the strike of the s-surface-planes and the B-axes gradually swing to the SE and E in the southern part. Simultaneously, the fold-axes become steeper towards the SE, where they form part of the famous vortex structure of Bellinzona.

The linear structures (fold-axes and lineations) displayed by the gneiss

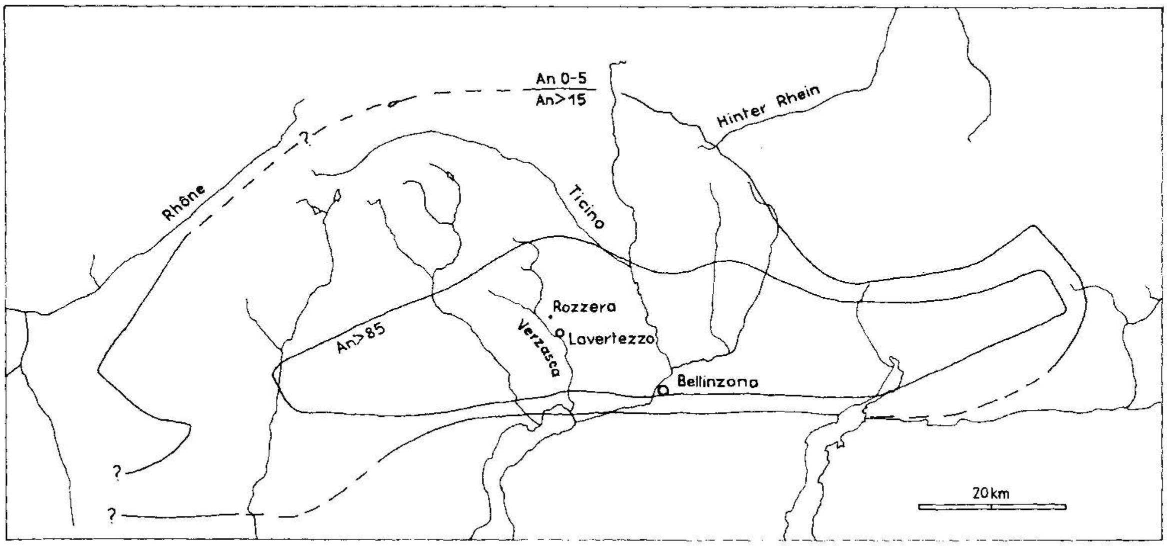


Fig. 1. Location map of the outcrops in the Verzasca Valley. Isogrades refer to the paragenesis plagioclase-albite after SCHWANDER and WENK (1967).

bodies agree with those of the overlying Bündnerschiefer. Moreover, the metamorphic facies presented by the Bündnerschiefer (metamorphosed Mesozoic sediments) and the gneissic rocks is exactly the same. These criteria indicate that existing structures, banding, migmatite pattern, anatectic mobilisates, and mineral assemblages are the outcome of Alpine regional metamorphism (Wenk, 1962, p. 759).

The rocks of the Verzasca belong to the amphibolite facies and thus represent a mesothermal grade of metamorphism (Fig. 1); they are characterised by synkinematic as well as postkinematic crystallisation. The isograds of metamorphism (established on the basis of An-percentage in plagioclase in plagioclase-calcite associations) cross several lithologic boundaries.

2. Purpose of the Investigation and Nature of the Problem

Generally speaking, studies of migmatites attempt to elucidate the processes by which the granitic component of a particular mixed rock has come into being. Such studies will be of special significance in a region which presents ready information with regard to macroscopic structures (lineations, fold-axes etc.) and other geological aspects, for example, grade and facies of metamorphism, age determinations etc. In such a region, a critical study of some representative outcrop will eventually lead to conclusions on the relationship between migmatisation and tectonic history of the area.

With this purpose, two migmatite outcrops in the region of the Verzasca Valley were selected for a detailed study. The main object was to compare the process of migmatisation at both outcrops which, though they display the same rock-types, are strikingly different in their structural pattern. The investigation was therefore directed towards establishing 1. the genetic relationship of the different rock-types, 2. the mutual behaviour of the mobile and immobile phases, and 3. their relation to the regional folding. Petrographical, geochemical and structural methods were applied and are described in the succeeding chapters.

The two selected outcrops – one at Lavertezzo and the other at Rozzera – occupy a similar geological position at the base of the main sheet of Verzasca-gneiss (Fig. 2). The former is in the isoclinally folded and steeply SW-dipping part of the series and displays the banded type of migmatite, while the latter occurs in the base of the sub-horizontal part of the huge gneiss-nappe, with very regular large-scale tectonics (although possessing perplexingly entangled migmatite structures).

The Lavertezzo outcrop (530 m above sea-level) stretches along the bed of the Verzasca river near the village and is of easy access over the Roman bridge (Ponte dei Salti). The outcrop of Rozzera above Motta lies 3 km to the NNW at an altitude of 1320—1360 m, in an extremely steep and rocky side-

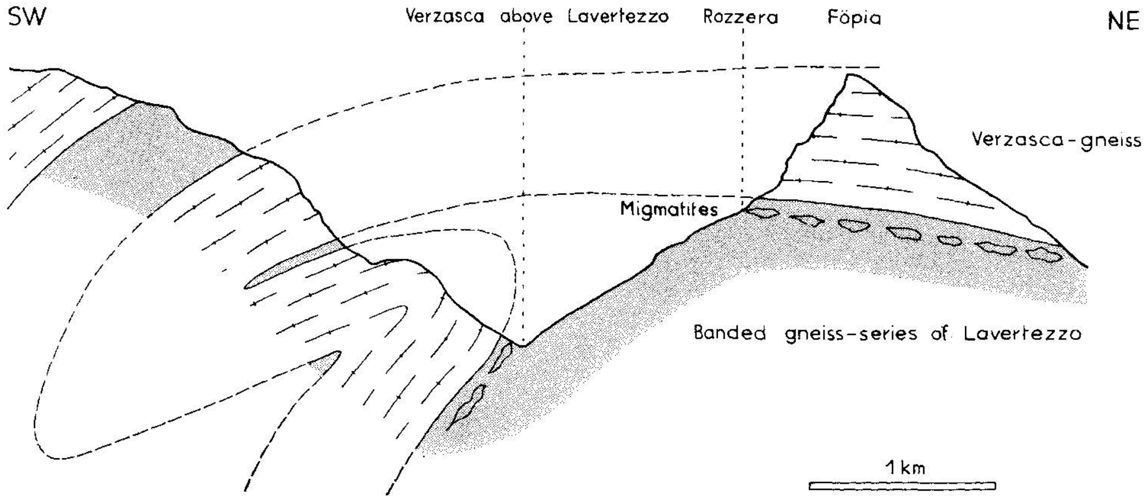


Fig. 2. Schematic section across the Verzasca Valley above Lavertezzo, showing the geological position of Lavertezzo and Rozzera, after an unpublished sketch of E. Wenk.

valley, and the path leading to the lonely and abandoned huts of Rozzera can only be traced with difficulty.

3. Banded Gneisses and Migmatites

a) *Definition:* In view of the different theories of migmatisation, voluminous definitions in the petrological literature have been used for migmatites and their component parts. The author adopts in the present work the definition of migmatite given by DIETRICH and MEHNERT (1960), who state that a migmatite is a "megascopically composite rock that once consisted of geochemically mobile and immobile (or less mobile) parts (i.e. it consists of igneous or igneous-looking and/or metamorphic materials)". This definition is based on the opinions expressed by different petrologists throughout the world. Moreover, the definition is purely descriptive and neutral, and comprises a wide range of rocks including banded gneisses which really belong to the migmatite group. This becomes obvious when the leucocratic part of a veined gneiss is considered to undergo kinematic metamorphism. The rock is then indistinguishable from the banded gneiss, since the nature of the banding is no criterion to call a metamorphosed composite rock a banded gneiss of arterite origin, or a derivative of venite. In the field, all variations are encountered: the banding can be thick or thin, and regular or discontinuous. A banded gneiss may therefore be regarded as a special type of migmatite, and this will be examined in the present work.

Lastly, in this paper all other terms related to the migmatisation strictly follow the definitions presented by DIETRICH and MEHNERT in the "Symposium on migmatite nomenclature" (1960). However, the special meaning of certain terms will either be stated or put under inverted commas or italics.

b) *Historical review:* The idea of mixing of solid rocks and magmatic materials is an old and familiar one. French geologists have described the mixing of rocks, varying qualitatively and quantitatively, under the names of lit-par-lit injection, imbibition, permeation etc. It was only after 1907, when SEDERHOLM defined his interesting mixed rocks, the migmatites, and the process of anatexis, and when HOLMQUIST introduced venites and ultrametamorphism, that the problem of migmatites became of general interest to petrologists. The occurrence of migmatites was realised in metamorphic terrains all over the world; but subsequent studies aroused fundamental differences amongst petrologists with regard to the mode of origin of the leucocratic part of these rocks. Accordingly, migmatites can be formed by different processes, each qualifying itself in producing the leucocratic component and mixed appearance that characterise the migmatite rocks.

Broadly speaking, these processes of migmatite formation are:

1. Injection of the granitic portion, directly or indirectly related to granite magma (SEDERHOLM, 1907 and 1923).
2. Partial melting (differential anatexis) (HOLMQUIST, 1907 and 1921; SEDERHOLM, 1907; ESKOLA, 1933; MEHNERT, 1953).
3. Metamorphic differentiation or diffusion (segregation without melting (STILLWELL, 1918; ESKOLA, 1932; RAMBERG, 1952).
4. Metasomatism, which SEDERHOLM (1926) ascribed to granitic juices or ichors, and which WEGMANN (1935) attributed to aqueous fluids from unknown depth, or to ionic diffusion in intergranular films.

The last method (metasomatism) of the formation of granitic components or granitic rocks has been referred to in geological literature as "granitisation" (see for example MISCH, 1949). In the general sense of the term, granitisation includes "the process by which solid rocks are converted to rocks of granitic character" (READ, 1957, p. 88; also MEHNERT, 1957, p. 59–60).

Until recently all these different hypotheses pertaining to the migmatite problem differentiated themselves purely on field observations and petrographic studies. However, the results of laboratory experiments on the granite systems carried out by TUTTLE and BOWEN in America, and WINKLER and VON PLATEN in Germany, have greatly inspired the studies of migmatite rocks.

DESCRIPTION OF THE OUTCROPS

In the following pages the two migmatite outcrops of Lavertezzo and Rozzera are described individually, because of their contrasting features of general interest. At both places the outcrops are nicely polished by river erosion, and excellent exposures, with fairly high relief, are provided for studying the petrological variation in three dimensions.

A. Outcrop at Lavertezzo

The outcrop lies in the river bed of the Verzasca, immediately NW of the church of Lavertezzo (536 m). Besides being of easy access, this outcrop has become well-known through the works of PREISWERK (1925, 1931) and WENK (1943, 1967) and also by the fact that several international excursions have been conducted to the outcrop during the last decade.

The exposure shown in Plate IV occupies an area of 160×50 square meters in which bands of leucocratic and mesocratic gneiss alternate with amphibolites and constitute together the characteristic banded gneiss complex of Lavertezzo. The contacts between the light and dark bands are fairly sharp. Megascopically, the gneiss complex resembles closely the famous banded gneisses of Ornö Huvud, Sweden. But the structural implications are much clearer at Lavertezzo, where characteristic antiforms and synforms occur, with an interesting superimposed folding. Fold-axes and lineations dip gently and generally coincide with each other, though local variation may be noted. A dominant joint-system runs normal to the fold-axes and lineations. These ac-joints are hair-thin to a few millimeters wide and filled with quartz, chlorite, iron ore etc.

The general strike is N 45° W and the SW dip varies from 30° to almost vertical (Plate III).

The texture in the leucocratic bands changes from coarse-grained gneisses to aplitic. The mesocratic gneiss forms clear and fairly thick bands (several centimeters); it alternates with small, thin and thick foliated leucocratic veins, which appear to be concordantly intrusive in the gneiss. Also, both thick (some tens of centimeters to a few meters) and thin bands (a few millimeters wide) are bordered by mica-rich selvedges. These bands extend several tens of meters along the strike and surround numerous inclusions as schollen, schlieren, restites etc. The inclusions usually show reaction phenomena in contact with the enclosing rock. Due to weathering of iron-magnesian minerals, the mesocratic gneisses particularly show a brownish colour on the surface. Amphibolites occur as thick bands, lenses, and also thin bands which are folded together with the leucocratic bands. The amphibolites are generally concordant to the banding but local discordance is also seen.

A semi-concordant quartz mass showing bulge and neck, and cross-cutting dykes of pegmatite (sometimes with pinch-and-swell) and aplite are interesting rocks of the outcrop. Their age relations can easily be read from their mutual intersections, in which the aplite stands as the youngest and the quartz the oldest.

The rock-complex as a whole possesses several small folded aplitic and also quartz layers which have their fold-axes parallel to the schistosity plane. However, discordant-concordant veins of quartz and feldspar (unfolded) are not uncommon in the gneiss complex.

Pyrrhotite and associated ores in the form of disseminated and small segregated minerals occur in the quartz mass, joints, and also in the gneiss bands.

Finally, the outcrop is fractured by dip faults and oblique faults which are vertical with more or less straight trend. These faults are commonly rotational as is apparent from the nature of the displaced rocks, particularly pegmatites.

The outcrop is thus unique in the sense that it records almost all geological phenomena which otherwise could only be studied in separate outcrops distributed over several kilometers. Moreover, this outcrop is situated at the lower most visible limit of the Verzasca-gneiss which is seen lying horizontally in the surrounding mountains. In spite of the high dips in the banded gneisses, no discordance is observed with the horizontally lying Verzasca-gneiss at high levels. The reason is that the schistosity of the banded gneisses swings around the core-gneiss and orients itself parallel to the walls of the Verzasca-gneiss (cf. WENK, 1948).

B. Outcrop at Rozzera (Fig. 3)

The outcrop is exposed at about 1320 meters M.S.L., and overlies the hamlet of Motta-Brione. This outcrop, like that of Lavertezzo, is also placed at the lower contact between the core-gneiss and mantled paragneiss of the Verzasca-gneiss nappe. But this outcrop is located at a higher elevation (see Fig. 2).

Petrographically, the rocks are true migmatites, and the degree of mixing of the light and dark rock-components yields all gradations from veined-gneiss to agmatite or eruptive breccia and nebulite (after SEDERHOLM, 1926). This outcrop, like any other, is so typical and demonstrative that nobody except a Bourbon, using READ'S expression, will doubt the phenomena of anatexis in the Alpine metamorphism (see Plate I). The mobilisate is slightly coarse-grained (aplitic to pegmatitic) and contains quartz, feldspar, and small amounts of biotite and also garnet which is not uniformly distributed.

The bands of the migmatite are composed of mesocratic biotite gneiss commonly with hornblende, leucocratic mica-plagioclase-gneiss, and amphibolite bands and lenses. The banding is apparently clear, but the different bands frequently show imperceptible gradations, both along and across their strike. However, the contact of gneiss bands and mobilisate is always sharp. The diverging leucosome veins in the gneiss complex are sometimes margined by biotite-rich stripes.

The bands have a general strike N 55° W and dip 30° towards the N.

Folding is commonly seen in the individual bands, and the fold-axes and mica-orientation show parallelism between themselves and lie in the "s"-plane. At places, the mobilisate appears to have intruded along the axial plane of the folds. Moreover, faulting of the bands in the pattern of step-faulting is seen along the pegmatoid material, where the amphibolite bands give place

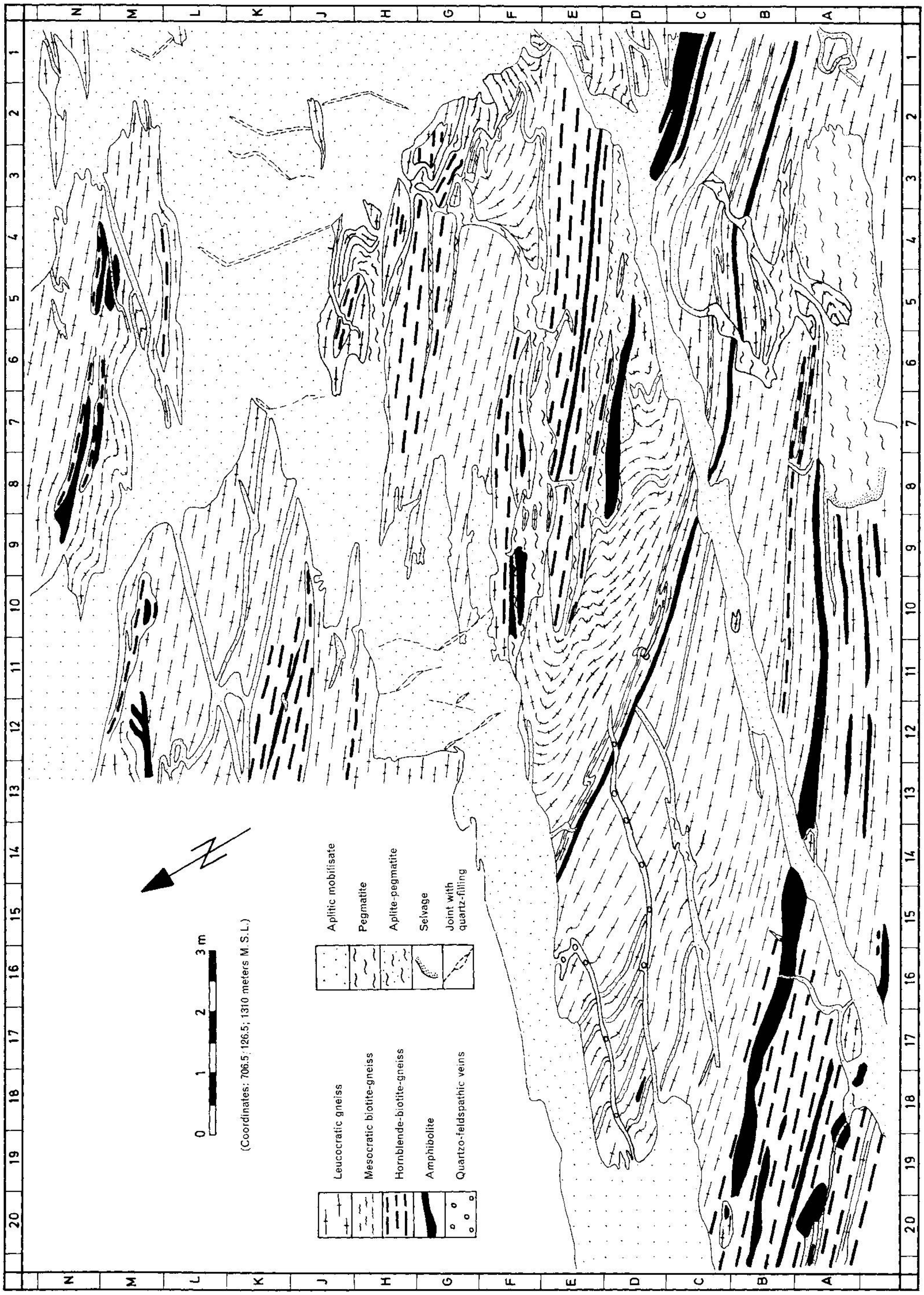


Fig. 3. Migmatite outcrop at Rozzera (Valle Verzasca, Canton Ticino).

to biotite-rich ones. Drag effects are also noted. Strikingly, biotites from dark bands are seen but very seldom penetrating inside the pegmatoid mobilisate. In the aplitic mobilisate, which is widespread, occur cracks which are filled with quartz and chlorite. The quartz is fractured always across the length of the cracks. Contortion and a sort of puckering of biotites in the gneisses is common.

However, attention is drawn to some leucosome veins which on their way through the aplitic mobilisate are cut by another generation of leucosome veins. This suggests three subsequent phases of the penetration of the country rock by anatectic material (Plate I, Fig. 4). Further, there are interesting occurrences of many schollen (at times folded), and schlieren particularly in the mobilisate, which are also present in the leucocratic gneisses which sometimes contain amphibolite inclusions. Penetration of these inclusions by quartz-feldspar mobilisate is a common feature.

Lastly, the aplitic mobilisate and mesocratic gneisses show a yellowish-brown colour on their surface, but this is not the case if garnet is absent.

METHOD OF MAPPING, SAMPLING, AND MODAL ANALYSES

1. *Mapping*

The nature of the problem necessitates mapping on a large scale. Both the outcrops apparently represent advanced stages of anatexis, since the "pure" parent material as well as intermediate stages of mobilisation (metablastesis, feldspathisation or augengneiss) are virtually absent. The detailed mapping on the scale of 1 : 10 makes it possible to estimate the volumetric relationship of the mesocratic-, leucocratic-, and melanocratic components in the field – a very important aspect in migmatite studies –, although their mixing at places is very complicated and intricate. It is only the detailed mapping which enables us to assess whether the reaction products are confined within the small area (in situ) and therefore whether the different rock-groups bear some reaction relationships amongst themselves. In other words, whether Leucosome + Melanosome = Paleosome, as has been admirably demonstrated in several papers by Mehnert (1953, 1962 etc.). Or, alternatively, if Leucosome + Melanosome = parent rock (Wirtgestein) + introduced material (Zufuhr), as is envisaged by Wegmann. Quantitative information on the mineralogy, petrography, structure, and geochemistry of the different rock-phases of a migmatite complex can thus be gathered successfully.

Both outcrops were mapped by a right-angled coordinate system whereby the exposure was divided into several quadrangles, each a square meter in area. At Lavertezzo, the mapping is a horizontal surface-projection of the outcrop, irrespective of the undulations and variable dips of the exposure. On the other hand, the mapping at Rozzera included an almost constant slope of 20° in the direction opposite to the dip.

2. Sampling

Selection of the material was mostly from adjacent bands of the rock-units, both across and along the banding. Almost all the rock specimens were orientated, but only a few suitable ones were selected for petrofabric studies. Further, a collection of fresh specimens (occasionally by drilling) of leucocratic rocks (including aplite dyke), mesocratic gneisses, and schollen was made, for geochemical studies, from favourable bands.

About 200 rock-specimens from Lavertezzo, and 150 specimens from Rozzera were studied petrographically (mineral phases and their relations). Anorthite percentage of plagioclase was determined by the U-stage method and the zone-method. For this, the revised tables and graphs after BURRI, PARKER and WENK (1967) were employed.

3. Modal Analyses

Quantitative mineralogical determinations were made of those rocks which were homogeneous and cut essentially normal to the "s"-plane. All the rock-slides used for quantitative analyses were stained after the method of BAILEY and STEVENS (1960), whereby both K-feldspar and plagioclase were distinctly

Table 1. *Analytical error in the modal analyses of aplites and gneisses*

Rock		Quartz	Plagio-clase	K-feldspar	Biotite	Musco-vite	Acces-sories
*Aplite**)	I	26.1	40.0	28.6	3.4	1.0	0.9
(ShLz P 3)	II	25.3	42.2	27.0	5.6	0.6	0.5
	III	24.0	40.7	28.6	4.1	2.0	1.0
Average:		25.1	40.9	28.0	4.4	1.2	0.8
Mean deviation:		0.7	0.8	0.7	0.8	0.5	0.2
*Gneiss**)	I	28.8	58.1	3.4	8.4	1.5	0.3
(ShLz M 4)	II	25.5	57.5	6.4	8.9	0.8	0.8
	III	26.3	56.8	9.1	7.2	1.1	0.4
Average:		26.8	57.5	6.3	8.1	1.1	0.5
Mean deviation:		1.3	0.4	1.9	0.7	0.2	0.2
*Aplite***)	I	26.1	40.0	28.6	3.4	1.0	0.9
(ShLz P 3)	II	25.4	41.1	27.8	4.0	1.4	0.7
Average:		25.7	40.5	28.1	3.7	1.2	0.8
Mean deviation:		0.3	0.5	0.4	0.3	0.1	0.1
*Gneiss***)	I	28.8	58.1	3.4	8.4	1.5	0.3
(ShLz M 4)	II	28.2	57.8	4.1	8.2	1.4	0.3
Average:		28.5	57.9	3.7	8.3	1.4	0.3
Mean deviation:		0.3	0.1	0.3	0.1	0.05	—

*) Three thin sections from the same specimen.
**) The same thin section was counted twice.

coloured. Not less than 2000 points were counted from each slide. Three thin sections from the same hand specimen of aplites and gneisses were point-counted (differently oriented in massive aplite, but similarly oriented and hence normal to the foliation in case of gneisses) to examine homogeneity in the rock-specimens. In each case 2500 counts were taken with 0.2 mm distance between each count (CHAYES, 1956, p. 79–91). Also to eliminate personal error, the same rock-section was counted twice, keeping the same distance between steps but changing the starting point. The results obtained are shown in Table 1. It is evident that the aplite and gneiss rocks show a satisfying homogeneity with regard to their mineral distribution (see the values of mean deviation).

In spite of all these checks, errors still arose because of the size and distribution of the feldspar porphyroblasts, the presence of sieve-structure in hornblende, feldspar, and garnet, and because of indistinguishable alteration products in certain minerals. The occurrence of perthite and/or antiperthite also creates some inaccuracy in the modal analyses, particularly of aplite and gneiss rocks.

PETROGRAPHY

A. Lavertezzo

1. Gneiss

This group comprises all those medium to coarse-grained crystalline rocks (forming the banded gneiss) which, regardless of their mineral composition, are liable to split into centimeter thick sheets parallel "s", if hit with a hammer (WENK, 1963, p. 105). At Lavertezzo three types can be distinguished:

a) microcline-bearing biotite-oligoclase-gneiss (leucocratic gneiss) ± muscovite,

b) biotite-oligoclase-gneiss, commonly garnet-bearing, mesocratic,

c) sphene-bearing garnet-hornblende-biotite-andesine-gneiss, mesocratic.

The approximate volume proportions of these rock-groups estimated in the field are as follows:

$$\text{type a} = 52\%;\ \text{type b} = 32\%,\ \text{and type c} + \text{amphibolites} = 16\%.$$

a) Leucocratic gneiss (see Tables 2 and 3)

Texture: crystalloblastic, although the plagioclase and quartz often show granoblastic texture. Crystals are subidiomorphic with mica lepidoblasts which exhibit a good preferred orientation. In certain bands, the minerals are small xenomorphs with plagioclase and K-feldspar as poikiloblasts and mica as

Table 2. *Modal analyses (Vol.-%) of leucocratic gneisses at Lavertezzo*

S. No.	Specimen ShLz	Quartz	Plagio-clase	K-feldspar	Biotite	Mus.	Acc.
1.	A 18	29.0	41.0	19.4	5.6	2.5	2.0
2.	C 25 b	30.1	50.0	8.0	8.0	2.8	1.2
3.	C 33 b	19.0	67	—	11.6	—	2.4
4.	C 54 a	31.0	52	—	15	—	2.0
5.	C 59 a	20.5	71.0	1.1	6.0	—	1.4
6.	C 73 a	18.6	53.0	18.6	8.0	—	1.8
7.	C 73 b	12	68	6.0	12.6	—	1.4
8.	C 73 c	28.5	49	18	3.5	—	1.0
9.	C 73 d	24.5	64.0	1.0	9.0	—	1.5
10.	D 28	26.5	58.0	1.5	8.0	3.6	2.6
11.	D 31 a	18.8	66.5	—	12	—	2.7
12.	D 44	34	46	4.8	12.0	—	2.0
13.	D 59 a	20.5	71.0	1.1	6.0	—	1.4
14.	D 68	31	64	—	3.8	—	1.2
15.	E 45 b	32	49.8	10.6	6.0	0.9	0.7
16.	E 45 c	31.4	50.6	12.0	4.8	0.5	0.7
17.	E 45 e	30	56.4	5.3	0.6	6.0	1.6
18.	E 76	24	60.5	6.5	6.5	1.5	1.0
19.	F 34 a′	33.0	52	4.0	9	—	2.0
20.	F 44	16.5	68	2.8	11.4	—	1.3
21.	F 46	17.0	65.0	3.5	13.5	—	0.6
22.	F 51	27.6	44.0	11.6	13.5	2.5	0.8
23.	G 28 a	25	49	16	8.5	—	1.5
24.	G 28 b	19.7	64.0	14.0	1.6	—	0.7
25.	G 31 c	18.6	68	4.0	8.4	—	1.0
26.	G 38 a	30.4	54.7	12.4	1.5	—	1.0
27.	G 40 a	20.0	62.5	0.5	15.0	—	2.0
28.	G 45 b	25.2	61.6	1.2	10.2	—	1.8
29.	G 56 b	35.8	37.6	2.1	14.0	—	11.0*)
30.	H 46	18.8	60.4	8.4	10.4	—	2.0
31.	H 60	19.0	68	—	10.0	—	3.0
32.	H 61	18.6	69.2	—	10.1	—	2.1
33.	H 62	20.0	64	4.4	10	—	1.6
34.	H 68	21	65	—	12	—	2.0
35.	J 60	22.0	63.0	5.0	9.0	—	1.0
36.	M 36	25.6	60.4	2.4	10.0	1.0	1.6
37.	N 7 a	19.0	52	3.0	25.0	—	1.0
38.	P 27 c	22.6	64.0	—	11.6	—	1.8

*) Includes iron ore.

small thin laths. These characteristics tend to give the name aplitic gneiss to these rocks. Myrmekite is a common feature.

