

The igneous rocks, pyrometasomatism and ore deposition at Traversella, Piedmont, Italy

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The Igneous Rocks, Pyrometasomatism and Ore Deposition at Traversella, Piedmont, Italy

by *W. Q. Kennedy*, p. t. Zürich

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I. INTRODUCTION

The objects of the present paper are to describe the igneous rocks of Traversella and to discuss the series of changes which have affected the carbonate rocks along their contact with the intrusion. These changes have involved the formation of silicate skarn and the deposition of ore minerals, the whole process belonging to that type of phenomenon termed Pyrometasomatism by LINDGREN.¹⁾ The normal contact metamorphism (i. e. metamorphism without obvious transfer of material) of the crystalline schists will be dealt with very briefly and only in so far as it concerns the main problem.

Geographical Position of the Area Described. The village of Traversella in the province of Turin, North Italy, is situated on the eastern side of the Chiusella valley just within the southern margin of the Piedmont Alps and some eleven kilometres north-west of the town of Ivrea. Ivrea lies at the mouth of the Dora Baltea (or Aosta) valley where the latter opens into the Plain of Lombardy. The two rivers, the Chiusella and Dora Baltea, flow roughly parallel in a general north-west to south-east direction before entering the Plain of Lombardy and enclose a strip of mountainous country, the southerly portion of which comprises the area under discussion (Fig. 2).

Relation of the Area to the Alpine Orogenic Belt. The general relations of the area are shown on the tectonic sketch-map (Fig. 1). The Traversella region is located in the most southerly part of the Alpine belt, that is to say within the so-called Zone of Roots where the great nappes to the north plunge steeply down beneath the post-Alpine deposits of the Po valley. The actual tectonic unit of which the area forms a small part is the Zone of Sesia-Lanzo, a belt consisting predominantly of mica-schists some twenty kilometres in width which trends from north-east to south-west and forms, according to Argand, the roots of the Dent Blanche nappe.²⁾

¹⁾ W. LINDGREN, Mineral Deposits, 3rd. Edit., New York, 1928, p. 781.

²⁾ E. ARGAND, Les nappes de recouvrement des Alpes Occidentales et les territoires environnants. 1: 500 000. Mat. p. la carte géologique de la Suisse, nouv. sér., carte spéc. 64, 1911. — R. UFFICIO GEOLOGICO, Carta geologica delle Alpi Occidentali 1: 400 000. Roma 1908.

The igneous activity at Traversella does not form an isolated episode but is part of a general magmatic phase which commenced during the waning stages of the Alpine orogeny and gave rise to a series of extrusions and intrusions along the southern border of the Alps and Carpathians. In the western part of the southern Alps the volcanic stage is not represented but five plutonic masses were intruded into the folded rocks and form what may be termed the peri-Adriatic province. These five plutonic masses are shown on the sketch-map (Fig. 1) and comprise, from east to west, the igneous centres of Adamello, the Bergell, Baveno, Biella and Traversella. NIGGLI¹⁾ has studied the problem of the late-Alpine igneous activity and it is to him that we owe the greater part of our knowledge of the chemistry of the peri-Adriatic province. A glance at the map reveals the fact that the intrusions are mostly localised within the Zone of Roots, and NIGGLI believes that this is a direct consequence of the internal structure of the Alps as a whole. The absence of late-Alpine igneous rocks from the central area may be explained by the fact that this portion consists of a great thickness of horizontal, superimposed nappes which must have offered an almost insuperable obstacle to the rising magma which, on the other hand, found much easier access in the steeply tilted southern belt.²⁾

Summary of Geology. The geology of the region is comparatively simple and very uniform throughout (see sketch-map, Fig. 2). With the exception of the late-Alpine igneous rocks all the rocks of the area have suffered regional metamorphism. The country consists for the most part of a series of mica-schists with subordinate gneisses, all of which, according to the Italian Geological Survey, are of pre-Triassic age. In addition to the above mentioned types, there is a widespread development of lenses and elongated masses of eclogite and glaucophane-schist, these being highly characteristic rock types both for the Sesia-Lanzo zone and the Dent Blanche nappe. Nowhere however, do the eclogites and glaucophane rocks come into contact with the younger intrusion. The regional strike of the country varies between east to west and north-east to south-west. Local deviations from this rule occur and this is especially true in the neighbourhood of the intrusion where strikes and dips are much distorted.

From the point of view of ore deposition it is of primary importance that, in addition to the schists, carbonate rocks are also

¹⁾ P. NIGGLI, „Der Taveyannazsandstein und die Eruptivgesteine der jung-mediterranen Kettengebirge“, Schweiz. min. u. petr. Mitt., 2, 1922, p. 169.

²⁾ Personal communication.

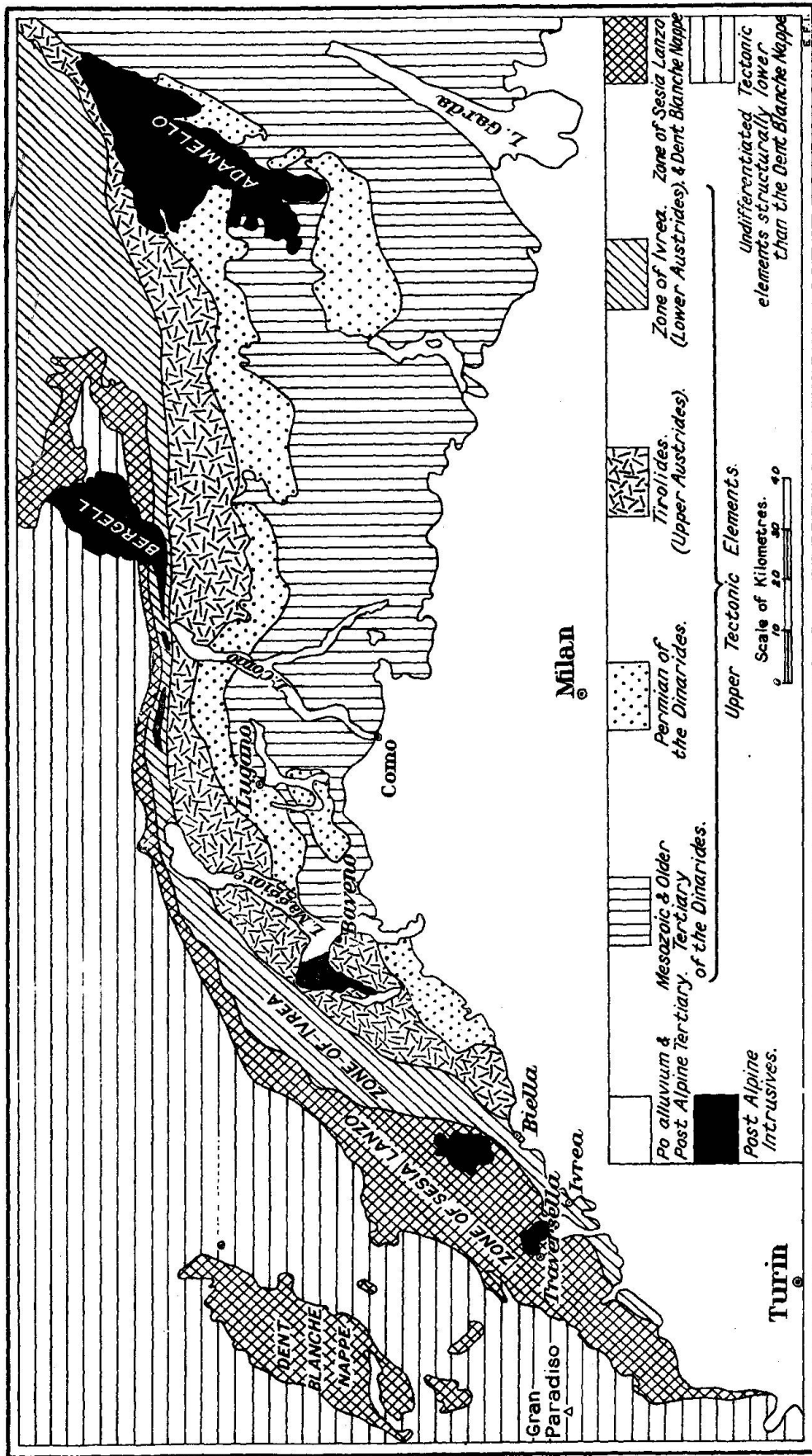


Fig. 1. Tectonic Sketch-map of the West-Alps. After ARGAND and STAUB.

found within the area. These are mostly dolomitic limestones, pure dolomites and limestones being of very minor importance. They form irregular and lens-shaped masses which, as noted by MÜLLER,¹⁾ are associated with the glaucophane rocks. These carbonate rocks are found in two well defined areas. To the west and north-west of the intrusion they are present at Inverso and Fornello, the easterly continuation of the latter outcrop bringing them against the plutonic mass on the extreme north-west side, and forming the mining region of Traversella *sensu strictu*. To the north, at Gias del Gallo and Montaju, carbonate rocks again outcrop and may occupy the same horizon as those at Fornello.

Occupying the southerly portion of the area between the Dora Baltea and the Chiusella is an intrusion of quartz-diorite accompanied by a suite of hypabyssal rocks which include biotite and hornblende-porphyrites, aplites and a few minettes. The intrusive body is elongated in a north-west to south-east direction and stretches from Brosso in the south to Traversella in the north. At Gias del Gallo are seen several small stocks of quartz-diorite identical with those of the main mass and which apparently form apophyses of the latter.

Intense alteration has affected the country rocks along their contacts with the igneous rock. Alteration is of two types (1) normal contact metamorphism (2) pyrometasomatism. The first is characteristic of the schists; pyrometasomatism on the other hand is strictly limited to carbonate rocks and takes place where the latter come into direct contact with the intrusion. Two such areas are found, (1) along the north-west of the diorite mass and (2) at Gias del Gallo. At both localities there has been transfer of material from the magma to the country rock giving rise to diopside and garnet skarns and eventually to deposition of iron and copper ores. During the later stages the first-formed silicates were broken down with the formation of serpentine, talc and chlorite rocks, while in other cases hydrous silicate skarns formed directly from dolomitic limestones under the influence of the same solutions. The whole series of changes illustrates in a very clear manner the evolution of the physical and chemical properties of the mineralizing solutions, to the activity of which the various rock modifications are due.