Plagioclase (53–65%) is subidiomorphic to xenomorphic and very frequently zoned (inverse). Sieve-structure and wavy extinction are seen. Crystal outlines are sometimes tinged with reddish brown pigment (hematitic?). Two generations of plagioclase are noticed:

1. Small (0.03 mm), fresh crystals devoid of mica inclusions. These plagioclases occur as inclusions in the second generation plagioclase (Fig. 4) and, with corroded outline, also in microcline. Twinning is well developed and the crystals are always optically negative with anorthite content about 28 mol %.
2. Second-generation plagioclases are fairly big crystals (0.5–1 mm) and

Table 3. *Mineral frequency (Vol.-%) in leucocratic layers from the banded gneiss outcrop of Lavertezzo*)*

S. No.	Specimen	Quartz	Plagio-clase	K-feldspar	Biotite	Mus.	Acc.
			Group 1				
1.	A 33	26	41	14.4	15	2.6	1.0
2.	A 64	28.5	43.5	11.0	11.2	5.5	0.5
3.	A 75	26	49.6	10.5	11.8	0.7	1.6
4.	C 20	24.0	61.6	5.6	7.6	—	1.2
5.	C 22	21	66	1	10	—	2.0
6.	C 24	21 0	60.0	9.8	8.2	—	1.0
7.	C 25 c	22.0	62.0	6.3	6.5	2.6	0.6
8.	C 27	26.0	55	7.0	6.4	4.8	1.0
9.	C 31	28.0	49.8	4.7	16.2	0.7	0.6
10.	D 10 a	29	60	—	10.0	—	1.2
11.	U 39	26.0	48.8	3.8	14.0	6.0	1.4
12.	U 42	24.1	47.1	10.3	14.5	3.5	0.5
13.	U 59	25.0	64.0	1.0	8.4	—	1.6
14.	V 35	24.2	48.5	15.2	9.6	1.5	1.5
15.	V 53	26.5	47.5	8.4	17.0	—	0.6
	Average	25.1	53.8	7.2	11.1	1.8	1.0
			Group 2				
1.	B 69	28.0	41.5	23.4	4.5	0.8	1.6
2.	B 75	24.0	67	—	7.5	—	1.5
3.	C 56 c	26.0	55.6	3.0	13.5	—	1.3
	Average	26.0	54.7	8.8	8.5	0.3	1.4
			Group 3				
1.	C 66	25.6	56.6	9.8	7.0	—	1.0
2.	C 66 a	24.0	60	2.0	13.0	—	1.0
3.	C 66 b	26	64.0	2.4	7.0	—	0.6
4.	C 73	22.0	57.0	12	7.6	—	1.4
5.	C 76	23	48	21.0	6	—	1.8
	Average	24.1	57.1	9.4	8.1	—	1.2
			Group 4				
1.	B 7	22.6	57.5	8.8	6.0	4.0	1.0
2.	C 3′	25.5	50.5	10.1	13.0	—	1.0
3.	D 3′	19	63	7.2	9.4	—	1.4
4.	D 4′	24.2	48.2	12	12.3	2.8	0.5
	Average	22.8	54.8	9.5	10.2	1.7	1.0
			Group 5				
1.	P 3 b	28.0	60.6	1.6	8.7	—	1.0
2.	P 5 a	26.1	55	8.8	9.7	—	0.4
3.	P 12 b	27.8	60.1	2.0	9.1	—	1.0
4.	P 27	23.4	62.5	3.4	10	—	0.7
	Average	26.3	59.5	3.9	9.4	—	0.9

*) Mineral frequency in rocks of each group represents the modal variation within individual leucocratic bands.

S. No.	Specimen	Quartz	Plagio-clase	K-feldspar	Biotite	Mus.	Acc.
			Group 6				
1.	D 45	22	64	1.6	10.0	—	2.4
2.	D 57	22.0	58.2	4.6	13.2	1.0	1.2
3.	D 60	20.8	62.2	3.0	12.8	—	1.2
4.	E 39	21.5	62	3.6	8.8	2.0	2.1
5.	E 46 b	26	61	1.6	10.0	—	1.4
6.	E 49	27	55	3.2	9.4	4.2	1.2
7.	E 53	21.0	59.5	5.5	12.0	0.5	1.5
8.	F 34	22.0	60	8.8	6.5	—	2.7
9.	F 56	20	57.0	10	11	1.0	1
10.	G 24	24.2	56.2	9.4	9.2	0.7	0.7
11.	G 40 a	24.5	57.5	6.2	10.2	—	1.0
12.	G 46 c	27.0	66.0	—	5.5	—	1.4
13.	H 32	19	63	6.2	10.0	—	1.3
14.	H 36	17.0	68.0	3.0	11	—	1.0
	Average	22.4	60.7	4.7	10.0	0.7	1.4
			Group 7				
1.	K 23	25.3	55.5	2.7	15.2	—	1.3
2.	L 23	28.0	55.4	3.6	10.0	1.0	2.0
3.	L 36	25.0	63.5	1	8.5	—	2.0
4.	M 4 a	26.8	60.1	2.3	10.2	—	0.7
5.	M 4 c	26.5	59.6	4.0	8.6	0.4	1.0
6.	N 4	22.5	59.0	7.5	10.1	—	1.0
7.	N 6	19.5	68	0.5	11	—	1.0
8.	N 15	19	66	2.8	10.6	—	1.6
9.	N 31	20	62.0	5.0	12	—	1.0
10.	O 9	18.3	67.0	4.6	7.2	0.5	2.4
	Average	23.9	61.0	3.4	10.3	0.1	1.4
			Group 8				
1.	F 8	26.0	48.6	7.5	12.9	4.0	1.0
2.	F 15	20.8	55.0	16.0	6.5	1.0	1.0
3.	F 17	22.2	63.8	3.6	8.8	0.8	0.8
4.	H 3′	22	43	12	16.5	5.5	1.0
	Average	22.7	52.6	9.8	11.1	2.8	1.0

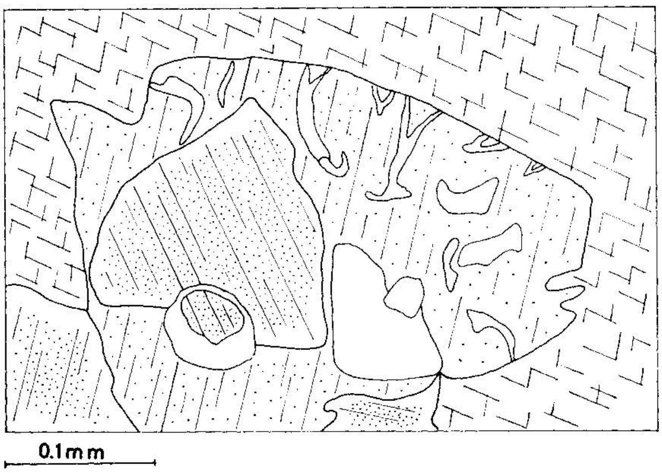


Fig. 4. Inclusion of a plagioclase inside another plagioclase with different crystallographic orientation. Both plagioclases are surrounded by a porphyroblast of microcline. Only the outer plagioclase shows myrmekite. (Sh Lz A 51-microcline-bearing mica-oligoclase-gneiss.)

often inversely zoned. Inclusions of mica and other fine minerals are visible in most crystals. Anorthite content varies between 20–28 mol %. Myrmekite is common.

Quartz (22–26 vol %) shows cracks which are occasionally filled with brownish material (leached iron).

K-feldspar amount is extremely variable (1–15 %) and the crystals are invariably xenomorphic, filling the interstices between quartz and plagioclase. Porphyroblasts are also visible. Occasionally, elongated thin microclines occur inside the plagioclase and along its twin lamellae. Cross-hatching is fairly visible, and in some crystals is non-existent. Sieve-structure is usually shown by big crystals which contain several inclusions of different minerals. Perthite also occurs.

Biotite (6–15 vol %). Laths show slight to perfect orientation. Pleochroism is dark reddish brown to light brown. Pleochroic halos are common. The biotite is strongly uniaxial. Alteration to chlorite and association with muscovite, iron ore, and microcline are common.

Muscovite occurs as thin to broad laths amounting up to 5 %. Small flakes of white mica are seen included in plagioclase crystals. At places these micas are bent and occur as inclusions in plagioclase (Fig. 5).

Zircon, monazite, apatite, secondary chlorite, white mica, sphene, iron ore and occasionally epidote and garnet are accessory minerals.

Myrmekite. In view of its occurrence in the leucocratic gneisses, the myrmekite characteristics are briefly discussed here. Myrmekite usually occurs at the contact of plagioclase with K-feldspar. This association does not always yield myrmekite in the gneisses of Lavertezzo. In fact, if a plagioclase is in

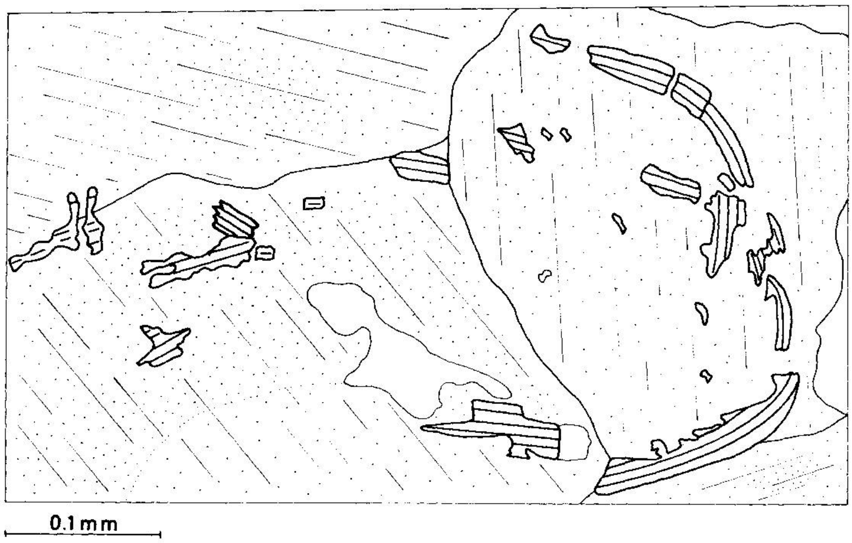


Fig. 5. Post-tectonic crystallisation in which plagioclase crystallised after the deformation of muscovite laths. Note the bending in the enclosed mica laths, while the surrounding plagioclase is free from any strain-effects. (Sh Lz A 51-microcline-bearing mica-oligoclase-gneiss.)

contact with K-feldspar which stands as a product of biotite-chlorite transformation, no myrmekite is visible. Moreover, a fresh plagioclase contains quartz vermicules more often than a plagioclase filled with inclusions. Strikingly, the K-feldspar in the gneisses is always found fresh. Furthermore, a zoned plagioclase in these rocks does not display any myrmekite.

To explain the myrmekite formation, BECKE's theory (1908) of the replacement of K-feldspar by plagioclase seems inadequate, since such a replacive nature of plagioclase in these gneisses is seldom seen. Viewed differently, the replacement of plagioclase by K-feldspar can be considered a possible, if not satisfactory, mechanism (DRESCHER-KADEN, 1948, p. 104), whereby quartz vermicules are seen even at those places where plagioclase is absent – a feature which cannot be explained by BECKE's theory (Fig. 6).

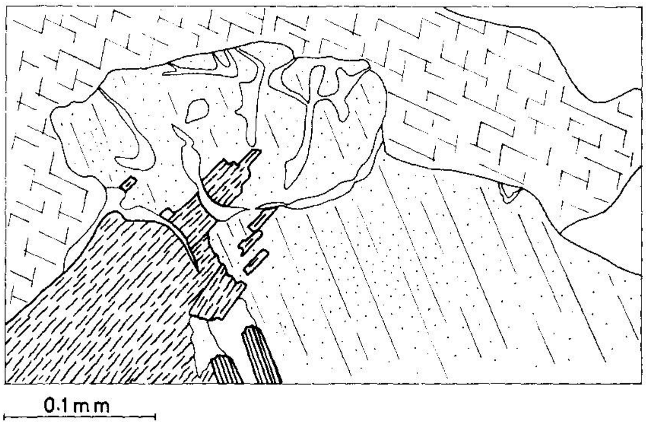


Fig. 6. Formation of myrmekite as a result of the replacement of plagioclase by microcline; the vermicules of quartz have developed pinch-and-swell structure. Note the vermicules along and across the muscovite where the plagioclase is absent. (Sh Lz U 34-microcline-bearing mica-oligoclase-gneiss.)

Lastly, it should be mentioned that the nature of the contact line – corroded, convex, plane, or plug-like – is no criterion for the presence or absence of myrmekite, because the occurrence of myrmekite in the examined rocks does not characterize any particular shape of the contact.

b) Mesocratic biotite-oligoclase-gneiss (see Table 4)

Texture: Crystalloblastic with porphyroblasts of garnet and plagioclase which usually show sieve-structure. Biotite lepidoblasts possess an excellent preferred orientation. Quartz and plagioclase show xenoblastic texture.

Biotite (30–45 vol %). Laths are 1.5–3 mm long and 0.5 mm broad. Pleochroic halos and inclusions of garnet, apatite, sphene, and iron ore are common. Occasionally the laths are bent and show non-uniform extinction. Alteration to chlorite is sometimes visible, with release of iron ore.

Plagioclase (42–50 vol %) shows inverse zoning. Anorthite content lies between 23 and 30%. Inclusions of garnet, quartz, sphene, and biotite may be noted.

Garnet (up to 3%). The crystals are usually small and rounded or irregular,

Table 4. *Modal analyses (Vol.-%) of mesocratic biotite-oligoclase-gneisses at Lavertezzo*

No.	Specimen Sh Lz	Quartz	Plagioclase	K-feldspar	Biotite	Accessories
1	B 59 b	23.5	43.0	0.5	31	2.0
2	B 60 b	11	47.8	—	40	1.0
3	C 57 a	18.8	48.0	2.0	30	1.2
4	C 57 c	18	47.5	1.4	32	1.0
5	C 57 d	10.6	48.0	—	40	1.4
6	D 49 a	18.0	48.0	0.6	32	1.3
7	D 49 c	18.8	44.0	3.0	32.2	2.0
8	D 49 d	19	46.1	2.8	30	1.1
9	E 45 a	16	45.0	1.8	35	2.2
10	E 46 a	12	42.0	—	45	1.0
11	F 18	16.5	50	—	31.5	2.0
12	G 31 a	24.0	43.8	2.2	28.2	1.8

but porphyroblasts are not uncommon. Colour is light pink to reddish brown and density 4.11. The composition obtained from X-ray analysis (powder method) of the garnet is as follows: almandine 70%, pyrope 20%, and andradite 10% (mol %).

Quartz (17–25%), apatite (at times fairly big crystals), sphene (up to 2%) and iron ore (3%) are other noteworthy minerals. K-feldspar, zircon, muscovite, and epidote are minor accessories.

c) *Sphene-bearing garnet-hornblende-biotite-andesine-gneiss* (see Table 5)

This rock-type adjoins amphibolite and biotite-gneiss bands, but sometimes is directly in contact with leucocratic gneiss. The minerals are inhomogeneously distributed.

Texture: Crystalloblastic. Hornblende and garnet are poikiloblastic.

Biotite (20–45%) bears irregular outlines and is closely associated with hornblende. Pleochroic halos are visible.

Plagioclase (An 30–35, inverse zoning) varies in amount.

Hornblende (up to 15%). Subidioblasts, more commonly xenomorphic.

Table 5. *Modal analyses (Vol.-%) of sphene-bearing garnet-hornblende-biotite-andesine-gneisses at Lavertezzo*

No.	Specimen Sh Lz	Quartz	Plagioclase	Biotite	Hornblende	Sphene	Accessories
1	B 59 c	18	23.5	45.0	7.0	4.5	2.0
2	B 59 d	14	24	42	12.5	5.0	2.5
3	B 60 a	10.5	26	40.5	10.0	10.0*)	2.0
4	D 12	12	32.0	38.2	13.8	2.4	1.6
5	E 60 a	20	40	30	8.0	1.0	1.0
6	F 57 a	21	45.6	19	10.4	2.5	1.5
7	G 29 b	24	43.0	24.0	6.6	1.6	0.8
8	N 6	16	37.0	29.0	15.0	2	1.0

*) Includes a notable amount (7.5%) of garnet.

Garnet (4–8 %). Commonly small and oval crystals. Big crystals with inclusions are also seen.

Sphene as aggregates of small elliptical crystals, and *ilmenite* as skeleton-like parallel ribs are scattered all over the slide.

Accessory minerals are secondary chlorite, epidote, and apatite.

2. Amphibolites (see Table 6)

The amphibolites form concordant bands which can be traced for several meters along the strike. These amphibolites commonly show diffuse zones with variable amounts of hornblende. The marginal parts are usually poor in hornblende and rich in biotite. These features and the occurrence of calcite in some bands support the sedimentary origin of the amphibolites (WILCOX and POLDERVAART, 1958, p. 1363; ENGEL and ENGEL, 1962, p. 1502).

The properties of the minerals in the amphibolites (see below) and the presence of aggregated quartz-feldspar material in the amphibolites suggest that a segregation process may have been responsible for the formation of amphibolites as a counterpart of the leucocratic bands. The mechanism of this band formation will be discussed later.

Petrographically, two types of amphibolites can be distinguished: first, the *banded amphibolites* which occur along the gneisses as parallel bands or elongated lenses. Plagioclase is characteristically acid andesine. Biotite and garnet are present in varying amounts. These amphibolites are commonly foliated, but compact. Second, the *schollen amphibolites* occur essentially as small inclusions of a few decimeters in length, either intimately associated with banded amphi-

Table 6. *Modal analyses (Vol.-%) of amphibolites occurring as schollen and bands in the banded gneiss complex at Lavertezzo*

No.	Specimen Sh Lz	Quartz	Plagioclase	Biotite	Hornblende	Diopside	Accessories*)
1	C 22	15.2	20	1.2	60.2	—	3.4
2	C 40	8.0	29	—	42.0	19.0	2.0
3	C 54	4.0	35	3.5	52.5	—	5.0
4	C 60 b	10	23	16	46	—	4.0
5	D 34	10	30	3	55	—	2.0
6	D 62 b	20.3	40.5	8.5	26.2	—	4.5
7	E 60 b	5.4	26	18	40.6	—	10
8	F 28 b	5.0	34	10	44.5	2.0	4.5+)
9	F 34 a	25.4	45	—	20	6.6	3.0
10	F 34 b	20.6	41	1.0	35.5	—	1.6
11	F 47	12.0	33	13.5	40	—	1.5
12	G 26	20.6	46.4	11	20.0	—	2.0+)
13	G 29 c	10	16	20	47	—	7.0
14	G 32	22.0	32.5	1.5	37	4.2	2.8
15	P 27 a	6.0	40	15	38.0	—	1.0

*) Mainly sphene, garnet, iron ore, and apatite.
+) Includes calcite.

bolites, or as isolated bodies enclosed in the gneiss complex. These amphibolites are characterised by the presence of diopside and/or high anorthite percentage ($> 45\%$) in the plagioclase. The schollen amphibolites are rather massive and even-grained with an average grain-size of about 1 mm.

Both these amphibolites generally contain quartz, sphene, and iron ore in notable amounts. Epidote is a significant mineral in the schollen amphibolites. Occasionally, calcite occurs but in variable amounts in both the amphibolites.

a) Banded amphibolite

Texture: crystalloblastic poikiloblastic, often the hornblende nematoblasts and biotite lepidoblasts determine a pronounced schistosity. The c-axes of the hornblendes usually lie parallel to the fold-axis and "a" almost normal to the foliation.

Hornblende: varies in amount (38–65%). Crystals subidioblastic. $2V_\alpha = 80–84°$, maximum extinction angle $c \wedge n'_\gamma = 14°$.

Pleochroism differs in hornblendes from the contact to the centre of the amphibolite bands:

	(contact)	(centre)
Z	= bluish green	dark green
Y	= green	green
X	= greenish yellow	yellow green

Chloritisation of hornblende and close association with biotite are common features.

Plagioclase (An 30–38%), constitutes 25–45 vol %, and is subidioblastic to xenoblastic. Twinning is well developed and mostly on the albite, pericline, and Manebach laws. Inverse zoning is strikingly common. Plagioclase inside plagioclase is often visible. Plagioclase in contact with hornblende shows a sort of "reaction zone" with lower relief and hence lower An % as compared to the main part of the crystal.

At times distinctly zoned plagioclase aggregates are seen. Inclusions of sphene, quartz, garnet, and hornblende are common.

Biotite (25–40%). Pleochroism dark reddish brown to greenish brown or brown. Pleochroic halos around monazite are seen.

Garnet (up to 8%). Crystals are irregular in shape with grey to yellow-brown colour (grossularite?). Shining inclusions like pseudomorph laths are often observed. Crystal outlines show faint anisotropism.

Sphene (1–6%) as euhedral crystals as well as aggregates. Twinned crystals are also visible.

Ilmenite: occurs as skeletal and stringlet rod-aggregates. Leucoxene is almost absent.

Calcite: sporadically present all over the slides, most commonly associated with garnet, hornblende, epidote, and plagioclase.

Quartz (8–15%). Accessories such as apatite, secondary chlorite, epidote (zoisite?), rutile, and zircon are other minerals which occur in the banded amphibolites.

b) Schollen amphibolite

Texture: Crystalloblastic, but diopside dominance results in a granoblastic texture. Sieve-structure is also present.

Hornblende (25–70%). Crystals are commonly xenoblastic but at times porphyroblasts with subidioblastic shape are seen.

Pleochroism: Z = bluish green
Y = green
X = yellow green

The chemical analysis and structural formula of an analysed hornblende are given on page 247.

Plagioclase (20–30%). Subidiomorphic with clear twinning and inverse zoning. Anorthite percentage varies greatly even in the same slide. Commonly the plagioclase has An 45–60%, but abundance of diopside and decreasing amount of plagioclase give An 70–100%.

Inclusions of pseudomorphs after hornblende give a distinctly patchy extinction and a "reaction zone" with low relief.

Diopside (20–35%): occurs as light greenish xenoblasts that are intergrown with hornblende and plagioclase.

Quartz (2–10%): very irregularly distributed in the slides.

Zoisite, garnet (most probably grossularite owing to calcite association), apatite, sphene, iron ore, and also occasionally zircon occur as accessory minerals. Biotite is characteristically absent in the diopside-bearing schollen.

At a few places in the sections, aggregates of epidote and microcline inside anorthite-rich plagioclase (An 90%) can be found. Occasionally calcite is enclosed in zoisite (Fig. 7). The formation of zoisite is considered to be due to the reaction of calcite with some aluminum-bearing ferromagnesian mineral.

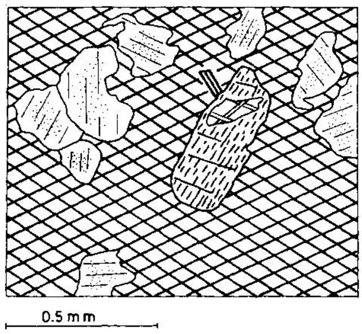


Fig. 7. Inclusion of calcite in zoisite. Both are surrounded by a poikiloblast of hornblende which also contains many plagioclase inclusions (An 65–80%). It is considered that the zoisite was formed by the reaction of calcite with some aluminum-bearing ferromagnesium mineral. In this reaction, the unconsumed calcite has remained as an inclusion in the zoisite. (Sh Lz C 22-Amphibolite as schollen in a gneiss.)

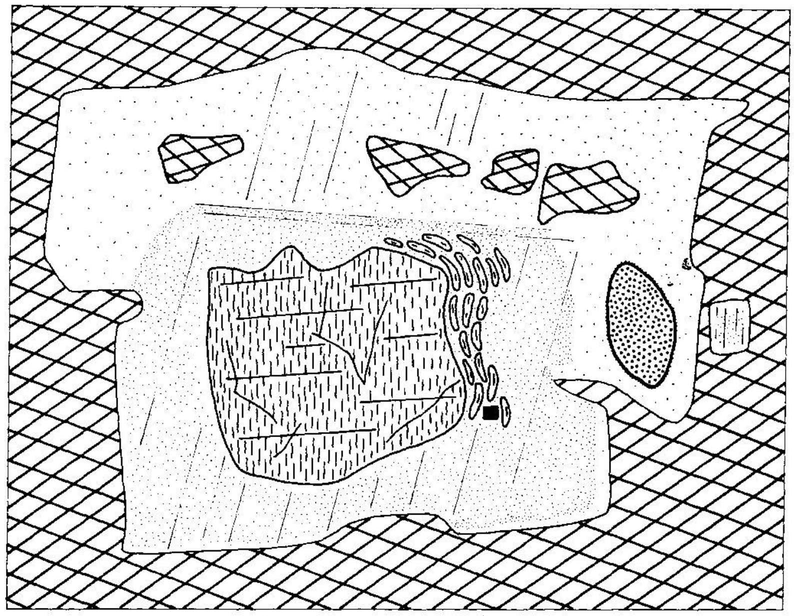


Fig. 8. Occurrence of zoisite inside a zoned plagioclase. Note the barrel-shaped zoisite crystals between the bigger zoisite and surrounding plagioclase. These barrels are in optical continuity with the zoisite crystal and their arrangement corresponds with the outline of the bigger crystal. The plagioclase is normally zoned with An 80% in the internal part, which contains inclusions of zoisite, and An 70% in the external zone in which a few inclusions of hornblende and sphene are seen. This whole assemblage is surrounded by a large poikiloblast of hornblende. Considering the relation between the zoisite crystals, and the calcium-content from the core to the margin of this assemblage, it is concluded that the plagioclase is growing at the expense of the zoisite. (Sh Lz C 22-Amphibolite as schollen in a gneiss.)

The unconsumed calcite is now seen as inclusions in the zoisite. There are also interesting occurrences of zoisite inside zoned plagioclase (Fig. 8).

3. Quartz bodies

Three generations of quartz bodies can be distinguished:

a) Synkinematic quartz layers, b) Late-kinematic quartz masses, and c) Late- to post-kinematic quartz-fillings. This sub-division is primarily based on the field-occurrences, although mineralogically these bodies are similar.

a) *Synkinematic quartz layers:* are commonly folded and their fold-axes invariably lie in the s_2-surfaces in the gneiss complex. Most layers, both folded and unfolded, are intrafolial in the mesocratic gneisses, and their maximum thickness reaches about a decimeter. They are essentially composed of quartz with a brownish tinge. A few veins and layers contain biotite, K-feldspar and/or oligoclase (An 19%) as accessory minerals. All the layers are, without exception, concordant with the gneisses and amphibolites.

b) *Late-kinematic quartz masses*

I. Occurring as thick lens-like bodies of concordant and discordant nature in the gneiss complex. They are chiefly composed of quartz, but feldspar, biotite and at times pyrrhotite are also to be observed. These lenses usually contain inclusions of gneisses and amphibolites.

II. Occurring as a dyke-like body, following to a great extent the compositional layering of the rock complex (see map). The body is of variable thickness along its entire length, and it crosses both gneissic and amphibolite rocks. At places the rock shows a sort of "necking". Also, locally, one notes "digitations" on the sides of the rock body. These features indicate that the host rock had not completely crystallised when this quartz mass was emplaced, and that this quartz body and the enclosing host rock underwent movements during their crystallisation.

Mineralogically, the body is composed mainly of quartz (including both clear and opaque varieties) in coarse interlocking crystals. The quartz is predominantly of milky appearance. Occasionally, a small amount of K-feldspar as perthite is noted. Biotite flecks are also to be seen, but are unevenly distributed.

In the event of the absence of mineral zones or gradational features in the quartz masses, local metamorphic differentiation is excluded as the process responsible for the formation of these masses. Hence the alternative remains that it is a product of silica-rich solutions which intruded along weak planes in the country-rock. This mode of origin would, however, appear at variance with the sequence of intrusion of the three late-kinematic dykes at Lavertezzo. In this sequence the quartz body is related with the following intrusion of the pegmatite, as evidenced by their nearly simultaneous crystallisation in which the pegmatite veins become invisible where they intersect the quartz body.