II. PREVIOUS LITERATURE AND RESEARCH

The history of investigation of the Traversella ore deposits falls naturally into two periods, a. prior to the year 1900 and b. work since

¹⁾ F. MÜLLER, Zeitschr. für prakt. Geol., Bd. 20, 1912, p. 212.

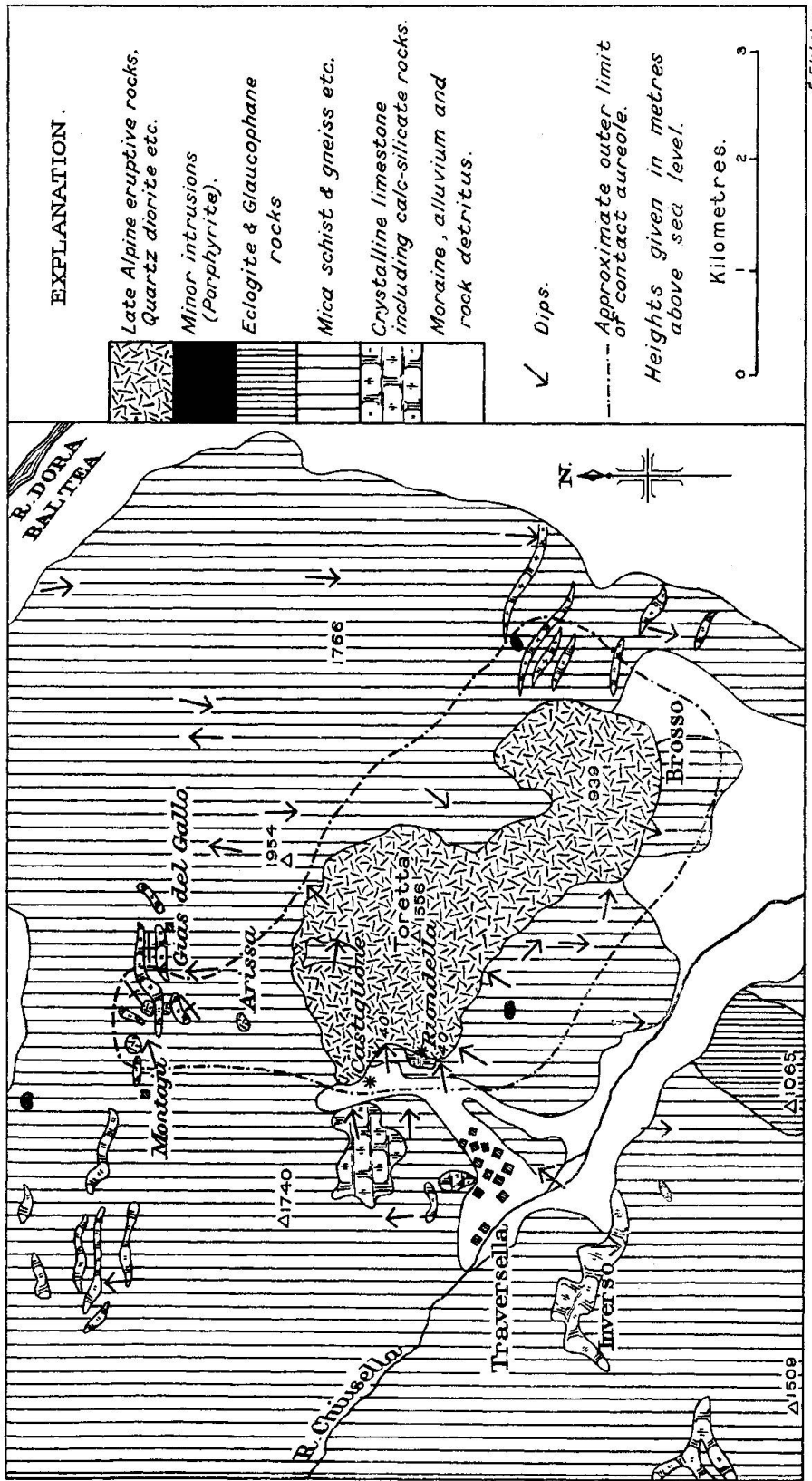


Fig. 2. Sketch-map of the Traversella district. After NOVARESE and MÜLLER,

1900. By the end of the nineteenth century there already existed an extensive literature on the subject of the mineral deposits of the region. In spite of this, however, the nature and genesis of the ore bodies were obscure, and observers had failed to grasp the significance of the diopside and garnet rocks. As the ore bodies form steeply dipping, interstratified masses possessing a certain resemblance to true veins it was only natural that they should be accepted as such. The name „filoni“ was thus applied to them. The heavy, compact skarn rocks were believed to be eclogites and the connection between the ores and igneous rocks passed unnoticed. However in 1893 FUCHS and DE LAUNAY¹⁾ classed the Traversella deposits together with those of Banat as contact iron deposits although a complete description was still lacking. In 1901 and 1902 NOVARESE²⁾ published papers dealing with the area, in which he pointed out that the so-called eclogites were skarn rocks similar to those of Banat and Christiania. In addition he showed that the vein-like nature of the ore bodies was accidental and due to the fact that they were replacement bodies in carbonate rocks and their metamorphosed equivalents. Moreover the carbonate rocks could be seen in an unaltered state outside the aureole where they had suffered only regional metamorphism. Not only did he show that the deposits owed their origin to contact metamorphism but in addition he drew attention to the presence of olivine as a common associate of the ore, and also to the development of hydrous silicates.

In 1912 MÜLLER³⁾ published a further contribution on the subject in which he gave a somewhat more detailed geological and petrographical account of the district. His observations corroborated, in the main, those of NOVARESE but he concluded that there seemed to be some connection between the ore deposition and the development of the hydrous silicates. MÜLLER also pointed out the remarkable absence of halogen minerals such as fluorite, scapolite etc., which commonly accompany deposits of this type. Today his maps are the most detailed in existence and form the basis of any work in the district. In the same year was published the sheet „Ivrea“⁴⁾ of

¹⁾ E. FUCHS and L. DE LAUNAY, „Traité des gîtes minéraux et métallifères“, Paris, 1893, pp. 671—673.

²⁾ V. NOVARESE, „L'origine dei giacimenti metalliferi di Brosso e Traversella in Piemonte“, Boll. R. Com. geol., Vol. I, 1901, also Zeitschr. für prakt. Geol., 1902, pp. 179—187.

³⁾ F. MÜLLER, Die Erzlagerstätten von Traversella im Piemont, Italien. Zeitschr. für prakt. Geol., Bd. 20, 1912, pp. 209—240.

⁴⁾ Carta geologica d'Italia 1: 100 000. Fo. 42. Ivrea. Novara 1912.

the geological map of Italy on the scale of 1:100 000. It covers the whole of the area under discussion in this paper. In 1913 L. COLOMBA published a paper¹⁾ on the petrography of the diorite area of Valchiusella and another²⁾ in 1915 concerning the metamorphism and ore-formation in the lower deposits of Traversella. Both papers give many careful petrographic observations and are particularly useful for the full lists and abstracts of the older and often little known Italian literature they contain.

The only further work carried out within recent years consists of several analyses of igneous rocks from Traversella published in NIGGLI's paper on the late-Alpine igneous activity and made from material collected by MÜLLER.³⁾

The author was engaged in the study of this problem during 1927—1928, the laboratory work being carried out in Professor NIGGLI's laboratories in the Federal Technical University in Zürich and the field work during the Spring of 1928. Through the kindness of Professor REINHARD the whole of MÜLLER's collection, consisting of some hundreds of specimens of rocks and ores, now in the collections of the University of Basel, was placed at the author's disposal. This allowed a considerable knowledge of the ore deposit to be acquired prior to visiting the occurrence in the field. The whole of the MÜLLER collection was studied and the results derived from the study incorporated in the present work.

III. THE COUNTRY ROCKS

a) *Crystalline Schists*. These have been described by MÜLLER⁴⁾ and others and as they have little bearing on the problem of ore genesis may be dismissed with a few words. The schists are uniform

¹⁾ L. COLOMBA, Ricerche sui giacimenti di Brosso e di Traversella. Parte prima. Osservazioni petrografiche sul massiccio dioritico di Valchiusella. Mem. R. Acc. delle scienze di Torino. Serie seconda, Scienze fis. mat. e nat. 63, 1913, p. 271.

²⁾ L. COLOMBA, Ricerche sui giacimenti di Brosso e di Traversella. Parte seconda. I fenomeni di metamorfismo e di deposito nei giacimenti inferiori di Traversella. Ibid. 66, No. 3, 1915.

³⁾ Op cit. supra. A later paper by L. COLOMBA entitled „Osservazioni litologiche e mineralogiche sul giacimento di Castiglione (Traversella)“, Atti R. Acc. delle scienze di Torino. Classe sc. fis. mat. e nat. 64, 1929, p. 373, did not come to my notice until after the present paper had been completed, so that no references to it could be made.

⁴⁾ F. MÜLLER, op. cit., 1911. See also additional references given by this author.

in character throughout the region and consist of normal biotite-schists which in places pass into gneiss. In the field a rude banding is common, due to the alternation of quartz-rich and biotite-rich bands. Under the microscope they consist of a granoblastic aggregate of quartz, orthoclase, biotite and subordinate oligoclase. Muscovite is less common than biotite and the latter usually shows alteration to chlorite. Associated with the mica-schists are various glaucophane rocks which contain in addition garnet, muscovite, rutile and quartz. Occasional kyanite-schists are also found.

b) *Carbonate Rocks.* The carbonate rocks of the Traversella region show a continuous variation between the end members limestone and dolomite. Pure limestones and dolomites seem to be comparatively rare, the commonest rock-type being a dolomitic limestone. The distribution of the magnesia is rather sporadic giving a patchy or banded appearance, which is well seen on weathered surfaces and results from the alternation of layers of different composition.