Because of the presence of scattered perthite crystals in the quartz body the author considers the latter to be an intruded silica-rich melt. The melt which gave rise to the pegmatite was more siliceous than some eutectic proportion of quartz and feldspar. As a consequence, quartz separated out early until the eutectic proportions were reached. The separated quartz with a few perthite crystals intruded the country rock at higher levels; the pegmatite melt then immediately followed. The intruded quartz body at one place gives off a thin (ca. 3 mm thick) branch which passes obliquely through the surrounding gneiss bands (see Plate IV).

c) *Late- to post-kinematic quartz-fillings* occur mainly along fault-planes, joints, and other cracks in the rock-complex. There are also quartz masses which are found at the noses of folds and which are bordered by thin, dark rims (about 2–5 mm thick) composed entirely of biotite. The border of the country-rock against these rims is always poor in quartz-content. Such quartz bodies are therefore considered to be the product of local diffusion and segregation of silica into the open fissures or pressure minima in rocks (cf. Chapman, 1950). In most cracks the quartz is associated with chlorite and also pyrrhotite.

4. Pegmatite

Broadly speaking, the pegmatite rocks at Lavertezzo can be divided into two groups according to their mode of occurrence, structural characteristics, and mineral parageneses. In fact, earlier workers (e.g. KÜNDIG, 1926; CORNELIUS, 1928) in the Tessin Alps, in general, have described two types of pegmatites – old pegmatite (pre-Alpine) and young pegmatite (late-Alpine) commonly characterised by the concordant and discordant occurrences respectively. The older pegmatites are naturally foliated, whereas the younger pegmatites are not.

At Lavertezzo, in particular, the pegmatite of the first group is foliated and occurs only in the leucocratic gneiss. The pegmatite cuts the gneiss both concordantly and discordantly. The feldspars are characterised by albitic rims which can be seen surrounding the plagioclase and K-feldspar when observed microscopically. This pegmatite, as will be discussed later, is synorogenic. The pegmatite of the second group is exclusively discordant, cutting the Alpine structures (schistosity, lineation, fold axes) in the rocks at Lavertezzo. This pegmatite is devoid of foliation and seems to have intruded along tensional joints in the rock-complex. This dyke rock is therefore late-kinematic (PREISWERK, 1931; WENK, 1948, 1967). Boudinage structure may, however, be seen at places.

Both pegmatites contain alkali feldspar, plagioclase, quartz, and mica. Garnet occurs mainly in the synorogenic pegmatite, in which the mineral grain-size varies from 1 to 5 mm, and is smaller than in the late-kinematic pegmatite. Attention is drawn to the small pegmatite veins which are discordant like the late-kinematic pegmatite, but the former are free of mica and garnet. Lateral shifting of the rock-bands along these small pegmatite bodies occurs, like that shown by the small discordant quartz veins in the gneiss complex. In the central part of the small pegmatite a pure quartz mass occurs at places around which the pegmatitic material appears to have swollen.

a) Synorogenic

Texture: granoblastic.

Potash-feldspar: remarkably fresh but with an irregular outline. Indistinct and patchy cross-hatching is seen. $2\,V_\alpha = 62°–80°$. The optic axial angle suggests the K-feldspar to be orthoclase, but the quadrille structure in most crystals, though faint, supports the assumption of microcline. Extinction angle $n'_\alpha \wedge [100]$ in (010): 6°–17°. The refractive index measured on cleavage flakes and using the immersion method (in Na-light) gave the following results:

$$n_\alpha = 1.518 \qquad n_\beta = 1.523 \qquad n_\gamma = 1.526$$

The microcline crystals are shattered, but the individuals are partially interlocked and surrounded by albite-oligoclase aggregates (0.03 mm) which give an appearance of mortar structure. Non-fragmented crystals appear as porphyroblasts in which albite-oligoclase and quartz fill the cracks. Inclusions of albite-rimmed plagioclase are common. Microcline-perthite is rarely seen.

Referring the above-mentioned optical data to the respective curves given by TUTTLE (1952), and considering the volumetric relation of the exsolved components of the alkali feldspar in the solid, the composition of the feldspar stands $Or_{70}Ab_{30}$.

Plagioclase: Almost all crystals are rimmed by clear albite, but only when the former neighbours, or is surrounded by microcline (Fig. 9). Two generations of plagioclase are distinguished. Fresh and sub-idioblastic plagioclase (An 15–18%) with well-developed twin lamellae which pass through the albite rim, if present. The twin lamellae thus denote crystallographic continuity. Myrmekite is almost invariably present.

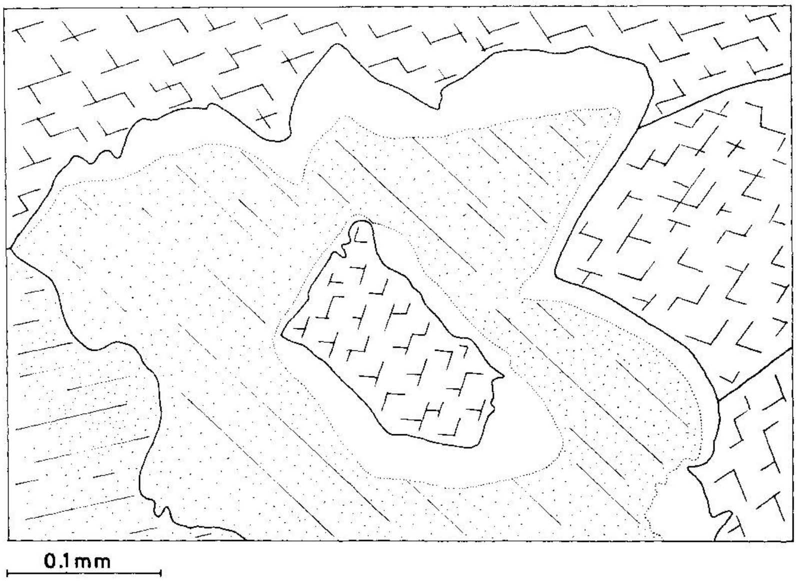


Fig. 9. Albite-rim on the outer and inner borders of an oligoclase in contact with microcline crystals. Note the absence of a rim on the borders between two oligoclase crystals. (Sh Lz U 34-Synorogenic pegmatite.)

Plagioclase of second generation is of varying shape: elongated, amoeba-shaped, and even sub-idiomorphic but mostly with sinuous outline. Without exception, the crystals are crowded with sericitic inclusions. The albite rim is always clear. Included plagioclase crystals with similar optical orientation but varying shape are seen in different stages of development in the host mineral (Fig. 10). The anorthite percentage of the second generation plagioclase is about 12–16%.

The albitic rim in all cases shows An 2–3%.

Quartz: Clear and of variable size, arranged along layers.

Mica: Occurs in aggregated layers. Preferred orientation is the rule; there are occasional transverse laths. Large muscovite is almost uniaxial and shows weak pleochroism. Small laths have $2V_{\alpha} = 35°$. Included flakes in plagioclase are without orientation.

Garnet: Crystals may or may not exhibit cracks; broken crystals are filled with quartz.

Fractured apatite, secondary chlorite (after biotite), and iron ore are accessories.

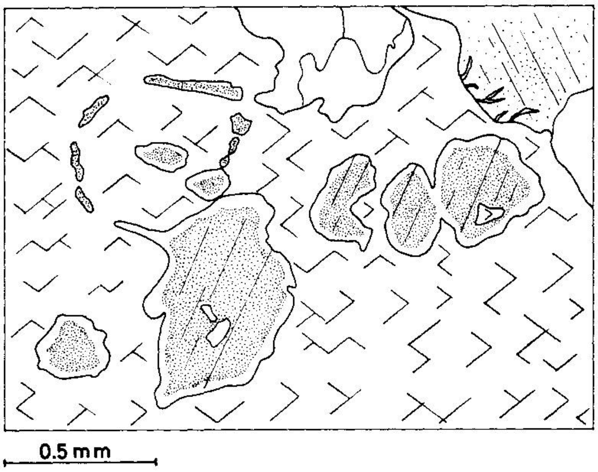


Fig. 10. Inclusions of albite-rimmed oligoclase in a microcline porphyroblast. The crystals of oligoclase are in different stages of exsolution but they show optical continuity. Two individuals on further growth coalesce with each other and share a common albite-rim at their borders. (Sh Lz U 34-synorogenic pegmatite.)

Albite-rimmed plagioclase and mantled microcline

As stated earlier, the plagioclase crystals in the foliated pegmatite are completely surrounded by an albite rim, when the former occurs as inclusions in the K-feldspar. If the plagioclase directly adjoins microcline, then the albite rim occurs only at their boundary (Fig. 9). This grain relationship has a striking similarity with that of the granite from Westerly, Rhode Island, and Beinn an Dubhaich granite, Skye, Scotland as referred to by Tuttle and Bowen (1958, cf. Plate III, and Plate VI, fig. 1). In explaining the albite-rim formation, the authors suggest that it represents a late-stage unmixing from alkali feldspar which originally contained albite molecules in solid solution.

In the particular case of the pegmatite at Lavertezzo, solid diffusion following the exsolution is considered as the main process in the rim formation, in which the K-feldspar supplied almost all albite molecules. This is seen in the albite rim between microcline and plagioclase. Moreover, the origin of the material is confirmed by the occurrence of albite-oligoclase rims around microcline which is not in contact with plagioclase crystals. This observation in the rim formation excludes the process of reaction between plagioclase and K-feldspar (Paraskevopoulos, 1953, p. 246; Sylvester, p. p., 1962, p. 605) and also excludes the mechanism of silicification of the marginal zone "Auslaugungszone" of plagioclase due to replacement by K-feldspar (Drescher-Kaden, 1948, p. 73).

Furthermore, the process of alkali metasomatism, in particular the introduction of sodium, to produce mantled feldspars (ORVILLE, 1962, p. 295) is rejected, because selective metasomatism solely in the 20 cm pegmatite rock seems unlikely; the adjacent country rock does not show any trace of such a replacement process. The crystallographic continuity from the feldspar into the albite rim – regarded as a criterion of replacement – can be explained by the exsolution process per se (TUTTLE and BOWEN, 1958, p. 141).

An analogous case of mantled microcline by sericitised albite-oligoclase as seen in the Lavertezzo pegmatite, is described by SYLVESTER (1962, cf. Fig. 1) who attributes the mantling to exsolution which occurred in order to maintain "environmental equilibrium".

Regarding the factors responsible for the exsolution and rim-formation around feldspar of the pegmatite at Lavertezzo, the following may be considered. Subsequent to its intrusion the pegmatite, being a high temperature small rock body, congealed rapidly, and the feldspar crystallised as a single homogeneous but metastable phase. The prevailing PT-conditions acted upon this freshly intruded body. As a result, the alkali feldspars (which are very sensitive indicators for changing stability conditions) underwent exsolution, and concurrent solid diffusion produced the albitic rims around the feldspars in the pegmatite.

Lastly, it may be mentioned that the exsolution phenomenon, in the production of rims around minerals, has been reported even in non-granitic rocks. SAHAMA (1960, p. 146) mentions the nepheline rim around kalsilite ($KAlSiO_4$) in the lavas of Mt. Nyiragongo, Belgian Congo. RETIEF (1962, p. 492) describes an albite rim around perthite in the alkaline rocks from Transvaal, South Africa.

b) Late-kinematic

The rock is very coarse-grained with a grain-size up to 6 cm. The branched portions are medium-sized. Absence of beryl and tourmaline is noteworthy, although they occur in pegmatites of neighbouring places.

K-feldspar. Includes both microcline and microperthite. The latter dominates particularly as vein perthite, in which the albite veins have a definite orientation. Cross-hatching is distinct. Crystals commonly show mortar structure in which the surrounding aggregate contains small crystals of quartz and plagioclase.

Plagioclase (An 14–18%). Twinning and myrmekite are abundant. Zoned crystals are common, and zoning is normal and at times even rhythmic.

Quartz. Occurs as small and big crystals.

Mica. Both biotite and muscovite are present, but the former is altered. No preferred orientation was observed. Secondary chlorite, apatite, and iron ore are accessory minerals.

5. Late-kinematic aplite (see Table 7)

The rock is massive and medium-grained (0.5–2 mm) with plagioclase, potash-feldspar, quartz, biotite, and muscovite in order of decreasing amounts.

Texture. Allotriomorphic.

Oligoclase (An 22–25%). Zoned crystals are frequent, at times with dusty inclusions which mark the zonal growth (normal). Inclusions of white mica, oriented as well as unoriented, are present in the oligoclase (Fig. 11). Oriented flakes are distributed along twin lamellae. Big phenocrysts are common. Inclusions of oligoclase (An 20%) in oligoclase are noted, as well as occasional antiperthite. Oligoclase crystals with myrmekite are not uncommon.

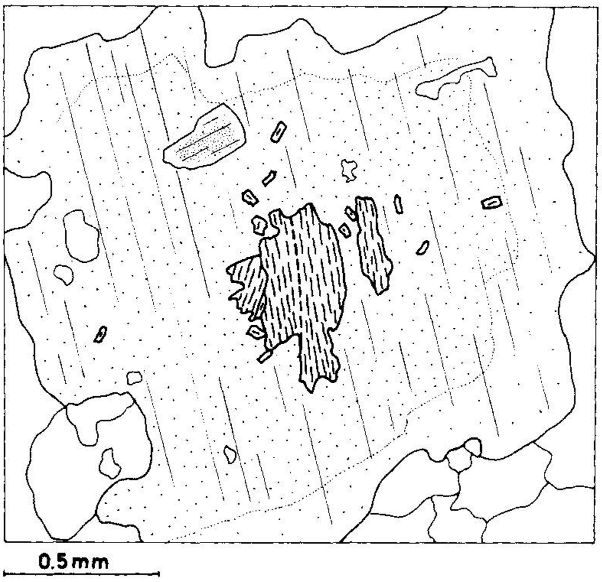


Fig. 11. Inclusions of white mica, quartz, and plagioclase in a large crystal of plagioclase. Observe that the large lath of muscovite (in the centre) is twinned; the trace of the twin plane is shown by a broken line. (Sh Lz C 3-Late-kinematic aplite dyke.)

Potash-feldspar. Mainly microcline, but film perthite is also occasionally visible. Characteristic microcline cross-hatching is sometimes seen as an indistinct grid. Most crystals are irregularly outlined. Zoning in microcline is strikingly present. Inclusions of plagioclase and quartz are frequent, but mica inclusions are nearly absent in potash feldspar.

Quartz. Often shows strain-shadows. Irregular cracks traverse the crystals.

Biotite. Shows very weak orientation. Pleochroism: Z = reddish-brown; Y = yellowish-brown; X = golden yellow. Pleochroic halos surround monazite.

Table 7. *Modal analyses (Vol.-%) of the late-kinematic aplite dyke at Lavertezzo*

No.	Specimen Sh Lz	Quartz	K-feldspar	Plagioclase	Biotite	Muscovite	Accessories
1	C 3	26.2	31.1	40.3	1.8	1.0	0.6
2	G 4	24.0	25	46	3.2	0.6	1.2
3	M 4 b	24.4	30.2	42.6	2.4	—	0.6
4	P 3 b	25.2	28.6	40.7	4.5	—	1.0
	Average	24.9	28.7	42.4	3.0	0.4	0.8

Alteration to chlorite with granules of released iron ore is common. Sometimes the chloritized biotite takes the form of fine multidirectional needles.

Muscovite. Occurs in very subordinate amounts. The author distinguishes two types. First, the laths with distinct cleavage and occurring in interlamination relationship with biotite. Second, those white micas which occur as inclusions in plagioclase.

Apatite, iron ore and a notable amount of secondary chlorite are accessory minerals.

6. Quartzo-feldspathic veins

Both regular and irregular quartzo-feldspathic veins are present. These leucocratic veins are a few millimeters to a decimeter thick and several meters long. They are concordant as well as discordant or oblique to the foliation in the gneisses. The discordant veins often cut the concordant ones and sometimes they grade imperceptibly into the surrounding leucocratic gneiss. At one place a discordant vein is cut by a late-kinematic quartz body. The concordant veins occasionally show a weak planar structure on their outer borders, while their inner portion is entirely massive, like the discordant veins. At times a single vein may be both discordant and concordant along its extension. Several veins are without observable feeder channels and occur as isolated bodies in the country-rock.

The veins are usually medium-grained and aplitic, but relatively coarse-grained veins are also found. Again, the grain-size may change along the length of a vein. These veins are similar to the leucocratic gneisses in mineral composition and are composed of quartz, oligoclase (An 20%) and a small amount of biotite. Microcline and at times muscovite and garnet are also present; the discordant veins contain microcline in notable amounts (ca. 8 Vol.-%).

Those veins which do not show any apparent connection with an outside source are regarded to be the result of segregation. The plagioclase composition of such quartzo-feldspathic veins is the same as that of the acid gneisses. The discordant-concordant character of veins is indicative of considerable mobility of the vein material which was injected towards the end of the main phase of deformation-crystallisation.

B. Rozzera

1. Gneiss

All the rocks under this heading show gneissose structure. Texture is crystalloblastic with biotite lepidoblasts. Hornblende, when it occurs, is xenomorphic. On the basis of the mineral proportions (see Table 8), three types of gneissic rocks can be distinguished at Rozzera:

Table 8. *Modal analyses (Vol.-%) of gneisses at Rozzera*

a) Leucocratic gneisses

No.	Specimen Sh Rz	Quartz	K-feldspar	Plagioclase	Biotite	Accessories
1	A 15	22.5	8.4	51.5	15.0	2.6
2	C 6	26	4	56	10	4
3	C 10	24	1.2	57.8	16	1.0
4	D 7	30.1	2.0	54.0	13.1	0.8
5	D 9	23.7	5.8	60	8	2.5
6	D 17	31	6.3	46.0	15.2	1.5
7	E 13	25.4	4.0	57.0	12.0	1.6
8	F 3	29.2	6.5	53.8	8.5	2.0
9	G 14 c	32.3	4.0	58.0	11.6	4.1
10	L 7	30.0	2.4	56.6	10.4	0.6
11	M 7	24.2	4.3	57	12.5	2.0
12	P 3	27	7.6	49.4	13.6	2.4

b) Mesocratic biotite-oligoclase-gneisses

No.	Specimen Sh Rz	Quartz	K-feldspar	Plagioclase	Biotite	Accessories
1	A 20	19.5	—	44.7	33.2	2.6
2	C 12	23.0	—	45.2	30	1.8
3	E 13 a	21.3	1.0	42	34	1.7
4	F 6 a	16.5	1.2	50.4	29.4	2.5
5	F 9	15.0	0.8	46.6	36.0	1.6
6	G 10	18	—	46	35	1.0
7	J 2 a	19.8	—	51.8	26.3	2.1
8	J 4	19	—	50	28	2.0
9	L 3	20.8	2.0	48.0	27.2	2.0
10	M 4 a	16.7	0.6	45.3	36	1.4

c) Hornblende-biotite-gneisses

No.	Specimen Sh Rz	Quartz	Plagioclase	Biotite	Hornblende	Accessories
1	D 5 b	15.6	46.6	12.0	24	1.8
2	K 9	17	47	20	15	1.0
3	L 12	12.6	51.0	20.4	14	2.0
4	M 6	11.5	45.2	17.8	22	3.6
5	N 6	13.7	43.0	24.6	16.2	2.5

a) *Leucocratic microcline-bearing biotite-oligoclase-gneiss* (type example Sh Rz C_6). *Oligoclase* (56 Vol.-%, An 26), shows inverse zoning and well-developed twinning. *Quartz:* 26 Vol.-%; *Microcline:* 4 Vol.-%. *Biotite* laths (10 Vol.-%) are small (0.5 mm) and show pleochroic halos around monazite. Chloritised biotite is also seen. An important accessory mineral is *orthite* which occurs as independent crystals as well as in association with epidote and apatite. Muscovite, iron ore and sphene are also present.

b) *Mesocratic biotite-oligoclase-gneiss* (type example Sh Rz G_{10}) grades imperceptibly into hornblende-bearing gneiss on the one hand and microcline-bearing biotite-oligoclase-gneiss on the other. The gneiss attains sub-augen to flaser-structure due to variation in its grain-size. The augen are commonly made up of plagioclase. Sometimes the biotite-laths, quartz and feldspar (plagioclase) are so small that the gneiss becomes fine-grained and appears slightly darker than similar medium- to coarse-grained types.

Plagioclase (46 Vol.-%) is strongly zoned. The zoning is commonly normal, but inverse zoning is also present. Anorthite percentage varies between 27–30. *Biotite* (35 Vol.-%). Laths are aggregated and alternate with quartz and plagioclase bands in the rock. Pleochroic halos around orthite inclusions are common.

Quartz (18 Vol.-%) occurs in big as well as in small crystals. Orthite and sphene are important accessory minerals (about 2% by volume). Apatite, secondary chlorite, and zircon are also present. Absence of microcline and muscovite is noteworthy.

c) *Hornblende-biotite-gneiss* (type example Sh Rz K_9). These gneisses occur mostly near amphibolites. Interesting is the gradual transformation of these hornblende gneisses into biotite-gneiss. This change is noted both along and across the strike.

Plagioclase (48 Vol.-%): crystals are mostly subhedral (An 30–38%). Inverse zoning is present. Sieve-structure is visible in big crystals in which quartz, biotite, and hornblende occur as inclusions. *Biotite* (20 Vol.-%): pleochroism from dark brown to light brown. Laths are associated and intergrown with hornblende. *Hornblende* (15 Vol.-%): $2V_\alpha = 80°$. Porphyroblasts are without exception poikiloblasts. Elongated crystals conform to the biotite orientation. Small equant crystals show twinning. Pleochroism is as follows:

Z = green to bluish green,
Y = brownish green,
X = greenish yellow.

Other constituents of the rock are *quartz* (17 Vol.-%) and sphene (0.8%). Accessory minerals are apatite, clinozoisite, iron ore and zircon.

2. Amphibolite (see Table 9)

These rocks occur as thin bands, a few tens of meters long, which alternate with thin bands of gneiss. There are also thick bands and lenses of amphibolites which are bordered by mesocratic biotite-gneiss. Some lenses occur as schollen in the leucocratic gneiss bands. The amount of hornblende and biotite is more variable than plagioclase in these amphibolites at Rozzera. When the amount of hornblende exceeds 40%, no foliation is discernible in the amphibolites. Quartz-plagioclase veins are seen penetrating the amphibolites, and on the borders of these veins biotite dominates over hornblende.

Texture. Crystalloblastic. Poikiloblastic texture is shown by hornblende porphyroblasts.

Hornblende crystals commonly have ragged extremities. Basal sections are usually xenomorphic, but equant crystals are also present. Elongated crystals

Table 9. *Modal analyses (Vol.-%) of amphibolites at Rozzera*

No.	Specimen Sh Rz	Quartz	Plagioclase	Biotite	Hornblende	Accessories
1	B 17	6.7	35.0	15.5	41.0	1.8
2	B 17 a	10.5	32.5	16.0	38.3	2.7
3	B 20	4.4	20	11	62.1	2.5
4	B 20 a	5.2	23	14.9	54.3	2.6
5	D 3	8	36.5	22	30.2	3.3
6	D 5 b	10.5	42.1	20.2	24.4	2.8
7	E 7	5	30	9.8	61	4.2
8	E 8	8.2	38.0	20.0	30.2	3.6
9	G 14 b	18	31.5	21.5	25	4.0
10	G 14 d	6.4	38.8	1.8	51.0	2.0
11	M 9	11.0	38.3	18.1	31.0	1.6
12	Q 4	15.0	42.4	22.0	18.6	2.0
13	R 2	14.2	33.4	30.3	20.8	1.3
14	S 4	13.6	40.0	25.0	20.0	1.4

are intimately associated with biotite, and both define a common "s"-plane. Porphyroblasts attain sizes of up to 5 millimeters.

Biotite. Derivation from hornblende is at places evident in that the biotite laths lack cleavages and their outlines show green pleochroism, while the main part is brown to dark brown. Moreover, sphene occurs in close contact with such biotite laths; this sphene is regarded as a by-product of the hornblende-biotite-transformation.

Plagioclase. Inversely zoned crystals are not uncommon. Anorthite percentage is 30–38.

Quartz, sphene, orthite, apatite and zircon are other mineral constituents.

3. Aplitic mobilisate (see Table 10)

It occurs both concordantly and discordantly in the gneiss complex at Rozzera. There are many mica-rich stripes and schollen inside the mobilisate. These inclusions possess the same trend as the general schistosity. Aggregated biotite-stripes define an apparent orientation, although individual biotite flakes in the rock are differently oriented. The distribution of the minerals in the mobilisate is, however, not strictly uniform. Grain-size variation also occurs, and the rock may become fairly coarse-grained.

Texture. Allotriomorphic; sieve-structure is frequently shown by plagioclase, sometimes also by microcline.

Quartz (20–37 Vol.-%). Two kinds of occurrences of quartz are distinguishable:

1. As small inclusions in other minerals, commonly in feldspars (Fig. 12).
2. As relatively big crystals associated with feldspars. Strain-shadows and cracks are seen without exception.

Plagioclases (45–60 Vol.-%) are subidiomorphic to xenomorphic crystals

Table 10. *Modal analyses (Vol.-%) of aplitic mobilisate at Rozzera*

No.	Specimen Sh Rz	Quartz	K-feldspar	Plagioclase	Biotite	Accessories
1	A 5	18.4	20.1	57.9	2.0	1.6
2	A 8 a	23.6	15.4	55.8	4.5	0.7
3	B 14	26.3	8.0	56.5	4.2	1.0
4	B 14 a	27	14	54	4	1
5	C 6	28.8	13.2	53.4	4.0	0.6
6	C 9	29.8	7.6	60.3	2.8	0.5
7	D 5 a	34.3	11.6	49.0	3.0	2.1
8	D 10	31.6	12	53.0	3.1	0.3
9	F 12	30	8	58	3	1.0
10	G 1	24.3	12.6	55.0	5.9	2.2
11	G 1 b	24.7	15.5	55.4	2.6	1.8
12	G 9 a	35.4	10.5	50.1	3.0	1.0
13	G 14	34.2	10.8	52.0	2.4	0.6
14	H 10	22.7	9.0	60.6	6.3	1.4
15	H 10 a	18.4	15.8	60.5	4.6	0.7
16	J 2 b	37.8	16.8	45.8	7.0	2.6
17	J 9	24.8	18.2	52.2	3.4	1.4
18	M 8	26.6	10.7	59.6	2.3	0.8
19	M 8 a	23.4	14.3	59.0	2.8	0.5
20	M 8 b	24	13	58	3.3	1.7
21	P 1	21.5	12	60.5	4.3	1.7
22	P 2	21.6	14.2	60.8	2.3	1.1
23	P 3 a	25.4	10.6	48.2	4.8	1.0
24	R 1	25.6	15	53.1	5.2	1.1
25	S 3 c	25.8	16	52	5	1.2

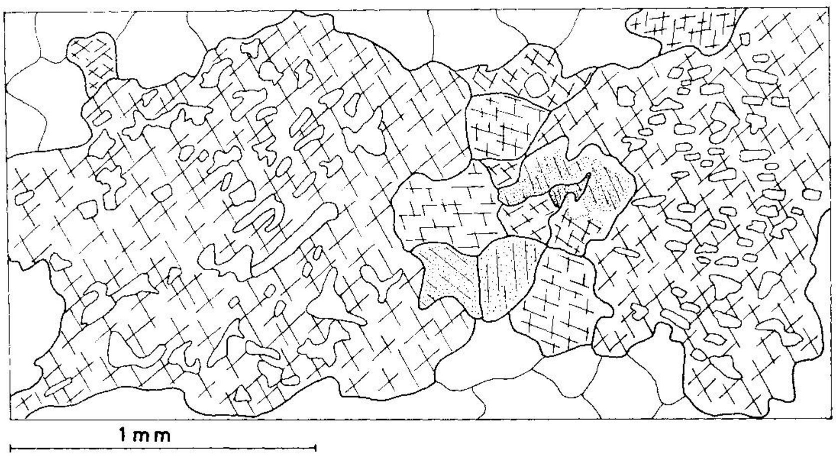


Fig. 12. Quartz-inclusions in microcline crystals. Note that both microclines have the same crystallographic orientation. The quartz-inclusions in each microcline show the same optical orientation, but their elongation-direction is different; these directions make an angle of about 130°. (Sh Rz A 5-Aplitic mobilisate.)

(An 22–24%). Plagioclase adjacent to K-feldspar possesses an albite rim. Some plagioclases show myrmekite. Replacement by microcline is common. Zoning is rare.

Alkali feldspars include microcline, perthite, and antiperthite. They collectively amount to 8–15 Vol.-% of the rock. *Microcline* is xenomorphic with variable grain-size (0.2–4 mm). Cross-hatching is usually present. *Perthite* occurs as excellent stringlet-, patch-, and bead-perthite. Few perthites show small plagioclase crystals with well-developed twin lamellae and albite rim.

Antiperthite occurs in varying amounts, and exhibits exsolution phenomena in which small and patchy microclines with a similar crystallographic and optical nature are embedded in big plagioclase crystals.

Biotite occurs as short laths without a definite orientation. Most laths are chloritized and associated with garnet.

Garnet is present in small amounts and is not uniformly distributed. It follows the trail of biotite-stripes and may have some relation with the latter. The garnet has D = 4.20 and shows reddish-brown to brown colour. X-ray analysis (powder-method) gave the following composition: almandine 80%, grossularite 15%, and pyrope 5%.