Prior to the intrusion of the quartz-diorite mass, the whole country was subjected to regional metamorphism which produced the crystalline schists and at the same time altered the carbonate rocks to marbles. During this recrystallization the siliceous impurities reacted with the lime and magnesia with the formation of calc silicates. Small amounts of tremolite and chlorite are found, therefore, in the marbles of the region. These silicate impurities are not present, however, except in a relatively small amount, a fact which testifies to the original purity of the carbonate rocks.

IV. THE INTRUSIVE COMPLEX

The igneous activity of the region has produced two main classes of rocks

- a) Plutonic rocks,
- b) Hypabyssal rocks.

Of these the second is of very subordinate importance and includes only a limited number of rock types; moreover no important metamorphism is related to the phase of minor intrusions.

1. *Plutonic Rocks.*

The main plutonic mass has an elongated outcrop four and a

¹) Carta geologica d'Italia 1: 100 000. Fo. 42. Ivrea. Novara 1912.

half kilometres in length and two kilometres broad at the widest part, giving a total outcrop of approximately nine square kilometres.¹⁾ The long axis runs from north-west to south-east and cuts obliquely across the regional strike of the country. Along the margins of the intrusion the country rocks have been much disturbed so that the schists strike approximately parallel to the igneous contact; cross-cutting relations are the exception rather than the rule. Dips are however for the most part *towards the igneous rock*. Exceptions to this general statement are seen locally, as for example on the extreme north-east and south. It seems very probable, as advocated by NOVARESE, that this deflection was caused by the intrusion of the magma. If such is indeed the case it is somewhat difficult to explain why the country rocks should strike parallel to the contact and at the same time dip towards it. At some points the field evidence suggests that the intrusion is funnel-shaped and belongs to the Ethmolith class of SALOMON.¹⁾ At the same time the presence of cupolas to the north (see below) is hardly consistent with such an interpretation. The second possibility, which seems more probable, is that the schists have been overturned due to doming in much the same manner as the schists around the granite of North Arran which were domed and now in some cases dip towards the intrusion.²⁾

To the north of the main quartz-diorite body several small outcrops of a very similar rock are seen at Gias del Gallo and Montaju while at Arissa, midway between, a peculiar fine-grained porphyrite is found. This latter, however, is not a true porphyrite but merely a chilled phase of the normal quartz-diorite. All the above exposures form small stock-like masses located entirely within the main metamorphic aureole which is continuous from the main intrusion at Traversella to Gias del Gallo. These facts, together with the close petrographic resemblance, seem to indicate that the small outcrops of quartz-diorite are cupolas of the main mass which as yet has not been completely deroofed by erosion. In this case the igneous rock must underlie the country between the northern margin of the main intrusion and Gias del Gallo at no great depth, a supposition which finds support in the extreme width of the metamorphic aureole in this area.

¹⁾ W. SALOMON, Sitz. k. preuss. Akad. Wiss., phys.-math. Classe, 14, 1903, p. 310, also R. A. DALY, „Igneous Rocks and their Origin“, New York, 1913, p. 88.

²⁾ E. B. BAILEY, Geol. Mag., Vol. LXIII, 1926, p. 486. — G. W. TYRRELL, „The Geology of Arran“, Mem. Geol. Survey Gr. Br., 1928, p. 159.

Age of the Intrusion

No direct evidence of the age of the magmatic activity is available, as the intrusion cuts nothing younger than schists of possible pre-Triassic age. NOVARESE however considered that the igneous activity must belong to a period slightly younger than the Middle Oligocene, and in support of this view it may be pointed out 1. that the diorite cuts obliquely across the regional strike of the country, 2. that there is entire absence of crushing or other cataclastic effects and 3. that the rocks exhibit marked consanguinity with intrusions of proved post-Alpine age such as the Bergell.

Classification

A satisfactory classification of the plutonic rocks presents certain difficulties, especially as any classification implies the existence of well-defined types whereas we have to deal with a continuous variation between certain limits. The quartz-bearing rocks are not true quartz-diorites and at the same time cannot be called quartz-monzonites. They occupy rather some intermediate position.¹⁾ Any one set of characters may not remain constant for more than a few yards at a time. On this account it has been thought best to refer to the quartz-bearing types as quartz-diorites and at the same time to allot each to a magma type according to the method of NIGGLI.²⁾ By this means the continuous variation is not lost sight of and a narrow definition of the nature of the rock in question is attained. The following classes may be recognised:

quartz-free	{ alkali felspar absent.	biotite-hyperite.
	{ alkali felspar present.	monzonite, diorite.
quartz-bearing	{ variable content of quartz	quartz-diorite to
	{ and alkali felspar.	quartz-monzonite.

Petrography

Quartz-free Types. This group is of limited distribution, its

¹⁾ This intermediate position has been noticed by some of the older Italian authors, e. g. Traverso, who places the rocks between granite, syenite and diorite. Rosenbusch was the first to classify them among the actual diorites and Novarese follows him in this respect. (COLOMBA, Mem. R. Acc. delle Scienze di Torino, 63, 1913, p. 273—274.)

²⁾ P. NIGGLI, „Gesteins- und Mineralprovinzen“, Bd. I, Berlin, 1923, pp. 96—197. — These magma types of NIGGLI are all defined in the above mentioned work and must not be confused with the „magma types“ in the sense used by BAILEY and THOMAS in „The Tertiary and Post-Tertiary Geology of Mull“ etc., Mem. Geol. Survey Gr. Br., 1924.

members forming only a small proportion of the whole plutonic mass and constituting merely local variations of the quartz-bearing types.

1. *No alkali felspar present, „biotite-hyperite“.* The only outcrop of this type observed occurs on the south slope just below the summit of Toretta in the centre of the mass. The outcrop is obscured by scree and the relations to the surrounding rocks are unknown.

In hand specimen the rock is dark-grey in colour and rather fine-grained in texture, consisting of white felspar and much granular pyroxene together with considerable biotite. Along joint planes amphibole together with a little sulphide may be recognised. The general appearance is quite unlike that of a gabbro.

Under the microscope this rock is seen to consist of plagioclase, diopsidic pyroxene, hypersthene, biotite and magnetite. Amphibole is only found as an alteration product of pyroxene and appears to owe its origin to the evolution of late-formed gases. The plagioclase is fresh and unzoned, differing markedly in this respect from the highly zoned plagioclases in the quartz-bearing rocks. In composition it is a somewhat acid labradorite of the composition Ab 52—An 48; twinning is common on the Albite, Carlsbad and Pericline Laws. Hypersthene forms small subhedral to euhedral crystals with well-marked pleochroism in green and pink shades; twinning is usually absent. The diopside is colourless and tends to form larger individuals with rounded outlines; granular pyroxene is also present and resembles the hypersthene in habit. Biotite and magnetite are of late formation and are invariably closely associated, exhibiting peculiar relations to the pyroxene. Generally the dark-brown, highly pleochroic biotite forms a broad rim surrounding or moulded on to a crystal or crystal aggregate of pyroxene. At the same time the magnetite forms blobs and irregular patches within the biotite crystals or else occurs as a narrow zone between the pyroxene and biotite. Both hypersthene and diopside take part in this reaction and in both cases the resulting structure is the same. The reaction which has produced biotite and magnetite at the expense of pyroxene must be related to the development of some residual liquor rich in iron and potash. The analysis of this rock is given in Table 1, page 88, No. 1.

2. *Containing alkali felspar, „monzonite etc.“.* Such types are restricted in distribution. They always contain augite as an essential constituent, and a small quantity of quartz is almost invariably present. The best exposure of monzonite occurs on the hillside above Riondella where rocks of this class show a gradation into normal quartz-diorite.

In hand specimen the monzonites are grey in colour, medium-grained and with a rich development of plates of glistening black biotite, together with white plagioclase and pink alkali felspar. Dark pyroxene is also conspicuous, a character which is confined to this particular group.

Table 1

	1	A	2	3	4	5	6	7
SiO ₂	48,93	47,90	54,96	55,90	58,42	59,76	60,02	75,83
TiO ₂	1,17	1,91	2,47	1,99	3,01	2,06	—	0,02
Al ₂ O ₃	16,84	16,55	12,95	14,97	14,18	15,49	18,32	12,77
Fe ₂ O ₃	3,85	5,67	4,16	2,75	2,99	3,10	} 5,22	0,23
FeO	5,65	7,50	5,30	5,92	4,08	5,13		0,58
MnO	tr	0,60	0,10	0,15	0,06	0,08	—	tr
MgO	6,00	4,44	3,80	3,22	2,41	1,46	2,59	0,37
CaO	11,10	9,35	6,83	7,22	5,68	5,52	5,84	1,03
Na ₂ O	3,05	3,23	4,14	3,85	3,94	3,80	4,16	3,04
K ₂ O	1,61	2,08	4,28	3,07	3,09	1,48	3,77	4,77
H ₂ O+	1,06	0,20	0,53	0,57	0,89	1,54	} 0,53	0,76
H ₂ O-	0,11	—	0,07	0,13	0,09	0,24		0,15
P ₂ O ₅	0,77	0,32	0,22	0,73	0,57	0,27	0,17	0,30
CO ₂	—	—	—	—	0,35	—	—	—
Total	100,14	99,75	99,81	100,38	99,76	99,93	100,62	100,03

1. Biotite-hyperite, summit of Toretta, Traversella. Anal. S. PARKER.
A. Essexite-gabbro, Toftelholmen, Kristianiafjord, Christiania. Quoted from NIGGLI, *Gesteins- und Mineralprovinzen*, p. 22.
2. Monzonite, Riøndella, Traversella. NIGGLI, „Der Taveyannazsandstein und die Eruptivgesteine der jungmediterranen Kettengebirge“, *Schweiz. min. u. petr. Mitt.*, 2, 1922, p. 173.
3. Quartz-diorite, Traversella. From NIGGLI, *op. cit.*, p. 173.
4. Quartz-diorite, Traversella. From NIGGLI, *op. cit.*, p. 173.
5. Quartz-diorite, Traversella (so-called Porphyrite), Arissa. From NIGGLI, *op. cit.*, p. 173.
6. Quartz-rich edge zone, north margin of the main intrusion, Traversella. Novarese, *Boll. R. Com. Geol. d'Italia*, 1901, pp. 75—93.
7. Aplite, Traversella. Anal. S. PARKER.