Muscovite, apatite, secondary chlorite, iron ore, and clinozoisite are accessory minerals.

4. Leucocratic veins

As stated already, there are at least two generations of leucocratic (aplitic) veins at Rozzera. This distinction can only be made in the field where the two types of veins appear to find their source in the aplitic mobilisate and one generation is seen cutting the other (Plate I, Fig. 4). Both generations intersect gneisses and amphibolites and sometimes also the aplitic mobilisate. In the gneisses and amphibolites the veins have biotite-rich borders.

a) *First-generation veins* are 1 cm to a few dm thick. Grain-size varies from vein to vein (0.5–2 mm) and even along the length of individual veins. Megascopically, these veins are mainly composed of quartz and feldspar; biotite is of sporadic occurrence. In *texture*, these veins are granular. Quartz amounts to 36–45% by volume. Plagioclase (48–57 Vol.-%) has an anorthite content between 20 and 25%. Microcline and biotite occur in small amounts (max. 2%). Garnet, apatite, and zircon are occasionally present.

b) *Second-generation veins*. These veins are almost solely composed of quartz and plagioclase (An 20%) which show a granular texture like that shown by the minerals of first-generation veins. Small microcline crystals are also visible in some veins. The veins are normally a few millimeters thick. Chloritized biotite is also present.

5. Pegmatite

It commonly occurs as small discordant bodies and fills up cross- to oblique-fractures in the rock-complex. Displacement of adjoining rock-bands along these pegmatites is common (Fig. 3). However, there are also concordant pegmatites which grade into aplite. Micas in the pegmatites occur in small bundles and also as individual laths. In concordant pegmatites the micas have perfect orientation, but this is indistinct in the discordant pegmatites. There are also discordant to semi-discordant quartz veins which apparently follow cracks in the rock-complex and produce a sort of drag-effect on the adjacent rock-bands.

Texture. Coarsely crystalloblastic to granoblastic.

Mineral constituents consist mainly of quartz and feldspars which are intersected by numerous irregular cracks. Plagioclases (An 24–28%) are commonly well-twinned, and also show normal and inverse zoning. Biotites are bent at places. The laths are associated with sphene and zircon. These two minerals plus garnet, apatite and iron ore constitute the accessory minerals of the rock.

STRUCTURAL ELEMENTS

A. Lavertezzo

Structural elements present in the outcrop include folds, foliation (schistosity), lineation, faults, joints and others, the description of which is given below.

1. *Folds.* The banded gneisses of Lavertezzo characteristically show antiforms and synforms (see Plate II, Fig. 1), which are usually asymmetrical, with slightly bent fold-axes and curved axial surfaces. Thus the folds are triclinic and nonplane noncylindrical in the definition of Turner and Weiss (1963, p. 108). Their axial surface dips very steeply, from 60° to 80° to the SW. The plunge of the fold-axis is moderate and can differ in adjacent antiforms and synforms; locally the plunge is steep. In some structures the trend as well as the plunge of the axis do not remain constant along the whole length of the individual folds. The folds therefore possess a sinuous trend (see map Plate III).

At a few places, there are excellent examples of refolding which is clearly visible at the noses of some folds. The second fold-axes are subparallel to the earlier fold-axes. There are also several rootless intrafolial folds in mesocratic gneisses. Their fold-axes coincide with the axial-plane schistosity (see below).

2. *S-surface.* Two types of s-surfaces are recognised in the rocks of Lavertezzo. The first corresponds to lithologic layering or banding and the second to the axial-plane schistosity of folds. In the outcrop, the s-surface (foliation) caused by compositional or lithologic layering generally coincides with the axial-plane schistosity. But at the noses of folds, as is well seen in three-dimensional sections, the axial-plane schistosity becomes sub-parallel and locally transects the compositional layering (Stoffbänderung). Hence, the

penetrative s-surface due to the axial-plane schistosity is designated s_2 and the s-surface due to compositional layering s_1. The mica flakes always lie in the axial-plane schistosity (s_2) (Plate II, Fig. 4).

3. *Lineation.* At all places, the direction and plunge of lineation conform to the fold-axis. Hence this is B-lineation. It is marked mostly by mica-orientation, but is also indicated by stripes or corrugations of leucocratic material which correspond to the mica-orientation. At some places, a second lineation is also apparent, particularly at the nose of some folds, where this lineation deviates very slightly from the dominant one.

4. *Joints.* A predominant joint-set occurs normal to the fold-axes, and hence the joints are cross-joints (ac-joints). They are tensional joints and are considered to have developed in the non-flowing rocks under residual stress conditions. It should be mentioned here that some pegmatites and aplites follow this joint system. At one place, a cross-joint intersects the late-kinematic aplite dyke. There are also a few oblique joints which locally have an appearance of feather-joints. The joints are hair-thin to a few millimeters wide, and almost all are filled with chlorite and quartz, occasionally with pyrrhotite. The joints in the leucocratic gneisses are filled with quartz in greater amounts than those crossing the mesocratic gneisses and amphibolites. On either side of these joints the biotites in the host rock have been chloritised. These features indicate small-scale diffusion even in the post-kinematic stage.

Lastly, there are cracks or fissures (although not common) which run parallel to the foliation of the rocks. These cracks are cut by cross-joints and are therefore older than the latter (see Plate III).

Text-description of the fabric diagrams Fig. 13

a) Quartz, optic axes of 200 grains in the same thin section of the leucocratic gneiss ((Sh Lz C 3 β) from which biotite poles, shown in figure b are measured. Contour intervals in per cent: (6–5)–4–0.5.

b) Biotite, 200 poles of (001) from a leucocratic gneiss (Sh Lz C 3 β) at the contact of the late-kinematic aplite dyke. Contour intervals in per cent: (13–10)–6–2–0.5.

c) Biotite, 200 poles of (001) from a leucocratic gneiss (Sh Lz C 31) situated near the nose of a synform. Contour intervals in per cent: (14–12)–9–5–2–0.5.

d) Biotite, 200 poles of (001) from a leucocratic gneiss (Sh Lz C 60) situated on the nose of a synform. Contour intervals in per cent: (10–9)–7–5–2–0.5.

e) Biotite, 300 poles of (001) from a leucocratic gneiss (Sh Lz D 6) situated on the nose of an antiform. Contour intervals in per cent: (20–18)–12–6–2–0.3.

f) Biotite, 200 poles of (001) from a leucocratic gneiss (Sh Lz F 17) occurring between the nose and a limb of a synform. Contour intervals in per cent: (13–12)–10–7–3–0.5.

g) Biotite, 300 poles of (001) from a leucocratic gneiss (Sh Lz V 35). Contour intervals in per cent: (13–10)–7–4–1–0.3.

h) Biotite, 100 poles of (001) from the late-kinematic aplite dyke (Sh Lz C 3 α). Contour intervals in per cent: 8–7–6–5–1.

i) Quartz, optic axes of 100 grains from a quartz vein (2 mm thick) in an amphibolite (Sh Lz D 53). Contour intervals in per cent: (13–12)–8–5–1.

5. *Faults* are all sub-vertical, mostly dip-faults and are parallel to the joints. Oblique faults are also present. The fault-plane in all the cases is almost vertical. Some of the faults are pivotal, as evidenced by the affected pegmatite and its host rock. The fault-plane is sometimes lined with quartz. Slickensides and drag-folds are also to be seen. At one place, cross-joints are displaced along the fault-line. It is therefore concluded that faulting marks the last phase in the evolution of the structural features of the rocks at Lavertezzo.

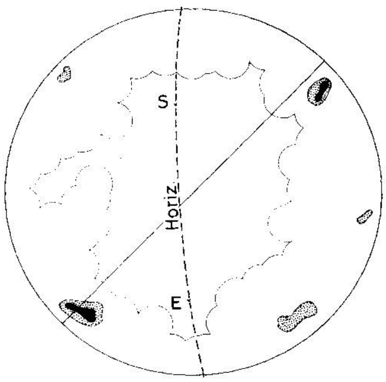


Fig. 13a

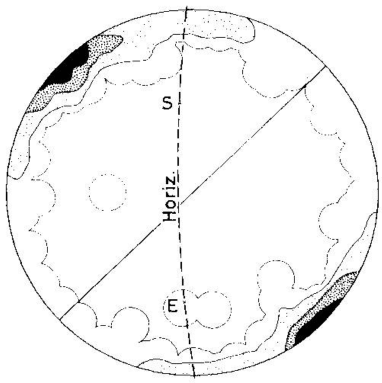


Fig. 13b

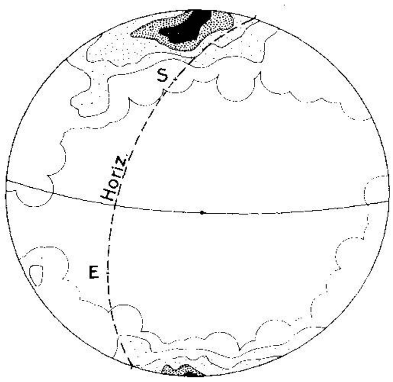


Fig. 13c

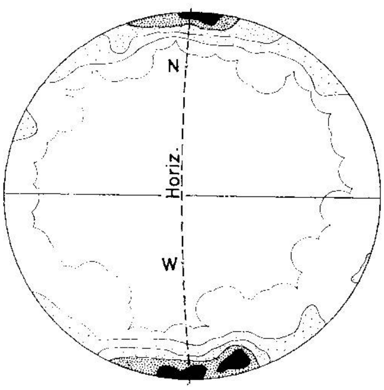


Fig. 13d

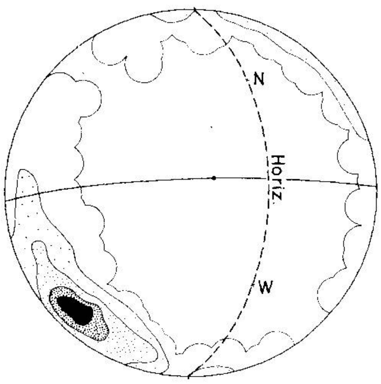


Fig. 13e

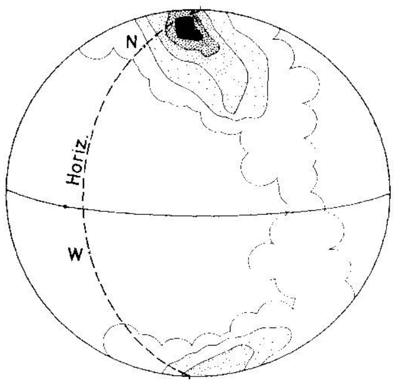


Fig. 13f

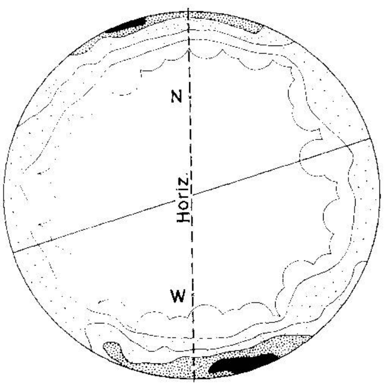


Fig. 13g

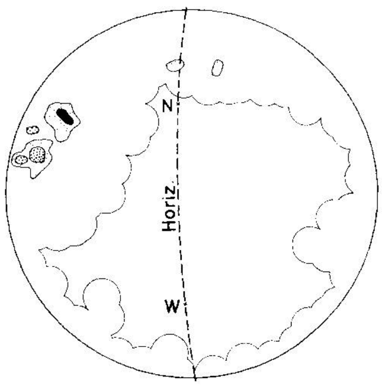


Fig. 13h

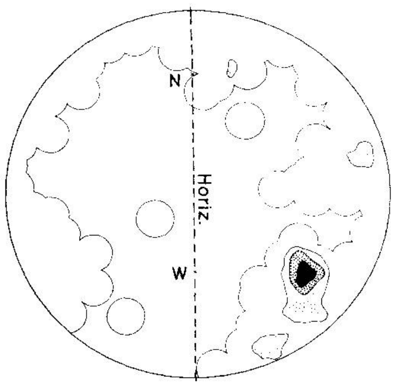


Fig. 13i

6. *Fabric studies.* Owing to the refolding of folds, particularly visible at their noses where s_1 (compositional layering) is sub-parallel to s_2 (axial-plane schistosity), microscopic analysis of biotite and quartz subfabrics was carried out for different parts of folds. This petrofabric analysis will also enable to assess structural homogeneity/heterogeneity in the rocks of Lavertezzo.

As seen from Fig. 13, out of six diagrams of biotite subfabrics from gneisses, only two diagrams (b and g) show orthorhombic symmetry and the rest monoclinic. Interesting is the occurrence of only one maximum in the diagrams – whether obtained from the nose or limb of folds. However, one diagram contains an additional maximum which lies very close to the peripheral maximum (Fig. 13d). All the diagrams show a remarkably well-developed ac-girdle.

The biotite diagram of the late-kinematic aplite dyke also displays one maximum and a peripheral girdle although only 100 poles could be measured (Fig. 13h).

In an attempt to check the relation between the lineation obtained from the microscopic analyses and that measured in the field, the maxima of all the diagrams were rotated into the geographical horizon, taken as the plane of projection. The girdle axis in these rotated diagrams coincides with the lineation measured in the field (Fig. 14 and Plate III). The lineations also agree with the corresponding fold-axes measured, directly or indirectly, in the field. Hence, the lineation is a B-lineation in the rocks of Lavertezzo.

These results lead one to conclude that the biotite-orientation is homotactic in relation to the mesoscopic structures in the studied rocks (cf. WENK, 1943, p. 270).

The subfabric diagram of biotite from the aplite does not bear any relation to the maximum defined by the biotite subfabric in the gneisses. This confirms the statement that the aplite is late-kinematic and was intruded after the formation of the axial-plane schistosity (cf. p. 228). It is, however, interesting to note that the girdle axis of the biotite maximum in the aplite approximates the pole of the joint-plane along which the aplite is intruded. If the said maximum is not accidental, it can be stated that the biotites in the aplite were oriented during the intrusion of the aplite parallel to the joint-plane. It may be recalled here that megascopically the aplite does not show any preferred orientation.

Finally, a comparison between the subfabric diagrams of quartz and biotite, prepared from the same rock, indicates that the quartz-orientation is entirely different from the biotite-orientation (cf. Figs. 13a and b); its orientation is rather the reverse to that of the biotite. An analogous case is found in the orientation of quartz from a quartz-vein which occurs inside an amphibolite. Here the maximum is strongly developed but with a weak peripheral girdle (Fig. 13h). When the rotated diagram (in Fig. 14) is viewed in relation to the

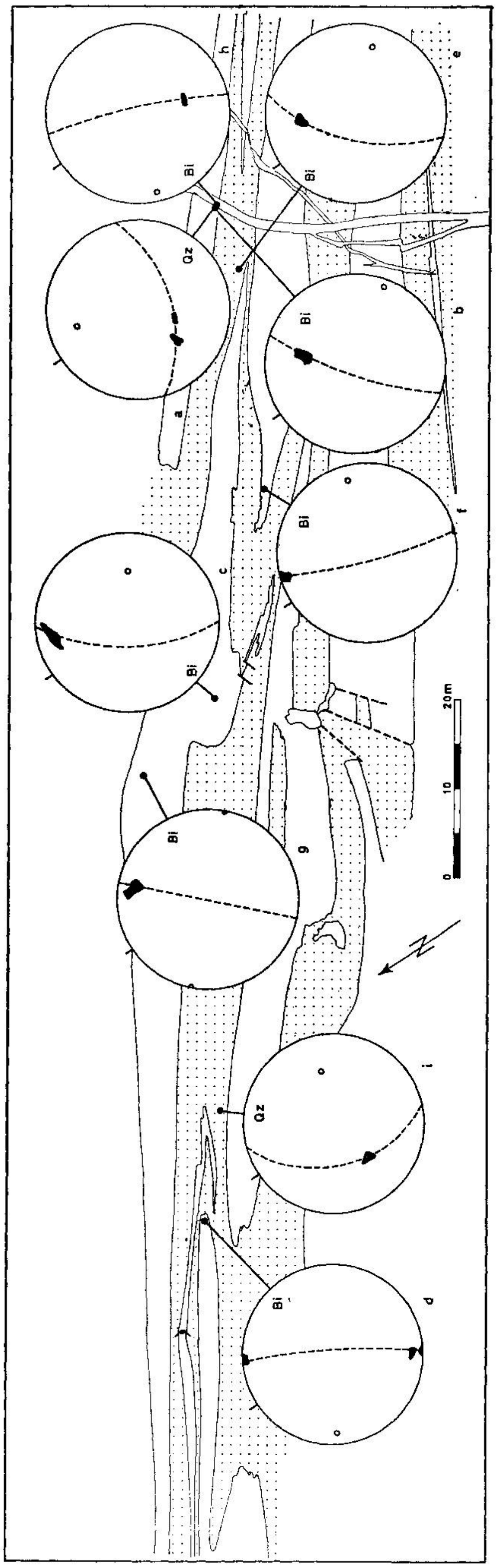


Fig. 14. Subfabric diagrams of biotite (Bi) and quartz (Qz) showing maxima and girdle axes (open circle), rotated into the plane of the geographical horizontal. Location of the diagrams in the simplified map of the Lavertezzo outcrop is shown. Small letters (a, b, . . . i) near the diagrams correspond to those of the diagrams in Fig. 13.

dip of the s-surface and the lineation thereupon, no relationship between quartz-orientation and the mesoscopic structures is noted. But the quartz-orientation in the gneiss and in the quartz-vein shows striking similarity. This suggests that the quartz-orientation is not related to the biotite-orientation. In other words, it is heterotactic with regard to the mesoscopic structures and biotite-orientation. The same relation was found by WENK (1943, p. 283), on a regional scale. On the basis of the uniform quartz-orientation in different parts of folds, he came to the conclusion that the quartz-orientation is almost unaffected by the componental movements of the rocks, and that the crystallisation of quartz postdates the main phase of deformation. The biotite-orientation, on the other hand, developed during the main phase of deformation.

Summarising, the refolding of folds at Lavertezzo took place about sub-parallel axes and the fold-axes approximate the lineations in the rocks. This coincidence is present not only on the mesoscopic scale but also on the macroscopic scale. It cannot be decided whether or not the folding and refolding were separated by a distinct interval in time. But the deflections in the direction and plunge of a single fold-axis suggest that the refolding probably resulted from flow. On the other hand, if this refolding is considered to be due to compressive or shearing stress, then the structural features in the studied outcrop would indicate a stress system varying from place to place. However, such a stress system seems rather improbable, hence the alternative that the refolding was due to unsteady flow of the rocks during which their rheologic state gradually changed in response to falling temperature. Although the mechanism of rock-flow is poorly understood, it is clear that flow is due to pressure gradients at high temperatures; factors affecting rock-flow are, of course, numerous.

B. Rozzera

1. *Structural features.* There are two surfaces, one formed by axial-plane schistosity (s_2) and the other by compositional layering (s_1) of the rocks. Both s-surfaces generally coincide, but on the noses of folds s_1 becomes sub-parallel to s_2. The foliation of the rocks strikes N 50° W and dips gently, 20–30° to the NE.

Folding in the rocks is common and the folds are mostly isoclinal. The fold-axis always coincides with the trend of the s-surface (foliation) and the lineation observed upon it. Refolding of folds has not been noted.

Lineation could not always be measured, since the outcrop shows an even surface due to erosion by the river. But the biotite elongation invariably parallels the foliation and fold-axis.

There are a few small fractures or faults which are filled with pure quartz or pegmatitic material. These faults are oblique as well as normal to the foliation (see map, Fig. 3). Across these faults the rock-bands undergo a horizontal offset of a few dm. Slickensides and dragfolds are not visible.

In the aplitic mobilisate there are many cracks that are filled with quartz and occasionally with chlorite. These cracks are about a meter long and may be up to 5 cm broad. The gneissic rocks are almost devoid of any joints or cracks.

2. *Fabric studies.* Although there exists a parallelism between lineation and fold-axis, a fabric study of biotite was undertaken in the nose of a fold, formed of mesocratic biotite-gneiss and leucocratic gneiss. The aim was to examine if the orientation is affected by the grain-size and proportion of biotite, since the leucocratic gneiss is coarser than the mesocratic gneiss.

A thin section which included both gneisses was cut almost normal to the fold-axis. Fabric diagrams of biotite are presented separately for leucocratic and mesocratic gneisses in Figs. 15a and b. The diagrams show differences: the biotites in the mesocratic gneiss show a stronger orientation than in the leucocratic gneiss. Furthermore, a composite diagram was constructed from

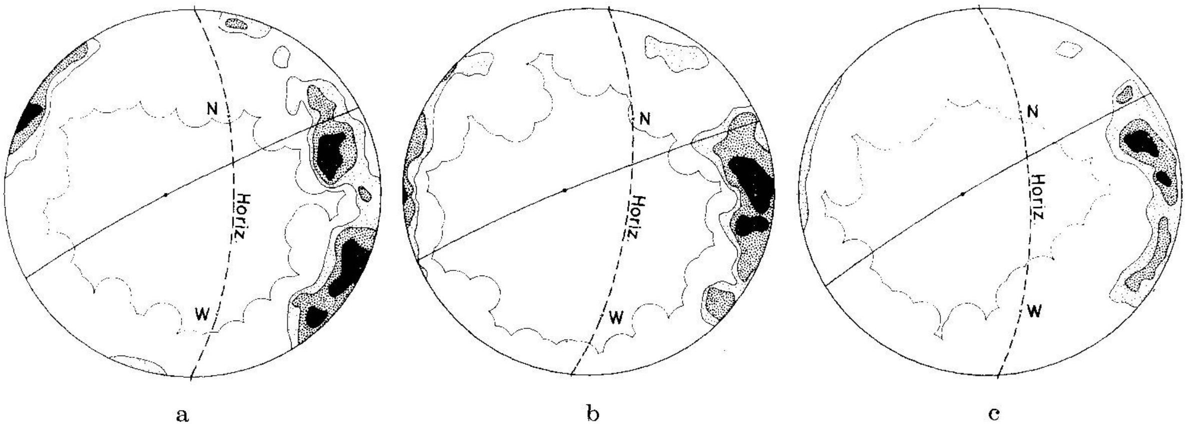


Fig. 15.

a) Selective diagram of 250 (001) poles of biotite in a leucocratic gneiss (Sh Rz E 13) from the part of a synform where the mesocratic gneiss occurs (see figure b). Both rocks were included in the same thin section. Contour intervals in per cent: (6–5)–4–3–0.4.

b) Selective diagram of 200 (001) poles of biotite in a mesocratic gneiss (Sh Rz E 13) from the nose of a synform. Contour intervals in per cent: (7–6)–4–3–0.5.

c) Composite diagram of 450 (001) poles of biotite; the data of figures a and b are combined. Contour intervals in per cent: (6–5)–4–3–0.1.

these two selected diagrams. The composite diagram resembles very closely, with regard to the symmetry and maxima, the selective diagram from the mesocratic gneiss. The diagram of biotite from the leucocratic gneiss, strictly speaking, shows triclinic symmetry. But it has a close approximation to the monoclinic symmetry shown by the other two diagrams.

The mica subfabric of the whole section shows a homogeneity with respect to the fold-axis, as seen from the position of the girdle axis of the rotated maxima in each diagram (Fig. 16). The appearance of a third maximum and its asymmetrical position in relation to the other two maxima in one diagram (Fig. 16a) can be ascribed to differences in the mechanical behaviour of these rocks and not to the influence of grain-size or deflection in schistosity.

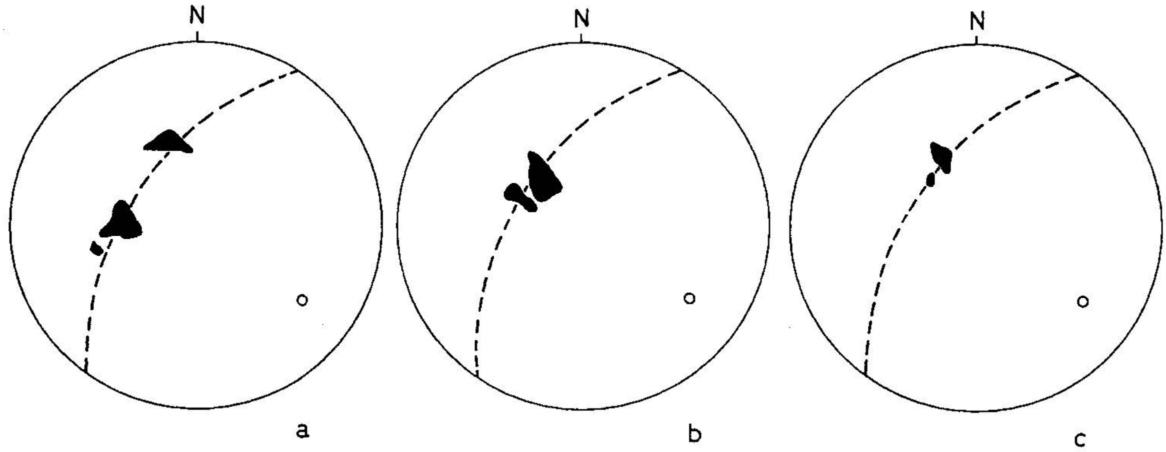


Fig. 16. The same diagrams in Fig. 15 are shown with their maxima and girdle axes, rotated into the plane of the geographical horizontal.
a) leucocratic gneiss, b) mesocratic gneiss, and c) composite diagram of the gneisses.

Chemically analysed rocks and their brief description (see Table 11)

Analysis	*Specimen No.*	*Location*
No. 1	Sh Rz A 17	Rozzera, 1300 m Coordinates: 726,5/126,5

A leucocratic *aplitic vein* in a mesocratic biotite-gneiss, very similar to the biotite-gneiss Vz 216 (see analysis No. 8). Medium-grained (ca. 1 mm grain-size). Quartz 44%; Plagioclase (An 20–22%) 48.5%; K-feldspar 4.5%; Biotite 3%.

No. 2	Vz 218 (No. 561 in the Chemismus schweiz. Gesteine, 1956)	Rozzera-gorge, 1320 m 706,83/126,67

Garnet-bearing *aplitic mobilisate*, medium to coarse-grained. Quartz 29%; K-feldspar 23%; Plagioclase (An 22–24%) 43%; Biotite 1%; Garnet 1%.

No. 3	HP 417 (in PREISWERK, 1931)	Lavertezzo, 530 m. 707,8/124,1

Late-kinematic *aplite dyke*. Quartz 26%; K-feldspar 30%; Plagioclase (An 17–19%) 40%; Biotite 3%; Accessories 1% (muscovite, apatite, chlorite etc.).

No. 4	Sh Lz P 3	Lavertezzo, 530 m. 707,8/124,1

Late-kinematic *aplite dyke*. Quartz 25%; K-feldspar 28.5%; Plagioclase (An 18–20%) 41%; Biotite 4.5%; Accessories 1%.

No. 5	Vz 201 (No. 561 in the Chemismus schweiz. Gesteine, 1956)	Alpe Rozzera, 1320 m 706,55/126,5

Verzasca-gneiss, leucocratic mica-microcline-oligoclase-gneiss. Quartz 28%; Plagioclase (An 18–26%) 51%; K-feldspar 8.5%; Muscovite 4.5%; Biotite 7.5%; Accessories 0.5% (zircon, apatite etc.)

Analysis	*Specimen No.*	*Location*
No. 6	Vz 215 (No. 562 in the Chemismus schweiz. Gesteine, 1956)	Monte Rozzera, 1300 m 706,85/126,75

Microcline-bearing mica-oligoclase-gneiss, the *Verzasca-gneiss* interlayered with paragneiss Vz 216 (see analysis No. 8). Quartz 27%; Plagioclase (An 21–25%) 54%; K-feldspar 8%; Biotite 7%; Muscovite 4%.

No. 7	Sh Rz K 9	Rozzera, 1300 m. 726,5/126,5

Mesocratic *hornblende-biotite-gneiss*. Medium-grained. Quartz 17%; Plagioclase (An 30 to 38%) 47%; Biotite 20%; Hornblende 15%; Accessories 1% (sphene, apatite, and iron ore).

No. 8	Vz 216	Mte. Rozzera, 1490 m 706,85/126,75

Mesocratic *biotite-oligoclase-gneiss* interlayered with microcline-bearing mica-oligoclase-gneiss, Vz 215 (see analysis No. 6). Quartz 32%; Plagioclase (An 23–28%, normal zoning) 42%; Biotite 25%; Accessories 1% (apatite, iron ore etc.)

No. 9	Sh Lz G 44	Lavertezzo, 530 m. 707,8/124,1

Microcline-bearing biotite-oligoclase-gneiss. Quartz 26.5%; K-feldspar 6.2%; Plagioclase (An 25–26%) 52.5%; Biotite 10.2%; Muscovite 3.2%; Accessories 1.4%.