Under the microscope are seen plagioclase, orthoclase, biotite, augite and hornblende with accessory quartz, sphene, apatite and zircon. Most of the components are anhedral but any of the dark minerals may show a tendency towards euhedral forms. Mafic constituents form roughly 30 to 35 per cent of the rock and consist for the most part of biotite and augite. The biotite is dark brown with strong pleochroism from brown to light yellow. The augite is colourless with high polarization colours, and a wide maximum ex-

inction angle ($Z:c = 50^\circ$). Its optical properties separate it at once from the pyroxene developed by endomorphic contact effects which is always a diopsidic variety. Hornblende occurs as a marginal alteration product of the pyroxene. In addition to the usual prismatic cleavage the augite sometimes shows a diallage parting. The remainder of the rock consists of almost equal amounts of plagioclase and orthoclase together with the accessories. The plagioclase is strongly zoned and varies from acid labradorite at the centre to oligoclase at the margin; the mean composition must approach that of an andesine. The orthoclase is weakly perthitic (a characteristic feature of all the alkali feldspars of the plutonic rocks) and is of later formation than the plagioclase. Quartz crystallized later than all the other components and occupies the interspaces between them; it occurs only in very small amount. Reddish-brown sphene is the most important accessory mineral. The specimen from which the slice was cut has been analysed by NIGGLI and is quoted in Table 1, the NIGGLI values are given in Table 2, page 93.

3. *Quartz-bearing types.* The rocks of this group form the main mass of the intrusive body and must be regarded as the normal Traversella magma type. Taken as a whole they may be considered as approaching quartz-diorite in composition. However, variation in the relative amounts of quartz, alkali feldspar and plagioclase gives rise to a variety of types. Thus simultaneous diminution in the proportion of quartz and orthoclase gives rise to dioritic types, increase in quartz but not in alkali feldspar produces normal quartz-diorites while quartz-monzonitic types result from increase in both minerals.

The rocks are grey in colour, fine to medium-grained in texture with conspicuous glistening black plates of biotite, greenish prisms of hornblende, feldspar and quartz. Usually the two types of feldspar may be distinguished in hand specimen as the orthoclase is pink whereas the plagioclase is white.

Under the microscope may be recognised quartz, plagioclase, orthoclase, biotite and hornblende, together with accessory sphene, apatite and zircon. The dark brown, highly pleochroic biotite and greenish-brown hornblende form euhedral to subhedral crystals in a base of anhedral plagioclase, orthoclase and quartz. A highly characteristic feature of this group of rocks is that the biotite commenced to crystallize *earlier* than the hornblende. It is quite common to find biotite forming small ragged flakes completely enclosed within a euhedral crystal of hornblende while only rarely does biotite enclose hornblende (Plate I, Fig. 1). This order of separation is the opposite

of that required by BOWEN for his reaction series¹⁾ and is probably connected with a high content of volatile components.²⁾

The plagioclase is twinned on the Albite, Carlsbad and Pericline laws and shows strong zoning, the crystals varying, in extreme cases, from acid labradorite at the centre to albite at the edges. It appears to have been corroded to some extent by the orthoclase which crystallized later and belongs to a weakly perthitic variety. Quartz is always anhedral, it is the latest mineral to crystallize and fills the interspaces between the earlier constituents.

By far the most common rock type is one intermediate between a quartz-diorite and a quartz-monzonite, that is to say, a type in which perthitic orthoclase forms an essential constituent and does not fall far behind plagioclase in importance. Neither orthoclase nor quartz have been observed to fail completely.

The variation in composition of these rocks is illustrated by the analyses Nos. 3, 4 and 5 in Table 1. The corresponding NIGGLI values are to be found in Table 2, page 93.

No. 3 is a quartz-poor type and contains a little augite in addition to the other mafic minerals. The intermediate nature does not allow it to fall readily into any one magma type but, as it is related to both dioritic and monzonitic rocks, it may be allotted to the *diorite-monzonite* magma. Quartz is not abundant and the rock approaches a quartz-free type.

No. 4 is the commonest igneous rock at Traversella. Again the chemistry is intermediate between that of a quartz-diorite and an opdalite. Plagioclase and orthoclase are present in almost equal amount, the monzonitic character being evident although the silica is rather low for a quartz-monzonite.

No. 5 is the so-called porphyrite from Arissa but it would be more correct to designate it as quartz-microdiorite. It has nothing in common with the true porphyrites to be described below and seems to represent a chilled phase of the plutonic. It possesses a more pronounced dioritic character, the potash amounting to 1.48 per cent as against 3.09 per cent in analysis No. 4. Mineralogically this is expressed by the very subordinate importance of orthoclase. This chilled variety exhibits a peculiar texture. There is a pseudo-proto-

¹⁾ N. L. BOWEN, „The Reaction Principle in Petrogenesis“, Journ. Geol., Vol. 30, No. 3, 1922, pp. 177—198.