No. 10	Sh Lz K 23	Lavertezzo, 530 m. 707,8/124,1

Microcline-bearing biotite-oligoclase-gneiss. Quartz 25.3%; Plagioclase (An 22–24%) 55.5%; K-feldspar 2.7%; Biotite 15.2%; Accessories 1.3% (muscovite, apatite etc.).

No. 11	Sh Lz M 4	Lavertezzo 530 m. 707,8/124,1.

Microcline-bearing biotite-oligoclase-gneiss. Quartz 26.8%; Plagioclase (An 25–27%) 60.1%; K-feldspar 2.3%; Biotite 10.2%; Accessories 0.7% (muscovite, apatite, zircon etc.).

No. 12	Sh Lz N 4	Lavertezzo, 530 m. 707,8/124,1

Microcline-bearing biotite-oligoclase-gneiss. Quartz 22.5%; Plagioclase (An 20–22%) 59%; K-feldspar 7.5%; Biotite 10.1%; Accessories 1% (muscovite, apatite, monazite).

No. 13	Sh Lz P 5	Lavertezzo, 530 m. 707,8/124,1

Microcline-bearing biotite-oligoclase-gneiss. Quartz 26.1%; Plagioclase (An 24–25%) 55%; K-feldspar 8.8%; Biotite 9.7%; Accessories 0.4% (muscovite, apatite etc.).

No. 14	Sh Lz V 36	Lavertezzo, 530 m. 707,8/124,1

Microcline-bearing biotite-oligoclase-gneiss. Quartz 25%; Plagioclase (An 22–25%) 54.6%; K-feldspar 9%; Biotite 9.7%; Accessories 1.7%.

No. 15	Sh Lz C 22	Lavertezzo, 530 m. 707,8/124,1

Amphibolite occurring as a schollen in leucocratic gneiss. Quartz 15.2%; Plagioclase (An 66–100%) 20%; Biotite 1.2%; Hornblende 60.2%; Accessories 3.4% (zoisite, iron ore etc.).

No. 16	HP 414 (in PREISWERK, 1931)	Alpe di Cangello

Microcline-bearing biotite-oligoclase-gneiss, representing a marginal facies of the Verzasca-gneiss. Quartz 30%; K-feldspar 3.5%; Plagioclase (An 24–26%) 55.2%; Biotite 10%; Accessories 1.3%.

No. 17	HP 493 (in PREISWERK, 1931)	Alpe Rozzera, 1300 m

Two-mica feldspar-gneiss, representing a core of the Verzasca-gneiss. Quartz 26%; K-feldspar 13.4%; Plagioclase (An 20–26%) 50.6%, mica 8.8%. Accessories 1.2%.

No. 18	Ng 36	

Average analysis (given by P. NIGGLI, 1936, Chemismus schweiz. Gesteine) of the Verzasca-gneiss. (Ref. Beitr. geol. Karte Schweiz, 1936, p. 145.)

Table 11. *Chemical analyses of the rocks of Lavertezzo, Rozzera, and neighbouring areas in the Valle Verzasca, Canton Ticino*

	Aplite (Leucocratic granular)				Gneisses										Schollen	Verzasca gneiss			
	Rozzera		Lavertezzo		Rozzera				Lavertezzo						Lavertezzo	Verzasca			
	Vein	Mobilisate	Dyke		Leucocratic		Mesocratic		Only Leucocratic						Amphibolite				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Weight %	A_{17}	Vz_{218}	Hp_{417}	P_3	Vz_{201}	Vz_{215}	K_9	Vz_{216}	G_{44}	K_{23}	M_4	N_4	P_5	V_{36}	C_{22}	Hp_{414}	Hp_{493}	Ng_{36}	Weight %
SiO_2	76.60	73.41	73.23	74.90	73.18	70.74	58.00	66.54	70.00	70.90	70.40	69.30	69.80	69.90	54.40	69.59	72.67	71.53	SiO_2
TiO_2	0.10	tr.	0.19	0.10	0.19	0.77	0.70	1.58	0.30	0.30	0.30	0.20	0.40	0.40	2.0	0.56	0.25	0.45	TiO_2
Al_2O_3	14.50	15.20	15.40	14.70	15.12	15.55	18.80	14.02	16.30	16.60	17.00	16.50	15.90	15.80	14.30	15.27	13.89	14.91	Al_2O_3
Fe_2O_3	—	0.03	0.66	—	0.31	0.31	0.60	0.60	0.30	0.60	0.50	0.10	0.60	0.70	1.0	1.28	0.86	0.94	Fe_2O_3
FeO	0.60	0.60	0.67	0.60	0.69	1.69	4.40	4.84	2.00	1.50	1.70	1.60	1.90	1.90	8.40	1.95	1.28	1.41	FeO
MnO	—	0.02	—	—	0.02	0.01	—	0.03	—	—	—	—	—	—	0.20	—	0.04	0.13	MnO
MgO	0.20	0.19	0.27	0.30	0.70	0.61	3.30	2.58	0.90	0.80	0.80	0.70	1.10	0.90	6.30	0.78	0.41	0.50	MgO
CaO	2.90	2.15	1.69	1.50	2.40	2.50	5.90	2.64	2.80	2.90	3.00	2.70	3.00	2.90	11.00	3.52	2.28	2.45	CaO
Na_2O	3.90	3.53	4.82	4.40	4.59	4.98	5.10	3.17	4.50	4.10	4.30	5.40	4.80	5.00	0.30	4.18	4.98	4.64	Na_2O
K_2O	0.80	4.14	3.02	2.60	2.64	2.12	2.00	2.37	1.70	1.40	1.20	2.30	1.50	1.50	0.70	2.22	3.34	2.50	K_2O
P_2O_5	—	0.05	0.22	—	0.09	tr.	—	0.03	—	—	—	—	—	—	—	0.32	0.04	0.09	P_2O_5
H_2O^+	0.40	0.77	0.20	0.90	0.32	0.70	1.30	1.26	0.80	1.00	0.90	1.10	0.80	0.70	1.60	0.58	0.45	0.50	H_2O^+
H_2O^-	—	0.06	—	—	0.09	0.07	—	0.11	—	—	—	—	—	—	—	—	—	0.05	H_3O^-
Total	100.00	100.15	100.37	100.00	100.34	100.05	100.10	99.77	99.60	100.10	100.10	99.90	99.80	99.70	100.20	100.25	100.49	100.10	Total
Niggli values	A_{17}	Vz_{218}	Hp_{417}	P_3	Vz_{201}	Vz_{215}	K_9	Vz_{216}	G_{44}	K_{23}	M_4	N_4	P_5	V_{36}	C_{22}	Hp_{414}	Hp_{493}	Ng_{36}	Niggli values
si	457.5	405	386.6	390.4	376	344	177.5	278	328.8	343.3	332.8	318.3	319.1	322.4	142.1	316.4	364.3	353.3	si
al	51.0	49.5	47.9	45.2	46	44.5	33.9	34.5	45.1	47.4	47.4	44.7	42.8	42.9	22.0	40.9	41.0	43.4	al
fm	4.8	4.5	7.7	15.6	9.5	12.5	27.7	34.5	15.2	14.0	14.1	11.3	16.8	15.9	45.3	17.1	11.8	13.5	fm
c	18.6	12.5	9.6	8.4	13	13	19.3	12	14.1	15.0	15.2	13.3	14.7	14.3	30.8	17.1	12.2	13.0	c
alk	25.6	33.5	34.8	30.9	31.5	30	19.0	19	25.6	23.6	23.3	30.8	25.6	26.8	1.9	24.9	34.9	30.1	alk
k	0.12	0.44	0.29	0.28	0.27	0.22	0.21	0.33	0.2	0.18	0.16	0.22	0.17	0.16	0.61	0.26	0.31	0.26	k
mg	0.37	0.36	0.28	0.75	0.55	0.35	0.54	0.46	0.41	0.41	0.4	0.42	0.45	0.39	0.54	0.31	0.26	0.27	mg
c/fm	3.88	2.77	1.24	0.54	1.39	1.08	0.70	0.35	0.93	1.07	1.07	1.18	0.87	0.90	0.68	1.0	1.03	0.96	c/fm
qz	254.8	171	147.1	166.7	150	124	1.2	171	126.3	148.8	139.3	95.0	116.4	115.2	34.2	116.8	124.6	132.8	qz
ti	0.4	—	0.8	0.4	0.62	2.9	1.6	5.0	1.1	1.1	1.1	0.7	1.4	1.4	3.9	1.9	0.9	1.7	ti
p	—	0.3	0.5	—	0.31		—		—	—	—	—	—	—	—	0.6	0.1	0.2	p
Cation %	A_{17}	Vz_{218}	Hp_{417}	P_3	Vz_{201}	Vz_{215}	K_9	Vz_{216}	G_{44}	K_{23}	M_4	N_4	P_5	V_{36}	C_{22}	Hp_{414}	Hp_{493}	Ng_{36}	Cation %
Si	72.08	68.8	67.69	68.88	67.9	66.0	53.46	63.5	65.68	66.62	65.96	64.37	65.26	65.34	52.63	65.19	67.30	66.81	Si
Ti	0.07	—	0.13	0.07	0.1	0.6	0.49	1.2	0.21	0.21	0.22	0.14	0.28	0.28	1.46	0.39	0.17	0.32	Ti

Al	16.00	16.8	16.78	15.93	16.5	17.1	20.42	15.8	18.03	18.38	18.77	18.06	17.52	17.40	16.31	16.86	15.16	16.41	Al
Fe‴	—		0.46	—	0.2	0.2	0.42	0.4	0.21	0.42	0.35	0.07	0.42	0.49	0.73	0.90	0.60	0.66	Fe‴
Fe″	0.47	0.5	0.52	0.46	0.6	1.3	3.39	3.9	1.57	1.18	1.33	1.24	1.49	1.49	6.80	1.53	0.99	1.10	Fe″
Mn	—	—	—	0.23	—	—	—	—	—	—	—	—	—	—	0.16	—	0.03	0.10	Mn
Mg	1.28	0.3	0.37	2.06	0.9	0.8	4.53	3.7	1.26	1.12	1.12	0.97	1.53	1.25	9.09	1.09	0.57	0.70	Mg
Ca	2.02	2.1	1.67	1.48	2.4	2.5	5.83	2.7	2.82	2.92	3.01	2.69	3.01	2.9	11.40	3.53	2.26	2.45	Ca
Na	7.12	6.4	8.64	7.84	8.2	9.0	9.11	5.9	8.19	7.47	7.81	9.73	8.70	9.06	0.56	7.59	8.94	8.40	Na
K	0.96	5.0	3.56	3.05	3.1	2.5	2.35	2.9	2.03	1.68	1.43	2.73	1.79	1.79	0.86	2.65	3.95	2.98	K
P	—	0.1	0.17	—	0.1	—	—	—	—	—	—	—	—	—	—	0.25	0.03	0.07	P
(H_2O)	(1.25)	(2.4)	(1.23)	(2.76)	(1.0)	(2.2)	(3.9)	(4.3)	(2.5)	(3.13)	(2.81)	(3.41)	(2.47)	(2.18)	(10.33)	(3.62)	(2.78)	(3.11)	(H_2O)
Cations in the standard cell	90.2	92.6	93.1	91.8	93.5	93.8	98.4	93.0	92.3	91.5	92.0	93.6	93.1	93.4	92.8	92.3	93.1	92.3	Cations in the standard cell
Standard catanorm	A_{17}	Vz_{218}	Hp_{417}	P_3	Vz_{201}	Vz_{215}	K_9	Vz_{216}	G_{44}	K_{23}	M_4	N_4	P_5	V_{36}	C_{22}	Hp_{414}	Hp_{493}	Ng_{36}	Standard catanorm
Q	44.13	29.8	27.78	30.80	28.1	25.1	1.55	26.4	26.86	31.45	30.15	19.58	25.24	24.76	15.45	26.45	21.92	26.84	Q
Or	4.80	25.0	17.80	15.25	15.5	12.5	11.75	14.5	10.15	8.40	7.15	13.65	8.95	8.95	4.30	13.25	19.75	14.90	Or
Ab	35.60	32.0	43.20	39.20	41.0	45.0	45.55	28.6	40.95	37.35	39.05	48.65	43.5	45.30	2.80	37.95	44.70	42.0	Ab
An	10.0	10.0	6.95	7.40	11.5	12.5	22.40	13.5	14.10	14.60	15.05	13.45	15.05	14.5	37.20	15.60	7.94	11.70	An
C	2.08	1.4	1.80	2.08	0.6	0.6	—	1.6	2.17	3.39	3.51	0.22	1.01	0.75	—	0.45	—	0.13	C
Fs	0.80	1.0	0.32	0.78	0.8	1.2	5.38	5.0	2.52	1.52	1.90	2.14	2.0	1.94	9.96	1.38	1.04	0.90	Fs
En	0.56	0.6	0.74	4.12	1.8	1.6	9.06	7.4	2.52	2.24	2.24	1.94	3.06	2.50	18.18	2.18	1.14	1.40	En
Wo	—	—	—	—	—	—	2.70	—	—	—	—	—	—	—	7.92	—	2.16	—	Wo
Ap	—	0.2	0.45	—	0.2	—	—	—	—	—	—	—	—	—	—	0.66	0.08	0.18	Ap
Il	0.14	—	0.26	0.14	0.2	1.2	0.98	2.4	0.42	0.42	0.42	0.28	0.56	0.56	2.92	0.78	0.34	0.64	Il
Mt	—		0.69	—	0.3	0.3	0.63	0.6	0.31	0.63	0.52	0.10	0.63	0.73	1.09	1.35	0.90	0.99	Mt
Ab/An =	3.5	3.2	6.2	5.3	3.56	3.6	2.0	2.1	2.9	2.5	2.5	3.6	2.8	3.1	0.08	2.4	5.6	3.5	= Ab/An
Mode-equivalent norm	A_{17}	Vz_{218}	Hp_{417}	P_3	Vz_{201}	Vz_{215}	K_9	Vz_{216}	G_{44}	K_{23}	M_4	N_4	P_5	V_{36}	C_{22}	Hp_{414}	Hp_{493}	Ng_{36}	Mode-equivalent norm
Q	42.22	30.2	27.44	32.92	28.9	25.8		30.5	28.42	31.92	27.92	20.68	26.67	26.5		27.36	21.70	26.84	Q
Or	—	19.0	13.30	9.10	11.0	9.5		2.0	2.85	—	—	10.0	3.85	4.1		8.70	17.55	12.05	Or
Ab	35.60	32.0	43.20	39.20	41.0	45.0		28.6	40.95	37.35	39.05	48.65	43.50	45.3		37.95	44.70	42.0	Ab
An	10.0	10.0	6.95	7.40	11.5	12.5		13.5	14.10	14.60	15.05	13.45	15.05	14.5		15.60	11.05	11.70	An
Bi	3.74	1.8	4.45	3.92	5.2	6.2		25.5	9.14	9.49	9.24	7.35	10.46	9.1		9.86	5.24	7.68	Bi
Ms	5.16	6.0	4.20	6.15	—	—		—	4.53	6.65	5.25	—	—	—		—	—	—	Ms
Ap	—	0.2	0.45	—	0.2	—			—	—	—	—	—	—		0.66	0.08	0.18	Ap
Garnet	2.70	0.8	—	—	—	—		1.0	—	—	—	—	—	—		—	—	—	Garnet
Il	—	—	—	—	—	0.6		0.5	—	—	—	—	—	—		0.14	0.08	—	Il
Mt	—	—	—	—	0.3	0.3		0.6	—	—	—	—	0.27	—		0.15	0.18	—	Mt
other Acc.	0.67	—	—	1.31				0.8	0.01	—	0.69	0.24		0.4		—	—	—	other Acc.
Ab/An =	3.5	3.2	6.2	5.3	3.56	3.6		2.1	2.9	2.5	2.5	3.6	2.8	3.1		2.4	4	3.5	= Ab/An

MAJOR ELEMENT CHEMISTRY OF THE ROCKS OF LAVERTEZZO AND ROZZERA

Some selected rock-specimens from the migmatite outcrops of Lavertezzo and Rozzera were spectrochemically analysed (total rock analysis). The main components – SiO_2, Al_2O_3, Fe_2O_3 (total iron), MgO, CaO, TiO_2, and MnO – were determined by a direct-reading spectrometer (Jarrell Ash 1.5 m-Atom-counter). The detailed procedure is described by SCHWANDER (1960). Alkalies were determined spectrographically, using a 1.5-m-Wadsworth spectrograph. Determination of FeO was made through titration against $KMnO_4$. Loss on ignition (mainly H_2O^+) was determined after heating the rock-powder up to $1000 \pm 20°C$ for about an hour.

The analyses, and their calculations according to different systems are listed in Table 11. All the leucocratic gneisses are characteristically rich in Na-content and show quartz-dioritic to trondhjemitic composition. The aplite dyke and mobilisate are chemically similar to the gneisses, but they have a slightly higher amount of K_2O.

Strikingly, the mesocratic hornblende-biotite-gneiss (analysis no. 7) shows an alkali content similar to that of the leucocratic gneisses. The high Na-percentage in this mesocratic gneiss cannot, however, be ascribed to the presence of hornblende in the rock, because an amphibolite contains far too little sodium; even the potassium is greater than the sodium-content in analysis no. 15. Furthermore, the hornblende from this amphibolite has also been analysed so that the effect on the alkali-content, caused by the presence of associated plagioclase in the rock, may be examined more precisely. In fact, the analysed hornblende contains an insignificant amount of alkalis (very much lower than that contained by a common hornblende). The aforesaid enrichment in alkalis and alumina in the hornblende-biotite-gneiss, as will be discussed later, can be considered to be due to interaction of the rock with anatectic liquids of granitic character (cf. ENGEL and ENGEL, 1962, p. 1502). It may be mentioned here that the optical properties of the hornblende from the hornblende-biotite-gneiss are exactly the same as those of the hornblende from the amphibolite mentioned above.

It is interesting to note that the chemical analysis of the hornblende from the amphibolite at Lavertezzo coincides very closely with the analysis of the hornblende from the layered amphibolite (belonging to the upper amphibolite facies) at Emeryville, New York (ENGEL and ENGEL, 1962, p. 1504). For the sake of rapid and easy comparison, the analysis of hornblende from Lavertezzo and Emeryville is given in Table 12, in which the structural formula of these hornblendes, and modal analysis of their respective parent rock are also presented (Table 13).

Returning now to Table 11, one may note that the mesocratic biotite-

Table 12. *Comparative Chemical Analyses of Hornblendes from Amphibolites of Lavertezzo and Emeryville*

	Lavertezzo (Sh Lz C 22)	Emeryville (AE 338)*)
SiO_2	42.4	42.18
TiO_2	0.9	1.30
Al_2O_3	13.2	13.09
Fe_2O_3	0.1	4.97
FeO	16.9	14.21
MnO	0.3	0.32
MgO	10.0	8.65
CaO	11.8	11.37
Na_2O	0.9	1.33
K_2O	1.2	0.96
P_2O_5	—	0.03
H_2O^+	2.4	1.81
H_2O^-	—	0.01
F	not determined	0.11
Cl	not determined	0.03
Total	100.1	100.37

Structural Formula

	Lavertezzo		Emeryville	
Si	6.32	= 8.0	6.319	= 8.0
Al	1.68		1.681	
Al	0.63		0.630	
Ti	0.01	= 0.66	0.145	= 1.33
Fe^{+3}	0.02		0.559	
Mg	2.22		1.930	
Fe^{+2}	2.10	= 4.36	1.779	= 3.75
Mn	0.04		0.040	
Ca	1.88		1.824	
Na	0.27	= 2.36	0.385	= 2.39
K	0.21		0.181	
OH	1.75		1.807	

*) Engel, A. E. J., and Engel, Celeste G. (1962): Hornblendes formed during progressive metamorphism of amphibolites, northwest Adirondack Mountains, New York. Bull. Geol. Soc. Amer. 73/12, 1499–1514, Table 2.

Table 13. *Comparative Modal Analyses (Vol.-%) of Amphibolites from Lavertezzo and Emeryville*

	Lavertezzo (Sh Lz C 22)	Emeryville (AE 338)*)
Hornblende	60.2	64.5
Plagioclase	20 (bytownite-anorthite)	17.5 (calcic andesine)
Quartz	15.2	15.1
Sphene	3.5	tr
Biotite	0.1	0.4
K-feldspar	tr	—
Opaque minerals	0.4	2.2
Others	0.6	0.3
Total	100.0	100.0

*) Engel, A. E. J., and Engel, Celeste, G. (1962): Progressive metamorphism of amphibolites, northwest Adirondack Mountains, New York. Petrologic Studies, Buddington Volume. 37–82, Table 2. Geol. Soc. Amer.

gneiss (analysis no. 8) from Rozzera is low in Na but high in K. Almost the same amount of K is present in the leucocratic gneisses. The leucocratic (aplitic) vein in a biotite-gneiss very similar to the above-mentioned one has a comparatively high sodium and low potassium content. This sort of alkali balance between the leucocratic vein on one hand and mesocratic biotite-gneiss on the other is further expressed by the consequent increase in silica in the former.

The amount of alumina is rather uniform, with the exception of analysis no. 7, in all the listed rocks. Moreover the percentage of Mg and Fe (total) in the leucocratic rocks is similar, although a small variation in Fe is noted in some rocks. This is shown by the biotite mineral analysis, where the chemistry of biotite changes according to the chemical character of the parent rock (see WENK et al., 1963, Fig. 4).

As seen from the Niggli values given in Table 11, the quartz index (qz) corresponding to si = 142 (for amphibolite C 22), is invariably positive for all these rocks. In the case of leucocratic gneisses (including Verzasca-gneiss) and aplites, the quartz index becomes positive from si = 316 onwards; whereas in the trondhjemitic rocks described by GOLDSCHMIDT (1916) qz = 0 corresponds to si = 260 (see PREISWERK, 1931, p. 53).

Q-Ab-Or PROPORTIONS IN PHASE-EQUILIBRIUM DIAGRAMS

1. Selection of a norm-method

Modern investigations of granitic and migmatitic rocks will hardly be considered complete and conclusive if their results are not discussed in the light of experimental evidence on the granite system. The rocks which have had a complete melting history, i. e. magmatic rocks, and also the light-coloured rocks which occur in the banded gneiss-complex or any other similar associations, equally deserve reference to these well-established phase-equilibrium diagrams. The basic requirements in such studies are the chemical analyses of the rocks. Since the use of the isobaric ternary diagrams demands Q-Ab-Or proportions, the given chemical analysis has to be computed to a set of minerals which actually make up the mode of the analysed rock. By re-calculating Q-Ab-Or = 100 and projecting the point into a suitable diagram the composition of the melt is obtained. Accordingly, the CIPW-normative feldspars cannot be used, because of the fact that the computed composition of the feldspars differs from that of actual feldspars (BARTH, 1959, p. 142).

BARTH suggested that "by calculating the mesonorm, the K_2O of biotites is considered, and the components of the granite melt are accurately determined" (1965, p. 220). He has graphically demonstrated that this adjustment is of prime importance for granitic rocks, and that the granitisation-process in the plotted rocks runs in opposite directions when the normative points of (1) the mesonorm and (2) the weight norm are viewed.

It may be mentioned here that the term mesonorm was introduced by NIGGLI (in BURRI and NIGGLI, 1945, p. 80), in his three-fold norm classification – catanorm, mesonorm, and epinorm corresponding, respectively, to high-, medium-, and low-temperature conditions. Further, each norm has its modifications by introducing mineral "Varianten" in which Niggli considered the actual minerals (with idealized composition) that are found in the modes of rocks.

2. *Mode-equivalent norm*

The present author, therefore, computed a norm in which not only biotite but also other minerals (if these are actually present) such as garnet, muscovite etc. are included. In doing so, the method differs from the mesonorm of BARTH (1959, p. 140), and also from the "Kata-Biotitvariante" (BURRI and NIGGLI, 1945, p. 615; BURRI, 1959, p. 152). Therefore, the author finds it reasonable to call these normative mineral-associations the *mode-equivalent norm*. The word mode-equivalent, as used here, literally stands as a prefix to the norm which identifies itself very intimately with the modal composition of the particular rock. The mode-equivalent norm defines neither a new system of norm calculations, nor contains taxonomical and etymological implications.

In view of the close correspondence between modal composition and mode-equivalent norm, the proportions of Q-Ab-Or from the planimetric analyses of the rocks were also calculated (WINKLER, 1961, p. 67). This also gives information, though limited, about the proportions of albite molecules dissolved in the K-feldspar (TUTTLE and BOWEN, 1958, p. 99). Also, for the sake of comparison, Q-Ab-Or proportions were calculated from the standard catanorm which is not markedly different from the molecular norm or CIPW-norm (cf. BARTH, 1948, p. 51). The mutual relationships between the mode-equivalent norm, standard catanorm, and modal analysis are shown in Fig. 17; all are calculated to Q-Ab-Or proportions for some of the rocks of Lavertezzo and Rozzera. The points of the leucocratic gneisses from Lavertezzo, obtained by these three methods, fall near the Q-Ab sideline and distinguish themselves from other rocks (plotted after each method).

3. *Method of calculation*

In the Verzasca valley in particular, and in the Tessin Alps in general, the mantle and core-gneisses, as well as the aplites are characterised by the minerals quartz, plagioclase, alkali feldspar, biotite, and subordinate muscovite. Besides, the occurrence of aluminosilicates such as sillimanite and kyanite is not uncommon. This indicates that the rocks are saturated or oversaturated with regard to alumina. This is also reflected chemically in the presence of corundum in the norm of these rocks (cf. TUTTLE, 1952, p. 118). Therefore, the relation $Al \geqq (Na + K + 2Ca)$, already suggested by NIGGLI, contains a basis and a guiding principle in the calculations of the mode-equivalent norm.

After having formed the minerals biotite, muscovite and feldspars, a small amount of aluminum in some remains to be consumed – if considerable, then sillimanite or kyanite is formed – if insignificant, on the other hand, the aluminum is assumed to find its place in the micas (BARTH, 1959, p. 140). In two cases where aluminum was found insufficient, the deficit amount is declared as "Al-manque". But, in order to consume the total amount of potassium in the formation of mica/K-feldspar, a certain required amount of aluminum was added, although it is not really present in the analyses. This amount of aluminum was of the order of a small decimal number, i. e. 0.6 and 0.8 Al given in cation percentage – an amount which constitutes an insignificant percentage of the total aluminum; on the other hand an equal amount of potassium, if left unused, will create serious mistakes in the normative minerals, particularly K-feldspar.

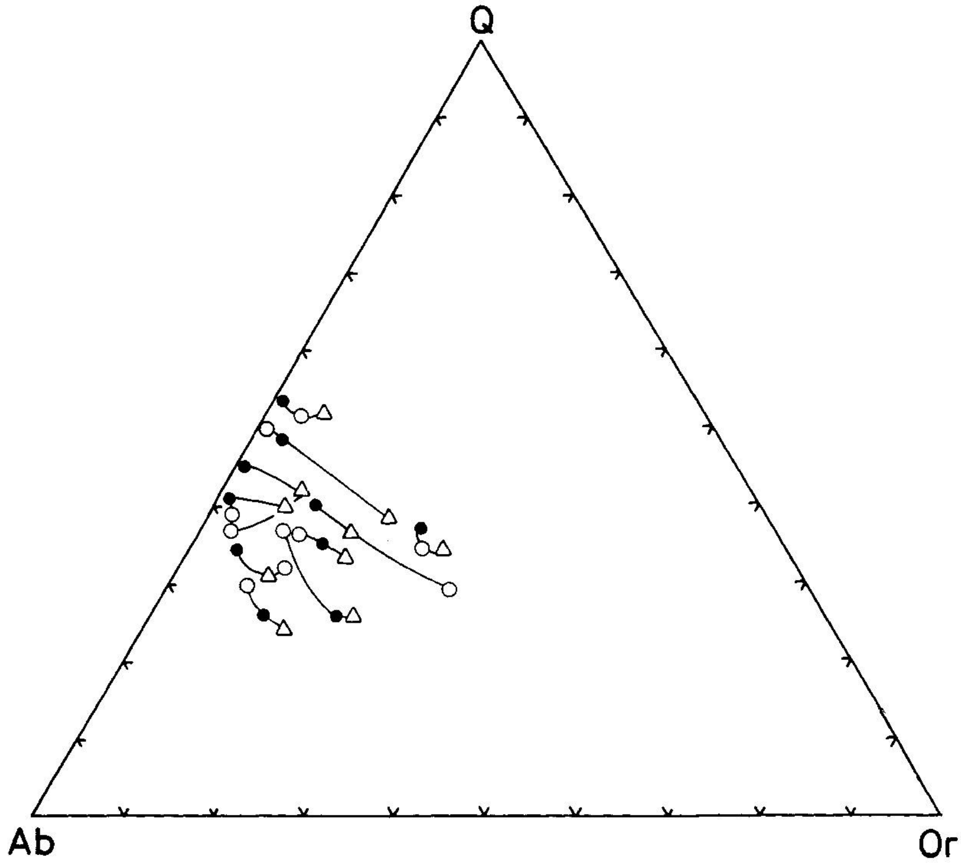
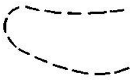


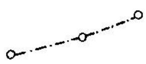
Fig. 17. Q-Ab-Or proportions showing the relationship between mode-equivalent norm (closed circle), standard catanorm (triangle), and modal analysis (open circle); each calculated for some of the rocks of Lavertezzo and Rozzera. Corresponding points of the same rock are joined by a line.

Explanation of Figures 17, 18, 19 and 24 (Phase-Equilibrium Diagrams)

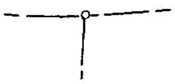
Closed contour encloses 86% of all granitic rocks (total 1190) plotted with respect to their normative Q-Ab-Or proportions (after WINKLER and v. PLATEN, 1961).



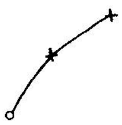
Dashed contour encloses Q-Ab-Or proportions of (I) eutectic points in granite system with different Ab/An ratio and (II) experimentally produced anatectic melts at $P_{H_2O} = 2000$ bars (after WINKLER, 1967).



Curve showing the shift of the eutectic point (circle) towards the Q-Or sideline in response to increasing anorthite content in the obsidian-anorthite mixture investigated at $P_{H_2O} = 2000$ bars (after v. PLATEN, 1965).



A cotectic line with Ab/An ratio = 7.8 at 2000 bars water vapour pressure (after v. PLATEN, 1965).



Curve showing the shift of the isobaric minimum (cross) and isobaric eutectic (circle) towards the Ab-corner in response to increasing water vapour pressure from 500 to 10,000 bars in the investigated simple granite system (after TUTTLE and BOWEN, 1958, and LUTH, JAHNS, and TUTTLE, 1964).

● Leucocratic gneiss and aplite from Lavertezzo.

▲ Leucocratic gneiss, Verzasca-gneiss, and aplitic mobilisate from Rozzera.

Ad = Aplite dyke. Am = Aplitic mobilisate.

■ Mesocratic gneiss from Rozzera.

◆ Leucocratic gneiss in a mesocratic gneiss at Rozzera.

Filled-in symbols: Ab/An (calculated) = 2.5–3.5, i. e. An 28–22%.
Open symbols: Ab/An (calculated) = 6–6.2, i. e. An 21.6–14%.

The following example will demonstrate the method of calculation of the mode-equivalent norm of a rock whose composition is given in cation percentage.

Vz 218 (Aplite)

Si	Ti	Al	Fe^{+3}	Fe″	Mn	Mg	Ca	Na	K	P	(H_2O)	Mode-equivalent Norm
68.8	—	16.8	—	0.5	—	0.3	2.1	6.4	5.0	0.1	(2.4)	
							0.1			0.1		0.2 Ap
19.2		6.4						6.4				32.0 Ab
4.0		4.0					2.0					10.0 An
0.7		0.4		0.2		0.3			0.2		(0.5)	1.8 Bi
3.0		2.0							1.0		(1.8)	6.0 Ms
11.4		3.8							3.8			19.0 Or
0.3		0.2		0.3								0.8 Gr
30.2												30.2 Q

	Mode-equivalent norm	Modal composition (Vol-%)
Quartz	30.2	29
Plagioclase	42	43
K-feldspar	19	23
Muscovite	6	3
Biotite	1.8	1
Garnet	0.8	1
Apatite	0.2	—

A glance at the calculations will show, unlike the mesonorm calculations after BARTH, that garnet and muscovite have been formed, and that biotite has not been assumed to have an ideal composition. Since the mineral analyses of biotite, muscovite and garnet from the same or a similar rock are at hand, the norm computation should naturally be based upon the mineral analyses. In the present case the biotite formula was calculated from the given mineral analysis (in cation percentage).

For the given example, the structural formula of biotite contains the following main cations calculated on the basis of 22 oxygen (WENK et al., 1963).

$K_{1.84}(Mg_{2.24}Fe^{+2}_{1.86}Fe^{+3}_{0.2}Al^{VI}_{0.86})(Al^{IV}_{2.48}Si_{5.52})(OH)_{1.4}$; the ratio $Mg:Fe^{+2} = 1:0.8$.

Now in the rock analysis (cation %), the total Mg combined with the given proportion of Fe^{+2} ($Mg : Fe = 1 : 0.8$) forms the basis, and accordingly biotite is built in the mode-equivalent norm; other cations will naturally be referred to the biotite formula (see above). Garnet, being almost almandine (X-ray results), will be formed from the remaining ferrous iron.

After having formed biotite, the formation of muscovite and orthoclase is considered. The remaining amount of potassium has to be distributed in relation to the quantity of aluminum left after the formation of Ab, An, Bi, and garnet. The equation $\left(\frac{Al' - K'}{2}\right)$ will give the amount of potassium to be used for the formation of muscovite, assuming it to be of ideal composition. It should be mentioned here that the muscovite analysis from a similar rock (Vz 218) corresponds very nearly to the ideal composition.

ORIGIN OF THE BANDED GNEISSES AND MIGMATITES IN THE LIGHT OF PHASE-EQUILIBRIUM DIAGRAMS

After having calculated the mode-equivalent norm, the Q-Ab-Or proportions were plotted for each rock in isobaric diagrams. Regarding the equilibrium diagram given for the granite system, TUTTLE and BOWEN (1958, p. 84) write:

> "Within the experimental error, the two contrasted natural granites begin to melt at the same temperature as synthetic mixtures having compositions near the ternary minimum. The PT curve for the ternary minimum may then be used with confidence to indicate the pressures and temperatures at which natural granites begin to melt in the presence of water vapor."

Also to make use of the isobaric diagrams (for the granite system with An-component) given by v. PLATEN and WINKLER, the Ab/An ratio for each of the plotted rocks was calculated, as this ratio governs the crystallisation of a granite melt. A melting diagram is then chosen, directly or by interpolation,

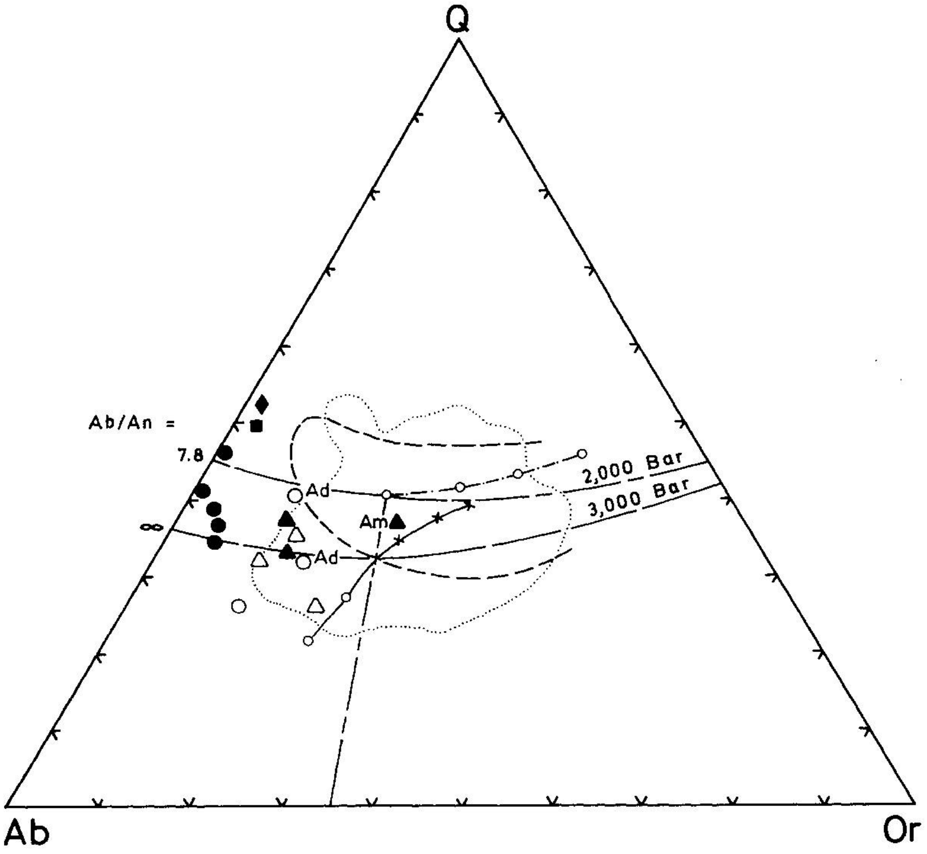


Fig. 18a. Normative Q-Ab-Or proportions (from mode-equivalent norm) for gneisses, aplites, and a leucocratic vein from Lavertezzo and Rozzera, projected into the granite system. (For explanation see page 251.)

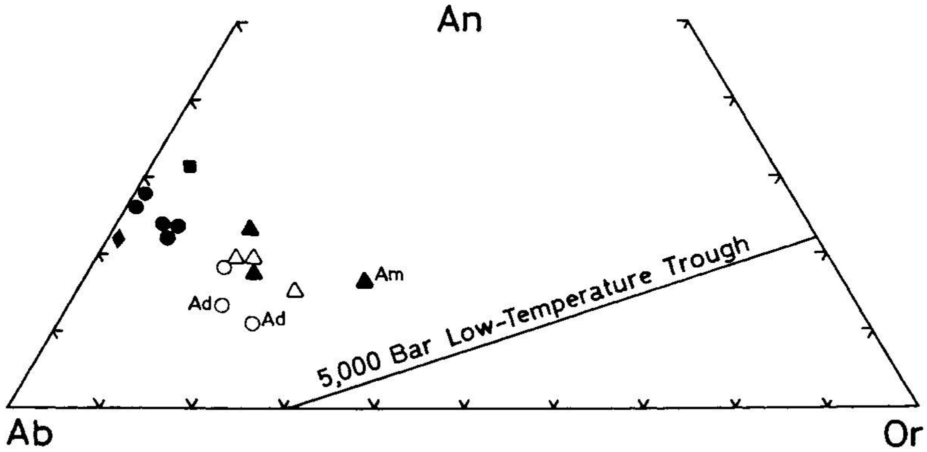


Fig. 18b. Normative Or-Ab-An proportions (from mode-equivalent norm) plotted into the Or-Ab-An projection of the silica-saturated surface of the Q-Ab-Or-An system (after KLEEMAN, 1965). (For explanation see page 251.)

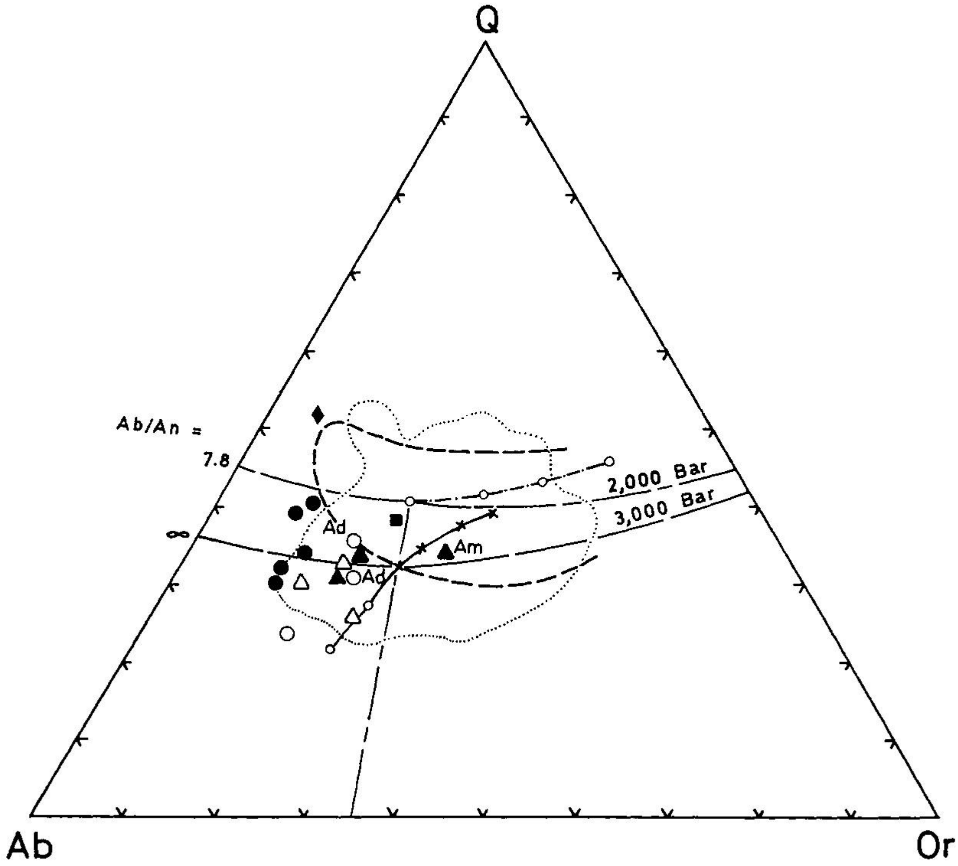


Fig. 19a. Normative Q-Ab-Or proportions (from standard catanorm) for gneisses, aplites, and a leucocratic vein from Lavertezzo and Rozzera, projected into the granite system. (For explanation see page 251.)

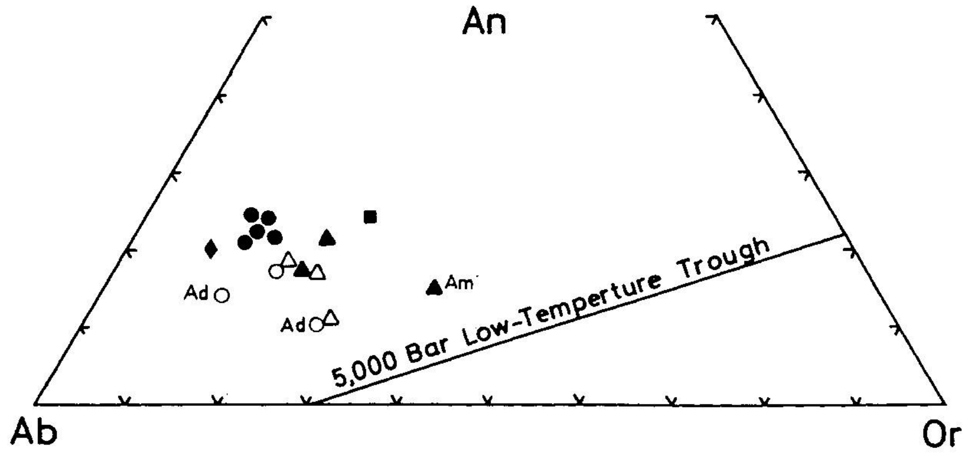


Fig. 19b. Normative Or-Ab-An proportions (from standard catanorm) plotted into the Or-Ab-An projection of the silica-saturated surface of the Q-Ab-Or-An system (after KLEEMAN, 1965). (For explanation see page 251.)

with an Ab/An ratio corresponding to that of the rock to be projected (WINKLER, 1967, p. 207). Furthermore: "These melting diagrams are valid not only for the crystallisation of melts but also for the anatexis of crystalline rocks" (v. PLATEN, 1965, p. 211).

However, the diagrams of v. PLATEN are only valid when, in addition to quartz and plagioclase, potash-feldspar and/or muscovite constitute the mineral phases of the rocks. When absent, and if biotite is the only K-bearing mineral, these diagrams should not be used (written communication from Professor Winkler).

Hence, the phase diagrams given by TUTTLE and BOWEN and v. PLATEN can be used for the rocks of Lavertezzo, Rozzera, and neighbouring areas in the Verzasca valley.

As seen in Fig. 18a, only the aplitic mobilisate from Rozzera lies in the field of eutectic melts and obviously between the ternary minimum and eutectic point for 2000 bars water vapour pressure. The leucocratic gneisses from Lavertezzo as well as the biotite-gneiss and the leucocratic vein (occurring in a paragneiss similar to the biotite-gneiss) from Rozzera fall near the Q-Ab sideline. The gneisses of the Verzasca type from Rozzera show a strong tendency towards the thermal trough (Fig. 18). Strikingly associated with these gneisses is the aplite dyke from Lavertezzo, which tends more than the Verzasca gneisses towards the thermal trough.

It is interesting to note that almost all the rocks fall on cotectic lines representing water vapour pressure below 3000 bars, and that the plots assemble towards the Q-Ab side, irrespective of their varying Ab/An ratios. However, the analyses of two gneisses, one from Lavertezzo and another from Rozzera, fall below the cotectic line of 5000 bars.

A very similar pattern is obtained in Fig. 19, where the Q-Ab-Or proportions for all these rocks are plotted according to a standard catanorm. Here, the biotite-gneiss from Rozzera falls in the eutectic field and very near to the aplitic mobilisate.

The different rocks shown in Fig. 19a bear a striking similarity to the Svecofennidic rocks of the trondhjemitic province in Finland (SIMONEN, 1960, Fig. 26), and to Lewisian granitic rocks of the NW Highlands of Scotland (BOWES, 1967, Fig. 2). On the other hand, the rocks from Verzasca plotted in relation to normative Q-Ab-Or proportions (Fig. 19a), scarcely show any resemblance to those from the eastern part of the Lepontine gneiss-region (cf. BLATTNER, 1965, Fig. 32). The Verzasca rocks contain lower amounts of quartz and K-feldspar.

A. Lavertezzo Outcrop

The position of the aplitic mobilisate within the field of eutectic melt and low-temperature thermal trough, and the tendency towards the thermal trough shown by the average Verzasca-gneiss, by the leucocratic gneisses from Rozzera and by the aplite dyke from Lavertezzo (Figs. 18a and b), suggest that melting processes have taken place in the formation of these rocks. However, in view of the synkinematic origin of the gneisses and the late-kinematic origin of aplites from the Verzasca, and their high alkali-content, the process of continual melting of sediments cannot be considered for their origin (see experimental results: WINKLER et al., 1958–1963). Furthermore, the plotted points for the leucocratic gneisses from Lavertezzo are away from the isobaric cotectic and eutectic points and thus distinguish themselves from the aplites and gneisses of trondhjemitic composition. Therefore bodily injection of granitic material into the country rock (GUTZWILLER, 1912, p. 58) is highly improbable. The significance of this discrimination will be discussed later.

a) Bodily injection

The idea of material injection is further excluded by the fact that the chemical character of the mesocratic biotite-gneiss closely resembles that of the leucocratic vein, as stated earlier. These two rocks, being near the Q-Ab sideline, have a close relationship with one another and also with the leucocratic gneisses from Lavertezzo. The only difference lies in the quartz-content, which is slightly higher in the mesocratic gneiss and leucocratic vein.

Critically examined, it is hardly possible that the metamorphic rocks, which were subjected to high pressure conditions, could be split up by cm to dm thick intruding liquid. If the banding in the gneiss complex is considered to be due to liquid injection, then each injected layer had to uplift and carry ~13 km load[2]) of overlying rocks. In spite of these difficulties, if one still considers the probability of bodily injection, then those layers and lenses of rocks at Lavertezzo which are abnormally rich in Fe and Mg will have to be explained by another process. Finally the striking deficiency of K-feldspar in some of the leucocratic gneiss bands at Lavertezzo does not support the hypothesis of injection of aplitic, pegmatitic, or granitic material into the country rocks (ESKOLA, 1933, p. 18). Lastly, there exists a genetic relationship between dark and light rock-bands with regard to their plagioclase composition (see below). This evidence completely rules out bodily injection of granitic liquids (cf. MISCH, 1968, p. 1).

b) Metamorphic differentiation

In order to examine the process of the formation of leucocratic gneisses and consequently the origin of the light and dark bands in the gneiss complex

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[2]) This estimation is considered probable by Professor Wenk for the region of the Verzasca.

of Lavertezzo, the proportions of quartz, feldspar, and mafic minerals, obtained from the planimetric analyses were projected in Fig. 20. The concentration of the mesocratic biotite-gneiss takes the intermediate position between leucocratic and melanocratic parts (see also Fig. 21), and the average in each group lies in a more or less straight line. Furthermore, the fields of individual rock-groups are not sharply marked; rather, a gradation is exhibited by a few rocks lying between the fields. This pattern cannot be considered fortuitous even by the followers of injection. Moreover, rock-volume calculations (after MEHNERT, 1953) by macroscopic integration in the field and by microscopic integration from Figs. 20 and 22 coincide satisfactorily. Accordingly, the band-formation process at Lavertezzo can be considered as a criterion for *in situ* formation of this gneiss-complex (Paleosome = Leucosome + Restite, according to MEHNERT, 1951, p. 186; 1966, p. 258).

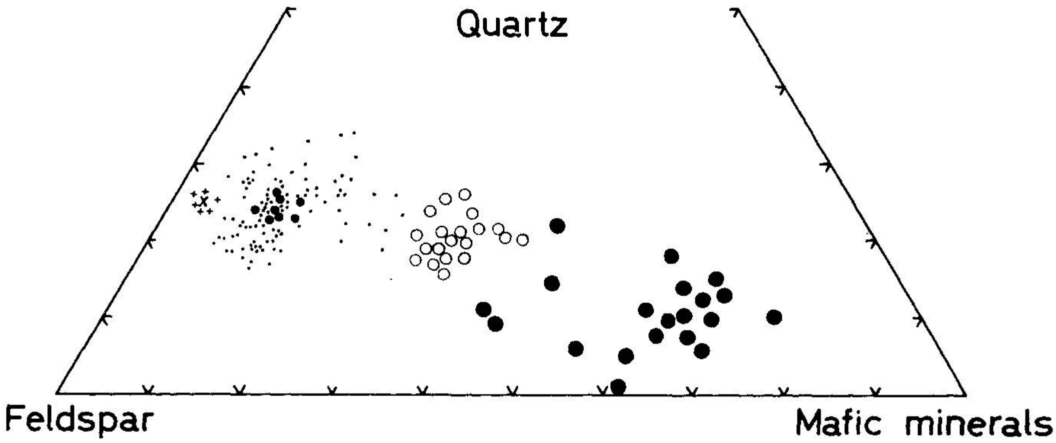


Fig. 20. Planimetric analyses (Vol.-%) for leucocratic, mesocratic, and melanocratic rocks and the aplite dyke from the gneiss complex at Lavertezzo. Total points 135. (For explanation see page 257.) Big dots = melanocratic rocks; circles = mesocratic rocks; smaller dots = leucocratic rocks; crosses = aplites.

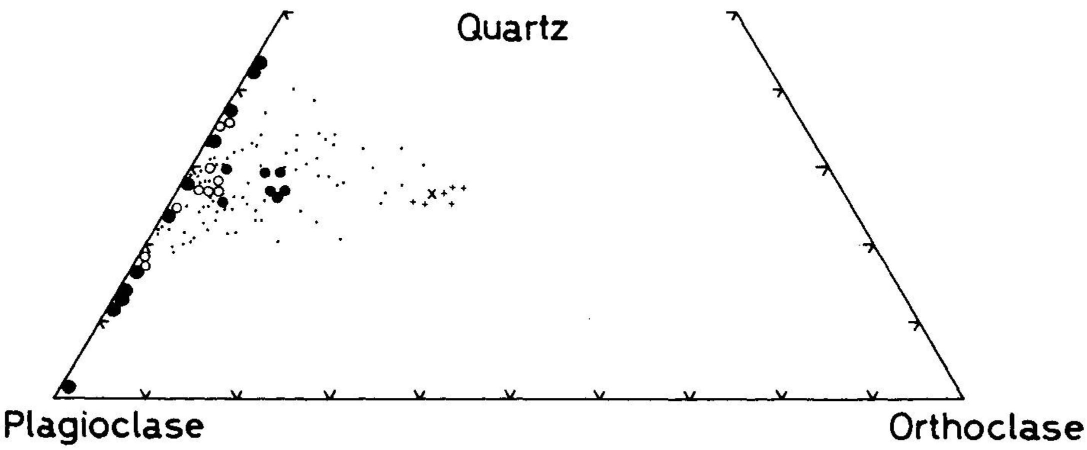


Fig. 21. Q-Pl-Or diagram for leucocratic, mesocratic and melanocratic rocks and the aplite dyke from the gneiss complex at Lavertezzo. (For explanation see page 257.) Same signs as in Fig. 20.

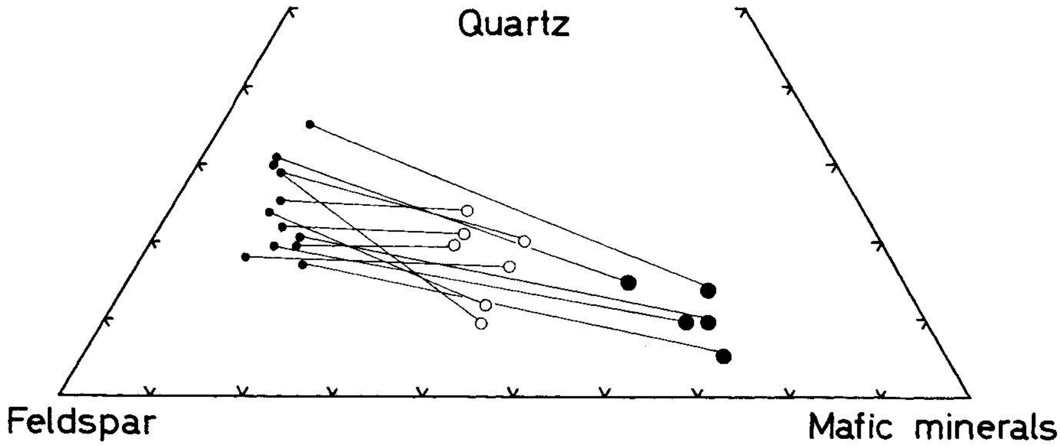


Fig. 22. Planimetric analyses (Vol.-%) showing the relationship between adjoining light and dark rock-bands from the gneiss complex at Lavertezzo. Bands in direct contact with each other are joined by a line. Note the more or less uniform composition of the leucocratic bands in contrast with the heterogeneous dark bands (mesocratic and melanocratic). (For explanation see page 257.) Same signs as in Fig. 20.

Explanation of Table 14

1. Sphene-bearing garnet-hornblende-biotite-andesine-gneiss (Sh Lz B 60 a)
2. Leucocratic oligoclase-gneiss (Sh Lz B 60 b)
3. Mesocratic biotite-oligoclase-gneiss (Sh Lz B 60 b′)

4a. Leucocratic oligoclase-gneiss (Sh Lz B 63)

4b. Leucocratic oligoclase-gneiss (Sh Lz C 60)
5. Amphibolite (Sh Lz C 60 b)
6. Leucocratic oligoclase-gneiss (Sh Lz C 60 a)
7. Sphene-bearing hornblende-biotite-andesine-gneiss (Sh Lz C 60 c′)

8. Sphene-bearing hornblende-biotite-andesine-gneiss (Sh Lz B 59 d)
9. Leucocratic oligoclase-gneiss (Sh Lz B 59 b)
10. Mesocratic biotite-andesine-gneiss (Sh Lz B 59 b′)
11. Leucocratic oligoclase-gneiss (Sh Lz B 59 a)

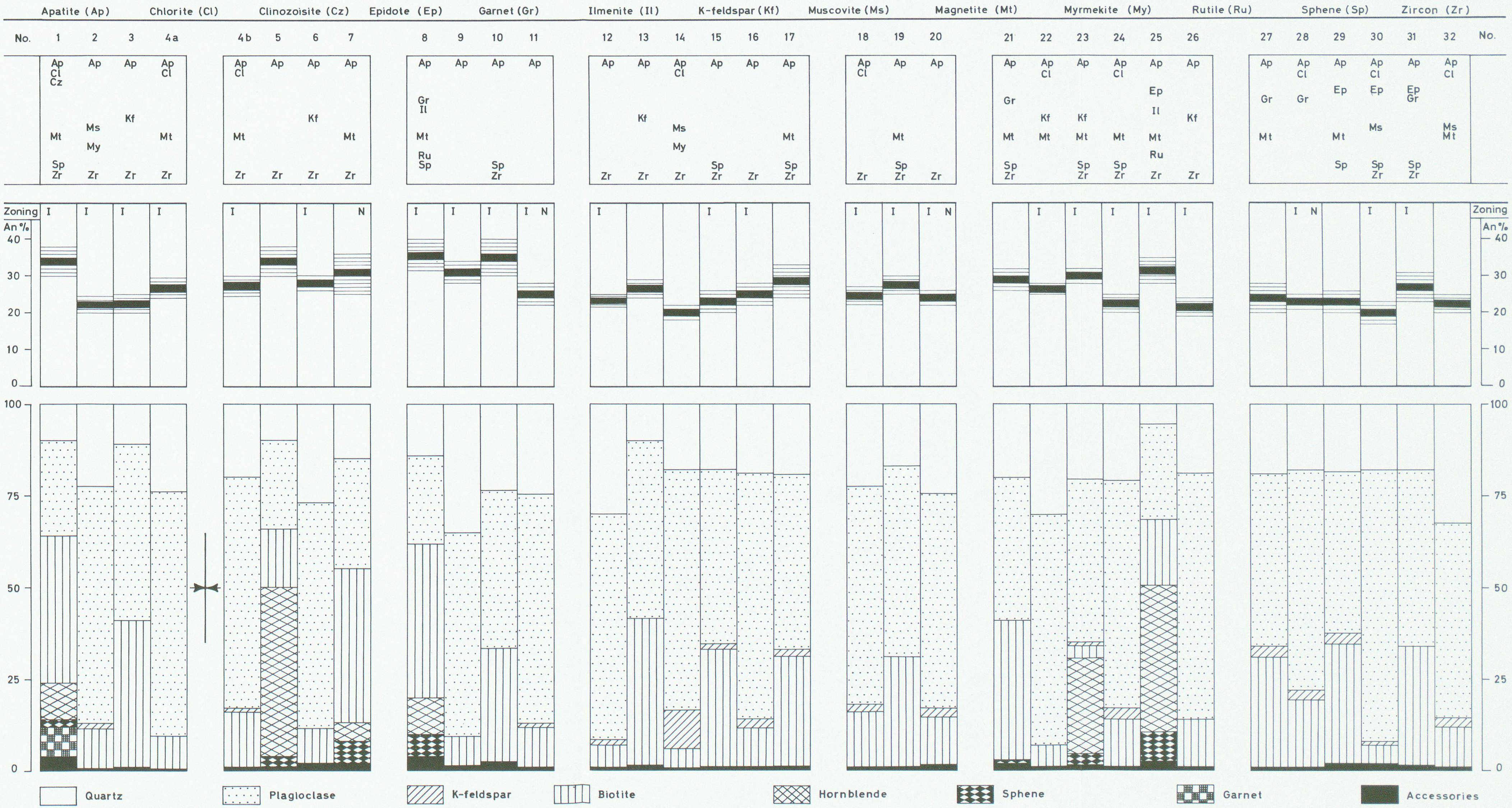
12. Leucocratic oligoclase-gneiss (Sh Lz C 57 d)
13. Mesocratic biotite-oligoclase-gneiss (Sh Lz C 57 d′)
14. Leucocratic microcline-oligoclase-gneiss (Sh Lz C 57 c)
15. Mesocratic biotite-oligoclase-gneiss (Sh Lz C 57 c′)
16. Leucocratic oligoclase-gneiss (Sh Lz C 57 b)
17. Mesocratic biotite-andesine-gneiss (Sh Lz C 57 a)

18. Leucocratic oligoclase-gneiss (Sh Lz C 56 c′)
19. Mesocratic biotite-oligoclase-gneiss (Sh Lz C 56 a)
20. Leucocratic oligoclase-gneiss (Sh Lz C 56 c)

21. Mesocratic biotite-oligoclase-gneiss (Sh Lz D 64)
22. Leucocratic oligoclase-gneiss (Sh Lz D 64 a)
23. Amphibolite (Sh Lz D 62 b)
24. Leucocratic biotite-oligoclase-gneiss (Sh Lz D 60)
25. Amphibolite (Sh Lz E 60 b′)
26. Leucocratic biotite-oligoclase-gneiss (Sh Lz E 60 b)

27. Mesocratic biotite-oligoclase-gneiss (Sh Lz D 49 d)
28. Leucocratic biotite-oligoclase-gneiss (Sh Lz D 49 d′)
29. Mesocratic biotite-oligoclase-gneiss (Sh Lz D 49 c)
30. Leucocratic oligoclase-gneiss (Sh Lz D 49 b)
31. Mesocratic biotite-oligoclase-gneiss (Sh Lz D 49 a)
32. Leucocratic biotite-oligoclase-gneiss (Sh Lz D 49)

Table 14. *Modal analyses (Vol.-%) relationships between alternate layers from seven different rock-groups of the banded gneiss at Lavertezzo*



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For further inquiry into this process, several neighbouring bands have been examined with regard to their volumetric composition and anorthite percentage.

In Table 14 the modal analyses and anorthite content of plagioclase in alternating dark and light rock-bands from various parts of the Lavertezzo outcrop are shown. The amounts of quartz, feldspar and biotite, and the anorthite percentage, show considerable variation in the leucocratic gneiss bands. The variation in mineral proportions is noted not only in the gneiss bands from different groups but can also be seen in alternating cm to dm thick light bands within one group, which probably indicates that either the mobility of the components was limited, or that there was a strong influence from the composition of the adjoining bands. Since the leucocratic bands in the gneiss-complex at times attain a thickness of over 3 meters, the first assumption does not seem to be sound. Hence, the alternative remains that these variations are due to the influence of the adjoining dark bands. This statement is supported by the anorthite content in these rock-bands.

The content of plagioclase varies slightly but distinctly in these rocks. The mesocratic bands containing hornblende (plus garnet and titanite/sphene), and those showing a predominance of biotite, contain acid andesine. All leucocratic bands and many mesocratic biotite-gneisses contain oligoclase (An 18–30). However, at some places, contiguous bands display the same anorthite content, although their mineralogical composition is not identical. In most bands the anorthite percentage varies with the variation of the mineral proportions. With a few exceptions in leucocratic bands, where the plagioclase composition (An %) is largely influenced by their plagioclase and K-feldspar content, there exists a genetic relationship between neighbouring leucocratic and mesocratic bands of the gneiss complex at Lavertezzo. The plagioclase in almost all the bands shows inverse zoning, but a few bands have both normal and inverse zoning.

The quantitative mineral relationship between the dark and light bands (in direct contact) is demonstrated more clearly by the proportions of quartz, feldspar, and mafic minerals, as plotted in a triangular diagram (Fig. 22). Here the leucocratic rocks show a variation which is definitely related to and dependent on the adjoining dark band (joined by a line). The variation of the mineral proportions in these gneisses is fairly narrow: quartz = 25–30%, feldspar = 60–70%, and mafic minerals = 10–15% by volume.

Furthermore, to show the already-mentioned genetic relationship between adjoining light and dark bands, the amounts of mafic minerals and the (corresponding) An-percentage of plagioclase in the neighbouring light and dark bands are plotted in Fig. 23. It becomes evident that the variation in the anorthite percentage in the leucocratic rocks is dependent on the chemical differences in the adjoining dark band (joined by a line) and probably also on the reactions of biotite-hornblende and other calcium-bearing minerals during the band formation (cf. MEHNERT, 1957, p. 53). On the other hand, the schollen and restites in the gneiss-complex show a very high anorthite content, which is to be expected in the case of *in situ* formation.

However, it remains to be examined whether this process of *in situ* formation occurred during partial melting.

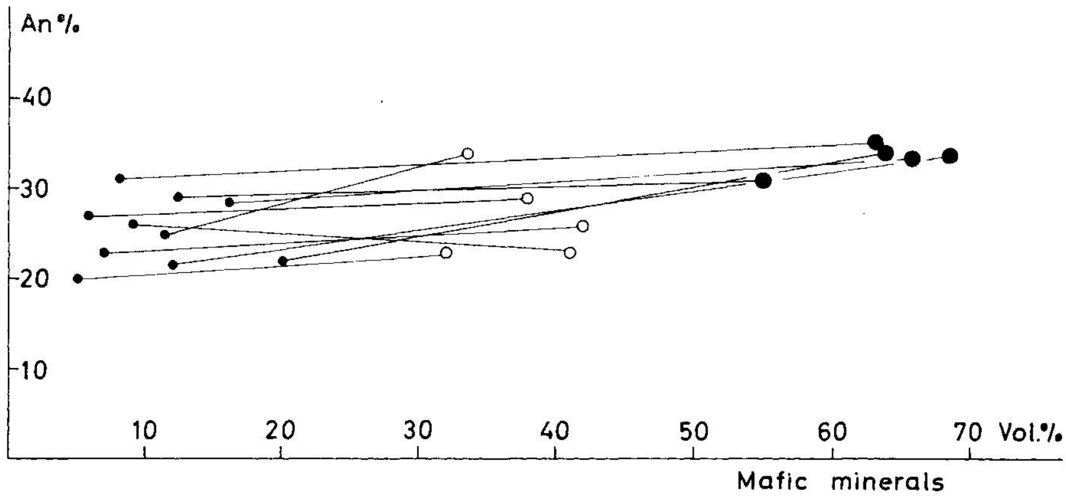

Fig. 23. An-percentage (Mol.-%) in adjacent light and dark rock-bands (as shown in Table 14) from the gneiss complex at Lavertezzo. Bands in direct contact with each other are joined by a line. Note that the An-variation in different bands is almost insignificant. (For explanation see page 259.) Same signs as in Fig. 20.

c) *Differential anatexis*

The PT conditions under which the rock-complex was formed, were primarily the deciding factors, whether the process was metamorphic differentiation or differential anatexis (partial melting). An estimation of the PT conditions for the rocks of Lavertezzo can satisfactorily be made by petrographical and mineralogical results and their reference to laboratory investigations.

The mineral assemblages found in the studied outcrop at Lavertezzo and in other parts of the Verzasca valley (WENK, 1962; SCHWANDER et al., 1967) and in vast areas of the Lepontine Alps (KELLER, 1968) belong to the almandine amphibolite facies (after FYFE et al., 1958). As a first approximation, temperatures of 600–700° C and pressures between 4–6 kb can be suggested (WINKLER, 1967) for this facies. Also, considerations relative to BARTH'S geological thermometer give 600–650° C for the gneisses of Lavertezzo. Again, on the basis of the temperature established for unmixing of the alkali feldspar ($Or_{70}Ab_{30}$) in the synorogenic pegmatite intrusion, a more accurate temperature can be estimated.

Since the synorogenic pegmatite is obviously an anatectic product of these gneisses, a temperature of not less than 660°C – the maximum temperature of the solvus (TUTTLE and BOWEN, 1958, p. 41) – may be accepted for the deeper part of these gneisses. To state that the parent rock should have at least the same, if not higher, temperature as its offspring is quite reasonable. However, temperatures over 660° prevailed chiefly in the deeper part from where the synorogenic pegmatite ascended. The temperature at higher levels, where the pegmatite emplacement took place, should naturally be lower than 660°, but higher than 630° which is the temperature for exsolution of the alkali feldspar in the intruded pegmatite. In any case, a temperature between 630° and 660°C can be proposed for the rocks of Lavertezzo. At this temperature range, the quartz and feldspar in a gneiss will normally go into solution, if the pressure is taken as 4000 bar and with sufficient water (TUTTLE and BOWEN, 1958, p. 79).

Since the proportion of quartz and feldspar in these rocks is more or less constant (Q = 25–30%, Feldspar = 60–70%), it is obvious that this proportion represents eutectic composition (cf. TUTTLE and BOWEN, 1958; WINKLER and v. PLATEN, 1961, Pt. IV, p. 53). Moreover, the An-percentage in the plagioclase of the leucocratic part is dependent on the composition of the adjoining band. This is additional support for differential melting. Lastly, the almost ubiquitous inverse zoning in the leucocratic rocks can only be explained by a process of differential melting *in situ*, during which the anorthite-rich solution was steadily available (BARTH, 1956; MEHNERT, 1963, p. 168).

From the aforesaid it may be concluded that the leucocratic gneisses are the result of differential anatexis *in situ*. Of course the presence of water, CO_2, and other volatile substances in the parent rock had some influence on the partial melting. Among the volatiles, fluorine is found in extremely small amounts in the rocks of Lavertezzo.

B. Rozzera Outcrop

Now we shall consider the origin of the rocks at Rozzera in the light of the phase-equilibrium diagram; of course, convincing examples of extensive mobilization of these rocks are clearly displayed in the field.

In Fig. 24 are projected the rocks occurring at Mt. Rozzera. As stated earlier, the biotite-gneiss (point 2) lies close to the leucocratic vein (point 1) which, in the field, occurs in a biotite-gneiss very similar to that shown in the diagram. The gneiss (point 3) found in the field in close contact and interlayered with the paragneiss (point 2), is situated far away from the two rocks mentioned above. The separate location in the isobaric diagram, in contrast with the field occurrence, suggests that the gneiss (point 3) has a different relationship than the leucocratic vein (point 1) to the paragneiss (point 2).

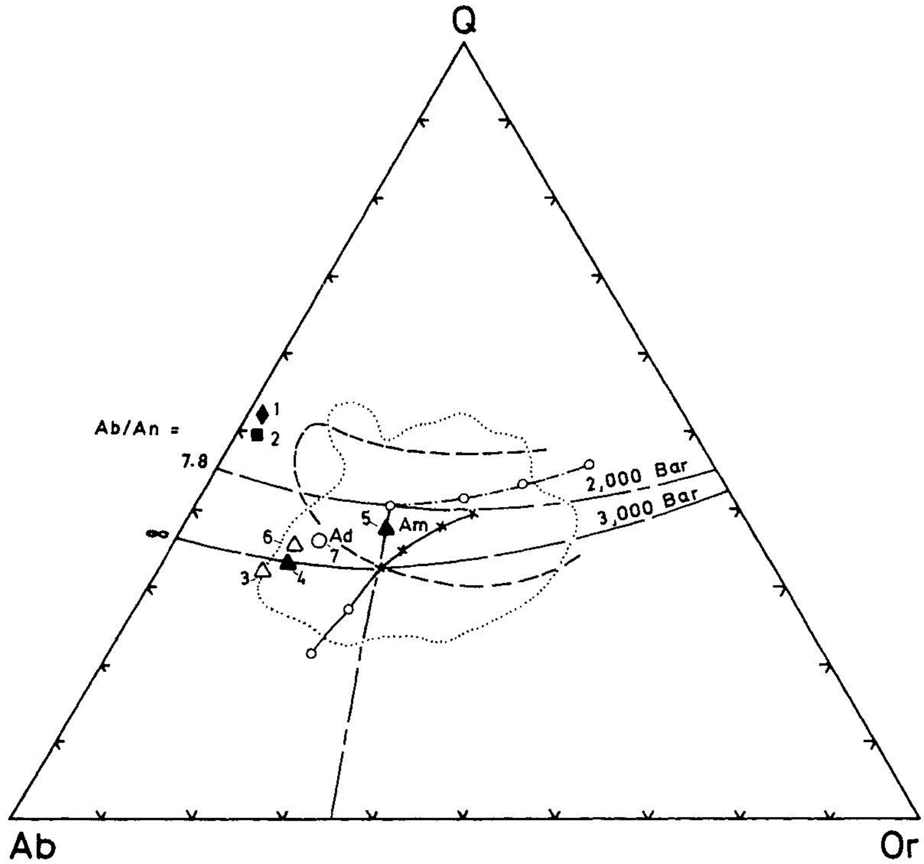

Fig. 24. Normative Q-Ab-Or proportions (from mode-equivalent norm) for rocks from Rozzera. An aplite dyke (average analysis) from Lavertezzo is also plotted. (For explanation see page 251.)

The last two rocks are undoubtedly consanguineous, and the leucocratic vein originated most probably by anatexis of the enclosing rock (cf. Eskola, 1933, p. 17).

Attention may here be drawn to the fact that the aplite (point 5, lying inside the eutectic field) occurs as a flow-like mobilisate amongst the mesocratic and leucocratic gneisses at Rozzera. Its petrogenetic relationships will be considered along with related leucocratic gneisses (points 4 and 6) from Rozzera and the aplite dyke from Lavertezzo, whose projection point (7) also lies in the same diagram. The reason for selecting these rocks is primarily due to their related chemical composition, a sequence of melting/crystallization in relation to geological time and place, and lastly to their geochemical mobility.

The Verzasca gneisses (points 3, 4, 6) from Mt. Rozzera plot near the field of eutectic melts (shown by dotted line) and all lie very close to one another. It may here be recalled that these gneisses occur in contact or are interlayered with biotite-gneiss, amphibolite, and other similar associations of metasedimentary rocks. The aplite dyke lies very close to these gneisses but more towards the eutectic field. To explain the origin of all these rocks, palingenesis of metasediments like the biotite-gneiss cannot be considered, since the compositional trend, as stated earlier, would be transverse to the geological sequence of development of these rocks. In fact, anatexis/palingenesis cannot be denied, but all the rocks at Rozzera are not the products of *the same* palingenetic material. Indeed, the gneisses (3, 4, 6) at Rozzera owe their origin to the same process which produced the granitoid rocks of the Verzasca valley in general, notwithstanding the fact that the gneisses at Rozzera occur inside the paragneiss mantle (WENK, 1948, 1956, 1962).

The aplite dyke, being late-kinematic (p. 228), is considered to be a palingenetic product of the Verzasca-gneiss (point 6).

Regarding the origin of the aplitic mobilisate (point 5), two alternatives seem possible: either the aplitic mobilisate is an anatectic product of the paragneiss at Rozzera, or it represents the liquid/melt remaining after the formation of the Verzasca-gneiss.

The chemical analysis of the mobilisate (Vz 218) is strikingly similar to the "ideal granite" of ESKOLA (1950, 1952), in which K predominates over Na (cf. ESKOLA, 1956, Table 1).

The sodium- and quartz-content of the mobilisate are very nearly the same as that of the Verzasca gneisses, but K_2O is remarkably higher in the mobilisate. This excess of K_2O can be attributed to the An-percentage, as laboratory experiments have demonstrated. Unfortunately, no remarkable increase of the anorthite ratio in the plagioclase of the aplite is observed. The An-percentage is almost the same in the Verzasca gneiss and in the aplitic mobilisate. The increase in Or-ratio cannot be accounted for by the decrease of water vapour pressure, as even at atmospheric pressure Ab is a little higher in percentage than Or (ESKOLA, 1956, p. 90).

Petrographical evidence does not support K-metasomatism, and its selective occurrence seems doubtful. Besides, the formation of garnet from biotite – a fact which cannot be denied – would be difficult to reconcile with this phenomenon.

Again, petrographical studies reveal that the plagioclases in the aplitic mobilisate contain no relict structures, e. g. muscovite inclusions like those in the plagioclase of the aplite dyke at Lavertezzo. There are also no rock-varieties transitional to the Verzasca-gneiss and the leucocratic mica-oligoclase-gneiss at Rozzera. In this aplitic mobilisate, there are several schollen of biotite-gneiss, all having a common trend, unlike the trend shown by the dark schlieren in the granitoid nebulite at Rozzera. Moreover, the schollen have corroded outlines, occasionally sharp but always poorer in biotite than the central part. Interesting is the uneven distribution of the garnets in this mobilisate, and their formation from biotite.

Hence, from the foregoing discussion that the author concludes the aplitic mobilisate is the result of anatexis of the metasediments at Rozzera, and that the mica-oligoclase-gneisses, interlayered in the paragneiss rocks, are the products of the same palingenetic process that gave rise to the Verzasca-gneiss.

Lastly, the leucocratic gneisses in the migmatite-complex at Rozzera are concluded to be the products of advanced anatexis of a parent rock of greywacke-like composition. This conclusion is based on quantitative analyses of the rock-units in the studied outcrop. The proportions of quartz, feldspar, and mafic minerals from the planimetric analyses of these rocks are shown in Fig. 25. Here, the leucocratic gneisses have a narrow field, whereas the mesocratic gneisses show a scattered field that gradually merges into the field of amphibolites (cf. Fig. 20). The proportions of Q-Pl-Or for the same rocks, plotted in Fig. 26, are strikingly constant in the individual rock-groups (cf.

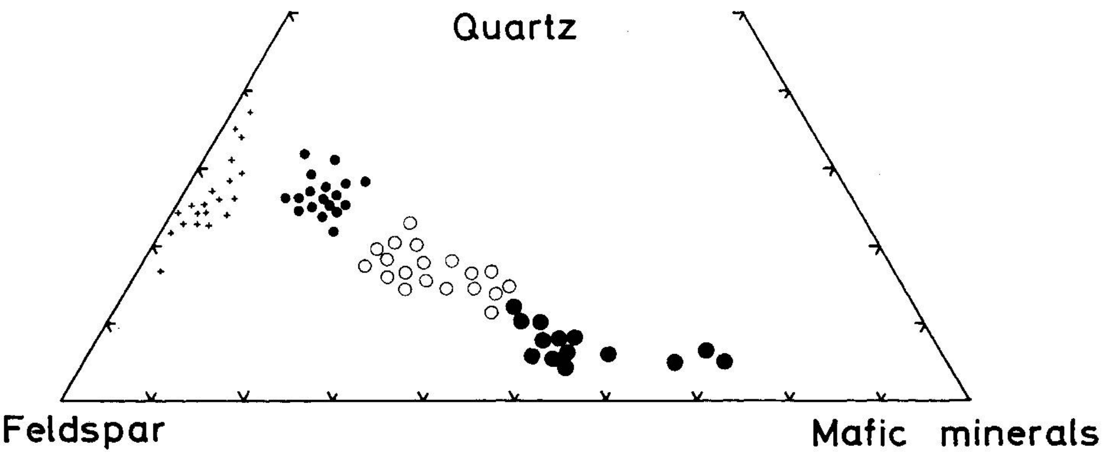

Fig. 25. Planimetric analyses (Vol.-%) for leucocratic, mesocratic, and melanocratic rocks and the aplitic mobilisate from the migmatite outcrop at Rozzera. Total points 72. (For explanation see page 251.) Same signs as in Fig. 20.

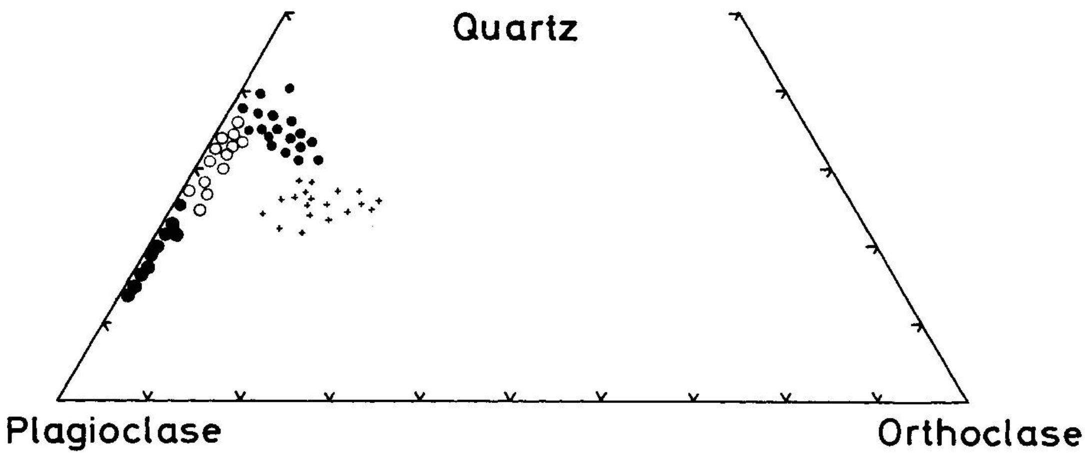

Fig. 26. Q-Pl-Or diagram for leucocratic, mesocratic, and melanocratic rocks and the aplitic mobilisate from the migmatite outcrop at Rozzera. (For explanation see page 251.) Same signs as in Fig. 20.

Fig. 21). This fact suggests that the rock-complex as a whole has acquired a large degree of mobility through which the anatectic products have become fairly homogeneous.

NATURE OF PARENT MATERIAL AND RELATED PROBLEMS

In and around the two areas, there exists neither the original sedimentary material, nor the "pure" metamorphic equivalent which could be considered as parent rock of the banded gneisses and migmatites of Lavertezzo and Rozzera. Hence it is very difficult, if not impossible, to find any conclusive arguments relative to the nature of the parent (source) material. However, the argument that these banded gneisses and irregularly occurring veined migmatites are merely reproduced by mimetic crystallisation (neomineralisation), and the possibility that the pre-existing structural pattern and banding was preserved during Alpine metamorphism, can be ruled out on the regional evidence already cited.

Considering the local and regional data relating to the field relationships, the petrography and geochemistry of the rocks, it seems plausible that the amphibolites and gneisses of Lavertezzo and Rozzera represent a supracrustal rock-complex overlying an old granitic basement. As regards the nature of the supracrustal rocks, arkoses or greywackes cannot be considered probable, for such sediments have not been recorded in the surrounding areas. Furthermore, in view of the aluminum content and its almost uniform percentage[3]) ($\sim$15 wt. %) in the rocks, average shale and its metamorphic derivates seem probable (Pettijohn, 1957, p. 344), although the given Na-amount in the rocks has to be explained in another manner.

Viewed on a regional scale, there exists a close similarity between the chemical and mineralogical composition of the huge Verzasca core-gneiss, and that of the leucocratic oligoclase-rich bands in the gneiss-complex. This chemical similarity has to be explained by one and the same process. However, the leucocratic lamellae in the banded gneisses do certainly not represent injected material from the Verzasca-gneiss; they are the result of partial melting of some metasedimentary complex. It is worth repeating that a genetic relationship, evidenced by the anorthite percentage of plagioclase, is found in adjoining dark and light rock-bands.

It is considered that the supracrustal rock was predominantly a pelite with interbedded calcareous and psammitic material, and basic layers. This supracrustal complex with well-developed layering was modified as a result of

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[3]) Aluminum in rocks is considered by many authors as an "internal standard" (see for example Misch, 1968, p. 66).

partial melting ± metasomatism and metamorphic differentiation giving rise to the banded gneisses and migmatites in the Verzasca region (cf. WENK in JÄGER, NIGGLI, and WENK, 1967). Such a proposition has been considered in several similar rock suites. In a brief description of "Banded gneisses of eight localities", amongst which the outcrop of Lavertezzo is included, DIETRICH (1963, p. 89) arrives at a similar conclusion for all the different outcrops.

COMPARATIVE STUDY OF THE OUTCROPS OF LAVERTEZZO AND ROZZERA

The following comparison is based on the already-mentioned account of the petrography, mineralogy, geochemistry, structures, and field-relations of the rocks of Lavertezzo and Rozzera.

1. Both outcrops are placed in a transitional zone between the leucocratic Verzasca core-gneiss and its mantle, composed of mesocratic gneiss and amphibolite.
2. The rocks of the outcrops belong to the same metamorphic facies.
3. Both outcrops have similar rock-types, and their parent material was of the same chemical character. In both outcrops, the leucocratic gneisses and aplites possess quartz-dioritic to trondhjemitic composition.
4. The migmatites of both places are characterised by a great variety in the pattern of mixing of leucocratic and mesocratic/melanocratic components, occasionally with schollen and schlieren.
5. Both outcrops contain late-kinematic aplite and pegmatite dykes and veins, and show post-kinematic structures such as faults and joints.
6. The foliation in the rocks at both places shows almost the same strike-direction.
7. Structurally, both outcrops show folds of varying size and nature, but there is always a parallelism between the linear structures, i. e. the fold-axes and lineations coincide with each other. Furthermore, at both places the biotite-orientation is homotactic in relation to the mesoscopic and also macroscopic structures, while quartz-orientation is heterotactic. Two s-surfaces are noted in both outcrops, the first (s_1) is due to the compositional layering, the second (s_2) to the axial-plane schistosity.

In spite of all these fundamental similarities, there are striking differences between the rocks of Lavertezzo and Rozzera, as given below:

1. The rocks of Rozzera show very intricate mixing of the mobile and immobile components, whereas those at Lavertezzo occur predominantly in the form of well-defined bands.

2. The outcrop of Lavertezzo shows moderate to almost vertical dips, whereas the rocks at Rozzera have gentle to moderate dips.
3. At Lavertezzo, the rocks show examples of refolded folds. No such refolding has been observed at Rozzera.
4. Antiforms and synforms with curvilinear fold-axes and curviplanar axial surface are prevalent in the rocks of Lavertezzo, whereas small isoclinal folds are seen at Rozzera.
5. Presence of orthite and absence of calcite-bearing inclusions are features of the rocks of Rozzera; the reverse is the case at Lavertezzo.
6. Phase diagram studies together with field and microscopic investigations have led to the conclusion that the leucocratic gneisses of Lavertezzo are the products of partial anatexis accompanied by intense differential movements, while those at Rozzera are the result of a more mobile stage of anatexis, whereby agmatites, nebulites etc. resulted.
7. The same studies have also led to the conclusion that the aplite dyke at Lavertezzo is a late-kinematic *intruded* anatectic melt of the Verzasca-gneiss, and that the aplitic mobilisate at Rozzera is an anatectic product *in situ* of the rocks that are presently seen as migmatites in various stages of mixing with the aplitic mobilisate.

DISCUSSION: BEHAVIOUR OF THE MOBILE AND IMMOBILE PHASES IN RELATION TO THE REGIONAL (ALPINE) FOLDING

These differences, particularly the last two, raise the problem of temperature and pressure conditions and of the behaviour of the rock-complexes during the regional (Alpine) folding. The area of Lavertezzo is situated about 700 m deeper than the region of Rozzera. In addition, the outcrop of Lavertezzo is about $3\frac{1}{2}$ km (as the crow flies) nearer to the "root-zone" or the central zone of anatexis.

If one assumes that this difference in altitude is insignificant in view of the superjacent load of 13–20 km, which is supposed to have existed in the region as a whole, it then implies that the pressure was nearly the same at both outcrops. It can therefore be recalled here that the distinct concentration fields (see Figures 18 and 19) shown by the rocks of Lavertezzo and Rozzera in the phase-equilibrium diagrams cannot be ascribed to different values of P_{H_2O}; nor can these separate fields be understood in terms of the anorthite percentage in the rocks, because the plagioclase composition in these rocks is almost the same.

Again, the differences in the pattern of rock-mixing cannot be attributed to temperature-variation, since both outcrops were subjected to the same temperature conditions, as evidenced by their similar mineral parageneses. However, if the difference in height of 700 m could create temperature differences, then the outcrop of Lavertezzo must have had a higher temperature than that of Rozzera (see their geological position, Fig. 2). There is however no such evidence. Also, the opposite argument that the temperature in the rocks of Lavertezzo was comparatively lower has no foundation either. Thus it is concluded that there were no temperature differences between the rocks of Lavertezzo and Rozzera.

Furthermore, the different patterns of the rocks cannot be understood through the assumption that there were variations in the water-content, for the parent rock at both places had the same chemical character. Moreover, the rare occurrence of sericitisation and chloritisation, and the complete absence of scapolite in both outcrops indicates a similar environment from the point of view of water and other volatiles.

Inasmuch as the hydrostatic pressure, chemical composition, and temperature were the same, the present pattern of the rocks will have to be explained by other factors, responsible for the band-formation during Alpine anatexis and migmatisation.

In both outcrops the formation of gneissic structure was connected with the main phase of Alpine deformation-crystallisation. During this regional metamorphism, the mechanical and chemical anisotropies of the pre-existing rock-assemblage were obliterated by rearrangement of the material. Componental movements, both direct and indirect, occurred during part of the period of deformation-crystallisation. This mechanism has been described by many authors, especially by SANDER (1930, p. 269–275). The net result of these movements was gliding and rotation of crystals, and transport of material by way of diffusion and solution (SANDER loc. cit., TURNER and VERHOOGEN, 1960, p. 585). The material thus migrated, was redeposited and rearranged until the acting forces were eventually neutralised.

Under the prevailing ultrametamorphic conditions in the Verzasca region, besides the process of diffusion, there occurred partial melting of the rocks. The mobile light components underwent bodily migration due to existing pressure gradients, and consequently the rocks reacted by plastic flow. During this mechanism the molten/semi-molten material probably differentiated in a way comparable to the "chemical squeezing" described by RAMBERG (1952, p. 220). The material thus differentiated/segregated was however arranged into two distinct patterns in the two places: in the form of banded gneisses at Lavertezzo, and as complex migmatites at Rozzera.

To account for this variety of rock-arrangements, one cannot completely depend on the data provided by the study of these small outcrops, especially when the conditions of P, T, and H_2O and the nature of the material were similar at both places. Hence, on the basis of the regional geological studies by WENK, the present author has endeavoured to investigate the factors responsible for the existing difference in the rock-pattern at the two outcrops. To be sure, the process of melting in the two places was the same. Besides the phase diagram studies, the field and petrographic data firmly support this similarity, as reviewed here. The occurrence of amphibolite schollen in a gneiss at Lavertezzo (Plate II, Fig. 2) shows that these schollen were once "swimming" in the mobile gneiss (cf. Plate I, Fig. 2). Furthermore, the outcrop of Lavertezzo presents excellent examples of plastic flow, in which thin amphibolite layers have been co-folded with the leucocratic bands, while thick amphibolite bands reacted by disruption and fracturing – a phenomenon involving competence differences. At Rozzera, on the other hand, such features are rather more convincing of the once-existing mobility (see Plate I, Figs. 1–4). These structural features, portrayed in Figures 1 to 4, and several others described earlier, suggest local bodily movements of the anatectic melt and plastic flow of the rocks. At many places, homogeneous granitic (aplitic) material occurs as veins and dykes, the latter transecting the flow folds in leucocratic gneisses.

Thus, with a similar melting-history in the same PT-environment, the arrangement of the anatectic material in the form of a banded structure (the banded gneisses of Lavertezzo) can be regarded as due to the differential movements operating during anatexis. This proposition is in full agreement with the regional data relating to deformation-crystallisation in Alpine metamorphism (see WENK, 1943, 1948, 1962, and in JÄGER, NIGGLI, and WENK, 1967). On the basis of structural analyses of the Lepontine Alps, WENK (op. cit.) has shown that the process of crystallisation accompanied Alpine deformation, but in many instances it has outlasted the latter.

If there was only one main deformational phase, the two studied outcrops could be taken as examples representing the two above cases of Alpine metamorphism, the rocks of Lavertezzo exemplifying simultaneous deformation-crystallisation, and those of Rozzera showing that the crystallisation outlasted the deformation. However, the possibility of more than one set of synchronous movements, belonging to the main Alpine deformational phase, within and around the areas of Lavertezzo and Rozzera, cannot be ruled out. Thus, for example, the occurrence of refolded folds at a few places in the outcrop of Lavertezzo indicates that more than one system of synchronous movements might have occurred, but, surprisingly, petrofabric studies have not been able to clarify the point.

Although this problem has not yet been solved, it has to be accepted that the structural patterns displayed by the rocks of Lavertezzo were formed approximately during the phase of Alpine regional metamorphism which also produced the intricate migmatite structures at Rozzera and in neighbouring areas, the factual basis of this statement being age-determination data (see

JÄGER in JÄGER, NIGGLI, and WENK, 1967) and the results of petrofabric studies (see WENK, 1943).

Following KRANCK (1957, p. 272), it can be assumed that the deformation of rocks under deep-seated conditions is mainly controlled by the amount of energy absorbed (cf. RAMBERG, 1952, p. 8). Thus, in the present case, the rest being equal, one should consider the transfer of thermal energy in relation to the geological situation and rock-disposition of the two outcrops (see profile in Fig. 2). The thermal energy, which brought about the metamorphism and the anatexis of the rocks, rose from a deep-seated source and formed the thermal dome defined by WENK (1962), which post-dates the great nappe-forming movements. The high-dipping rocks of Lavertezzo, which are situated close to the "root", seem to have received the energy earlier than the low-dipping rocks of Rozzera at a higher altitude. According to the experiments of H. R. WENK (1964), the thermal conductivity in these Alpine rocks is much better parallel to "s" than perpendicular to "s", and better parallel to "b" than in the "a" direction of the fabric. Hence it is plausible that the partial melting of the rocks of Lavertezzo started at an early stage. At the same time, and also subsequently, the rocks underwent deformation whereby the material was rearranged. This rearrangement is considered to have been accomplished by differential movements, perhaps along mechanical boundaries in the material (cf. WENK, 1936). Attention may, however, be drawn to the fact that there are several cases in petrological literature (see for example "Banded gneisses of eight localities" discussed by DIETRICH, 1963), where the formation of banded gneisses (Stromatites of P. NIGGLI) was related to deformation. An important factor perhaps also contributing to the formation of the banded gneisses of Lavertezzo could be a possible increase in volume through the melting of the rocks.

At Rozzera, on the other hand, anatexis started later, at a time when regional differential movements were fading out. Owing to the long-lasting heat-flow, which lowered the cohesiveness of the rocks, the prevailing stress deformation was partly replaced by confining pressure (cf. KRANCK, 1957, p. 278). In the rocks of Lavertezzo, the crystallisation process is considered to have set in at an early stage. As a result, the rocks perhaps behaved as thermal insulators (TUTTLE and BOWEN, 1958, p. 120).

Thus, the rocks of Lavertezzo, although they had attained the same melting stage as those of Rozzera, were strikingly constrained by the differential movements (in a zone of large-scale folding) that led to their present form. At Rozzera, the melting, flow and crystallisation exceeded the deformation and intricate mixing of mobile and non-mobile materials resulted.

The above-described mechanism is undoubtedly a very simple if not the simplest explanation for the existing rock-patterns in the outcrops of Lavertezzo and Rozzera.

Finally, it may be stated that in this process of melting, flow and differentiation, wide-spread diffusion and Na-metasomatism ensued, because

"the rather small and univariant sodium ion is able to diffuse through some mineral lattices very readily ... It would be unlikely if sodium does not possess a rather great mobility along most mineral surfaces" (RAMBERG, 1952, p. 205).

Under these circumstances, the process of Na-metasomatism is considered to have taken place almost simultaneously with the melting and flow of rocks. The added sodium diffused either through the pore-fluids or through the vapour phase existing during the ultrametamorphism (ORVILLE, 1963). The problem of Na-metasomatism has already been discussed. On this basis, it can be safely concluded that the transfer of thermal energy in the studied rocks occurred mainly by way of convection, in which the vapour phase or solutions enriched in sodium and causing Na-metasomatism may be considered to be heat conveyers (cf. MISCH, 1949).

CONCLUSIONS

From the preceding comments it can be concluded that there is no fundamental difference between the origin of the banded gneisses of Lavertezzo and that of the migmatites of Rozzera. In both places, the rocks have undergone partial melting under similar PT-conditions. Also, the source material and the H_2O-content during the metamorphism were similar. Under these circumstances, the existing difference in the arrangement of the material is considered to be mainly due to differential movements which occurred during or immediately after the process of anatexis in the rocks of Lavertezzo.

As in any other deformation, these movements (as internal movements) brought about a rearrangement of the rock material in the form of bands, giving rise to the banded gneisses of Lavertezzo. It seems plausible that these differential tectonic movements belong to late stages of the main Alpine deformation.

The rocks of Rozzera were, of course, also involved in the deformation, but the process of melting and crystallisation in these rocks was slow and long-lasting and continued after the cessation of the differential movements. The rocks therefore show intricate mixing of the mobile and immobile (or less mobile) material. From the arrangement of the rocks in the two outcrops, it seems as if deformation and temperature were mutually modifying their activity whilst the rocks were undergoing granitisation.

Furthermore, the process of Na-metasomatism, related to the formation of the mobile phase, was almost simultaneous with the melting, differentiation, and plastic flow of the material – thus demonstrating a close connection between anatexis and metasomatism during Alpine folding (WENK, 1948, p. 770). The results obtained from the detailed petrographical, mineralogical, geochemical, and structural investigations of the two outcrops support the conclusions derived from regional geological studies (cf. WENK, 1943, 1956, 1962). Since the melting and plastic flow of the gneisses at Lavertezzo occurred during and after the deformation, it would be difficult at the outset to compare directly the flow properties of their granitic components with those of the migmatite rocks at Rozzera, which evidence mobility.

Lastly, the author would like to quote some lines from GAVELIN (1960), who arrived at similar conclusions in his studies "on the relations between kinetometamorphism and metasomatism in granitization". He writes:

"It is evident, from the above surveys, that quite different factors must be considered as possible causes for the origin of 'granite-looking' rocks or granitoids. I think that READ's statement 'there are granites and granites' could be extended in the following way: Granite formation may often be the result of a very complex process, in which various factors and steps of mineral formation, the transfer of matter etc., may contribute to the final result. The end product formed depends on which of the factors was dominant on a particular occasion" (op. cit., p. 265).

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Fig. 1. Folded amphibolites and trondhjemitic gneiss (aplitic texture). The thin amphibolite band shows ptygmatic structure, while the thick amphibolites are fragmented. Note the presence of folded quartz-feldspar veins in the amphibolite fragments, and the flow folds in the gneiss. All these features indicate mobility and competence difference between the gneiss and amphibolites during anatexis. (Locality: Rozzera.)

Fig. 2. Agmatite showing amphibolite schollen in trondhjemitic gneiss (aplitic). A few schollen are seen to have been "digested" by the mobilised gneiss, and at places (near the knife) one observes some mica-rich remnants (dark schlieren). The schollen show reaction zones on their outer margins. Note that the gneissic material is squeezed into some of the schollen. Flow folds are clearly visible. (Locality: Rozzera.)

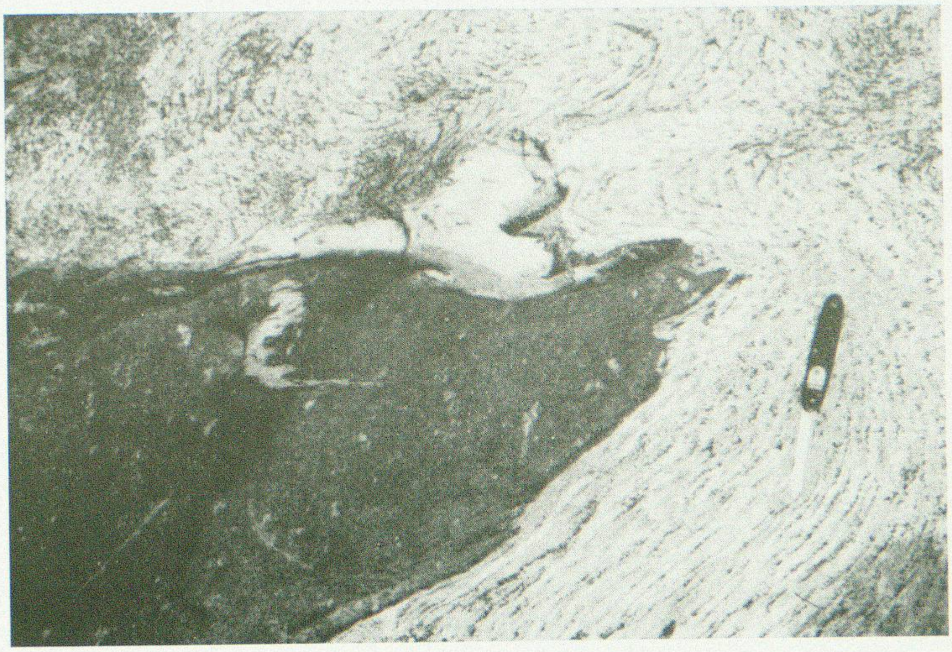

Fig. 3. Dictyonite structure in trondhjemitic gneiss in contact with an amphibolite. The latter shows a reaction zone on its borders. The white patch near the amphibolite is quartz in which the black spots are hornblende crystals.

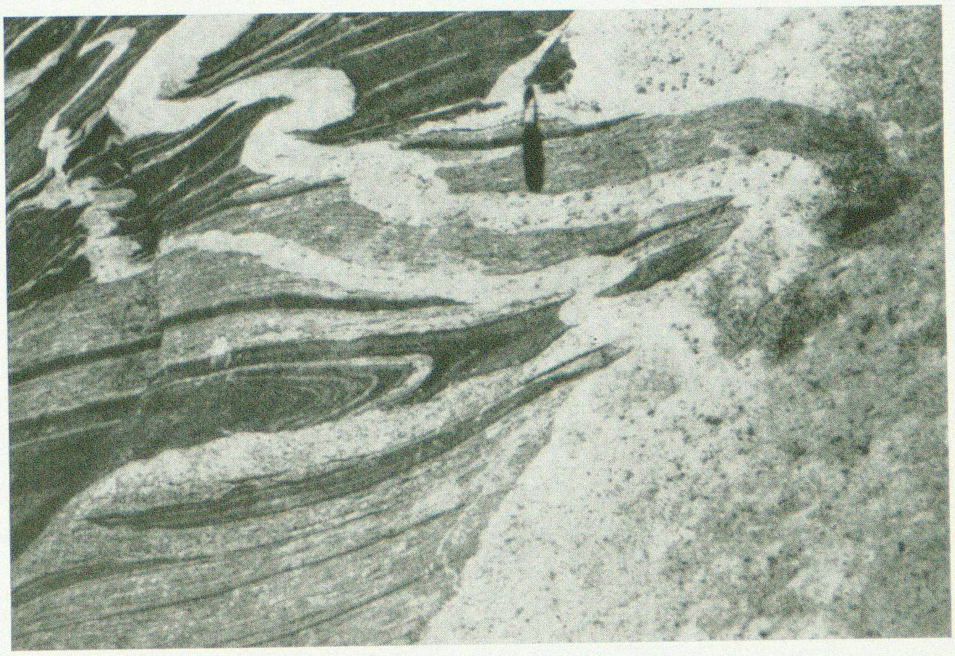

Fig. 4. A typical migmatite outcrop with amphibolite and gneiss bands discordantly cut by a garnet-bearing aplitic mobilisate. Two aplitic veins emerge and intrude the rock-bands, showing ptygmatic folds as they cross the amphibolite. The ptygmatic part is extremely poor in biotite and garnet. The rock-bands do not show any offset across these veins; the schollen (at the knife-point) and schlieren are geometrically aligned with their corresponding rock-bands. Note the dark schlieren of hornblende-biotite-gneiss in the leucocratic gneiss. Also note the folded gneissic veinlets inside the central amphibolite-band, and the unfolded, concordant aplitic veins in an amphibolite band (upper left). (Locality: Rozzera.)

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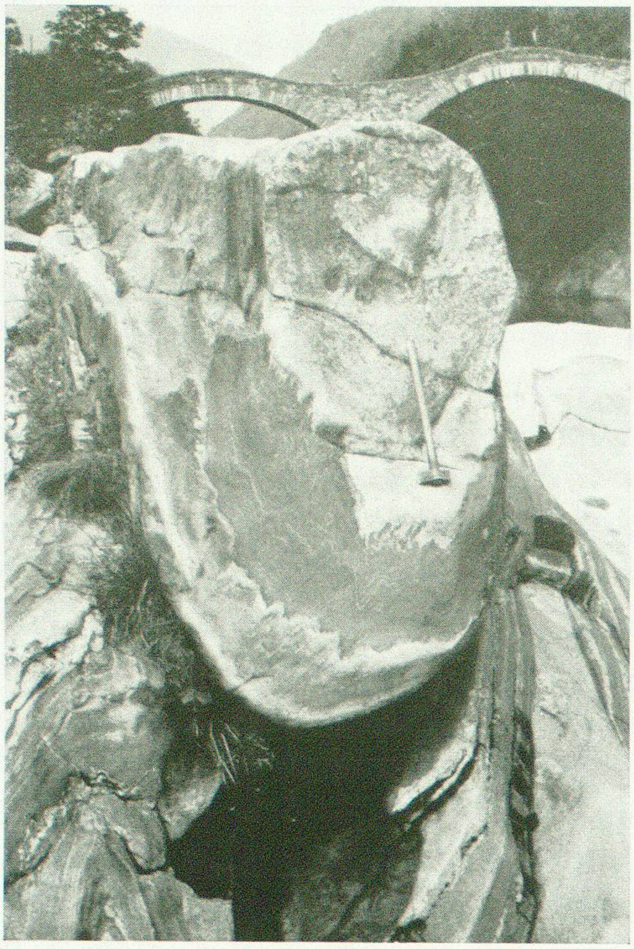

Fig. 1. A three-dimensional view of a synform showing curviplanar axial-surface and a plunging and slightly deflected fold-axis. Note the co-folding of quartzo-feldspathic veins (in the amphibolite) and of the thick gneiss (below hammer). (Locality: Lavertezzo.)

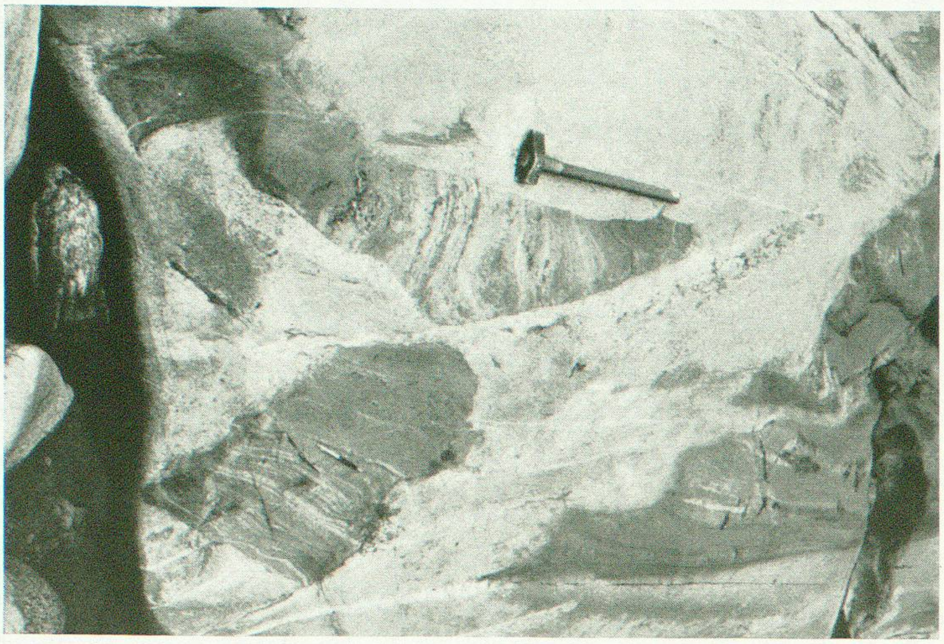

Fig. 2. Schollen of diopside-bearing amphibolite in trondhjemitic gneiss. Observe the coarse-grained gneissic zone around the schollen (near the hammer). The schollen are penetrated by mobilised leucocratic veins, the trend of which is different in each schollen. The straight contact between amphibolite and gneiss (see upper right) roughly marks the strike of the compositional layering. The edge of the amphibolite is in reaction relationship with the gneiss. (Locality: Lavertezzo.)

Fig. 3. Pinch-and-swell in the late-kinematic pegmatite dyke. Observe that adjacent rock-bands show a sort of drag-effect, and that the pegmatite boudins are connected only by thin leucocratic material. The micas are crumpled near the boudins. (Locality: Lavertezzo.)

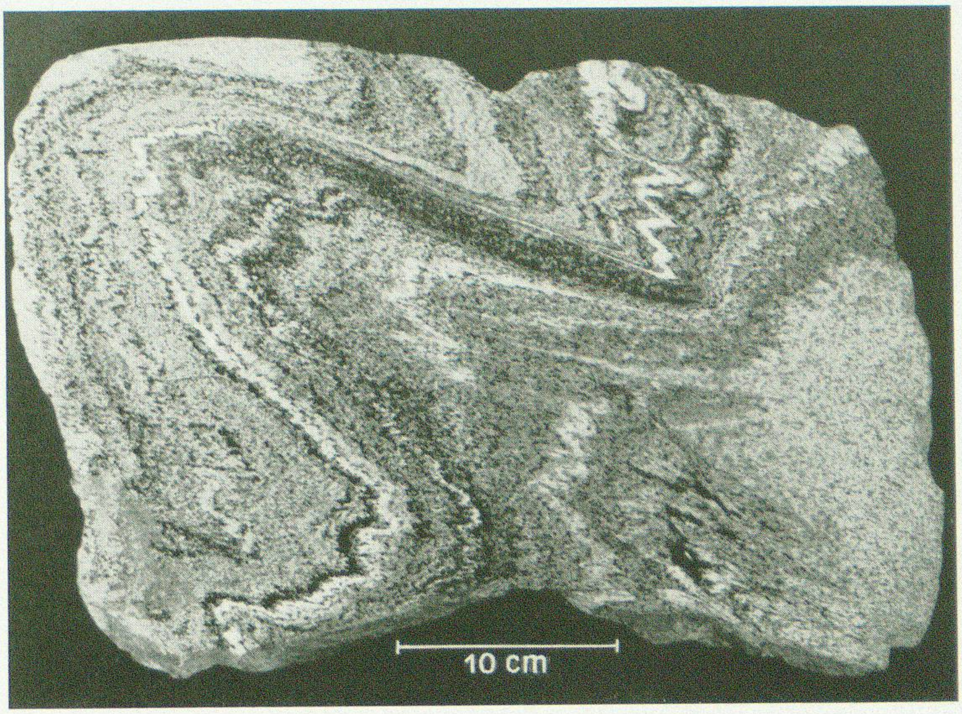

Fig. 4. Axial-plane schistosity (S_2) transecting the compositional layering (S_1). Note the orientation of biotite in S_2. (Polished specimen, Sh Lz C_{25}; Photo Hänny.) (Locality: Lavertezzo.)

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PLATE III

R. S. SHARMA: On Banded Gneisses and Migmatites from Lavertezzo and Rozzera (Valle Verzasca, Canton Ticino)

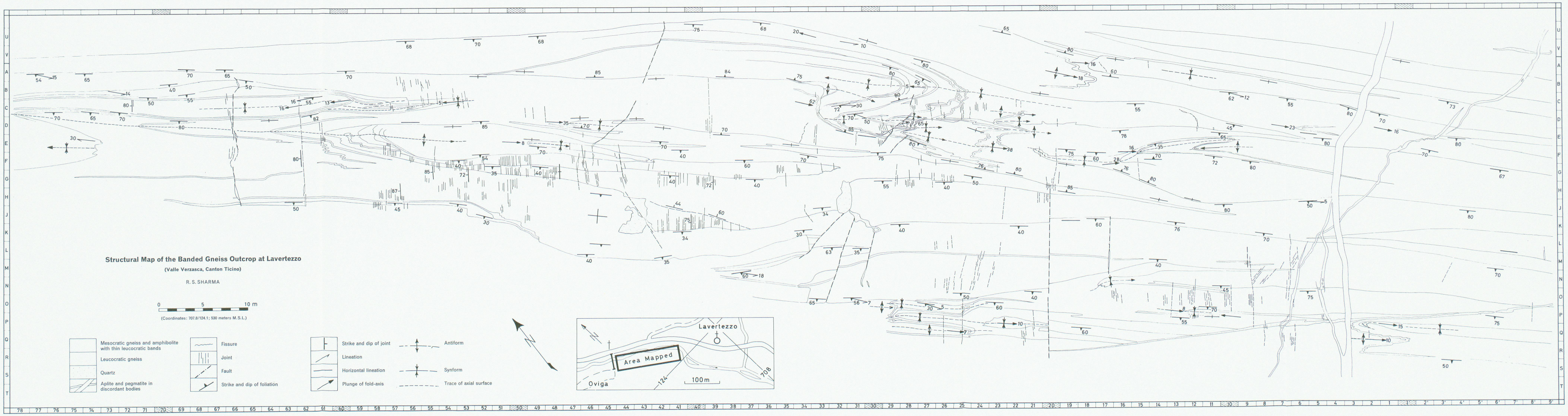

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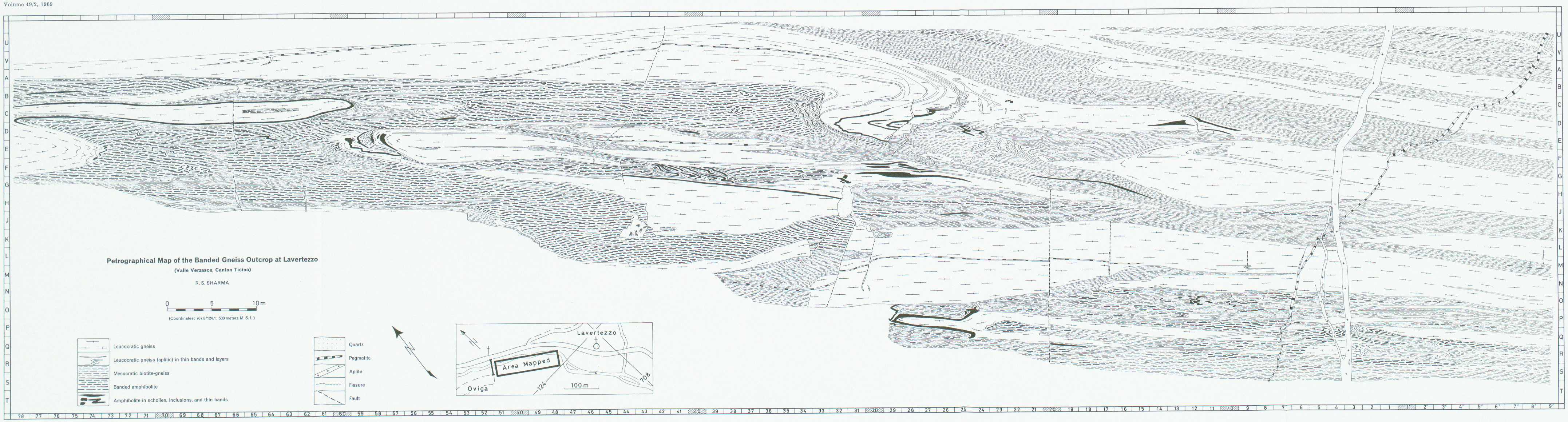
PLATE IV


Petrographical Map of the Banded Gneiss Outcrop at Lavertezzo
(Valle Verzasca, Canton Ticino)
R. S. SHARMA
0
5
10 m
(Coordinates: 707.8/124.1; 530 meters M. S. L.)
Leucocratic gneiss
Leucocratic gneiss (aplitic) in thin bands and layers
Mesocratic biotite-gneiss
Banded amphibolite
Amphibolite in schollen, inclusions, and thin bands
Quartz
Pegmatite
Aplite
Fissure
Fault
Lavertezzo
Area Mapped
Oviga
124
708
100 m