²⁾ P. NIGGLI, Über Verbindungen von extrem leichtflüchtigen mit extrem schwerflüchtigen Komponenten in besonderer Berücksichtigung minerogenetischer Probleme. N. Jb. f. Min., 1914, Bd. 2, p. 69.

clastic groundmass of albite and quartz which fills the interspaces between larger crystals of quartz, plagioclase and biotite, while hornblende is relatively scarce.

2. *Hypabyssal rocks*

These consist of an undifferentiated or relatively undifferentiated group represented by biotite and hornblende-porphyrites, and a differentiated group consisting of aplites. A few dykes of minette occur in the neighbourhood but are probably older than the remainder of the igneous rocks.

1. *Differentiated types.* Aplites are confined to the plutonic mass, where they form narrow dykes, seldom wider than one foot, which cut the diorite in a general east to west direction, i. e. parallel to one set of joint planes. This indicates that some of the joints at least belong to an early stage in the post-consolidation history of the intrusion, as they were in existence before the injection of the residual magma which entered them in the form of such aplites. It may be mentioned here also that a series of thin veins or seams of biotite penetrate the diorite in a direction parallel to the aplite dykes and seem to represent the action of volatile components during the final stages of cooling. From one point of view these biotite veins might be regarded as forming part of the lamprophyre phase which is otherwise absent from the eruptive mass. The veins however cannot be termed dykes, the maximum width observed never exceeding two or three millimetres.

The aplites are cream-coloured or white rocks with a fine granular texture, occasionally slightly porphyritic. Rounded quartz grains are conspicuous in hand specimen and are set in a feldspathic base. Mafic minerals are almost entirely absent. Under the microscope the rocks are typical diorite aplites consisting of plagioclase, orthoclase, quartz and a few shreds of chloritized biotite. The texture shows a peculiar protoclastic development, rounded crystals of quartz, orthoclase and plagioclase are closely crowded together and wrapped round with a scarce, very finely granular groundmass of interlocking grains of the same minerals. The plagioclase is zoned and has a mean composition Ab 60—An 40; the more basic centres show slight saussuritization, the outer shells being perfectly fresh. Plagioclase is subordinate to orthoclase which is here also a slightly perthitic variety. A few shreds of chloritized biotite represent the only remaining constituent. An analysis of this rock is given in Table 1 and the NIGGLI values in Table 2.

Pegmatites are uncommon and the only example seen formed a small vein about one centimetre in width cutting the quartz-diorite. This example is of interest in that it contains myrmekite of primary origin. The slice shows a microscopic intergrowth of quartz, orthoclase and plagioclase. On the one hand quartz is intergrown with orthoclase and shows a great diversity of eutectic structures, while on the other hand quartz and plagioclase (albite-oligoclase) also form intergrowths. This latter „myrmekite“ can only be interpreted as of primary origin, its relations to the remaining constituents of the vein excluding any possibility of secondary formation such as is usually the case with quartz-plagioclase intergrowths.

2. *Undifferentiated Types.* These form dykes and small masses outside the plutonic mass and consist of biotite and hornblende-porphyrites. The types studied include those with biotite as the sole ferro-magnesian mineral, those with both biotite and hornblende and those with hornblende alone. The most common type is however the biotite-hornblende-porphyrite (Plate I, Fig. 2).

The rocks are dark grey in colour with phenocrysts of plagioclase and the mafic minerals set in a fine-grained, felspathic groundmass. The plagioclase is highly zoned and twinned in a complex manner. It builds perfectly euhedral crystals which vary in composition from acid labradorite at the centre to oligoclase in the outer shells. The groundmass felspar is also zoned and varies from andesine to albite in extreme cases.

Biotite is dark chestnut brown and forms six-sided, euhedral plates. Here and there it shows alteration to green chlorite or else epidote may be seen to penetrate along the cleavage planes. Very often the crystals show broken contours and embayments due to resorption effects. The hornblende is a greenish variety with pleochroism in yellowish-green, greenish-brown and olive-green colours. The extinction angle (Z:c) is 15° and the optic sign is negative. It forms long prismatic crystals with well developed faces which are commonly twinned on (100). The phenocrysts are set in a highly felspathic groundmass with only a very small proportion of ferro-magnesian minerals. Quartz appears to be totally absent and was observed only in one slice where it formed a porphyritic aggregate of small grains, probably of xenolithic nature.

3. *Provincial Relations of the Igneous Rocks*

It has been pointed out above (p. 78) that the localized igneous activity at Traversella belongs to the more regional magmatic activity

which, during the waning orogenic movements, gave rise to a series of intrusions and extrusions along the southern margin of the Alps and Carpathians. Closer examination reveals the fact that, not only does Traversella fit closely into the general scheme of differentiation but the chemical and mineralogical variation of this centre recapitulates the magmatic variation of the province as a whole.

The problem of late-Alpine igneous activity, treated from the point of view of petrographic provinces, has been exhaustively studied by NIGGLI¹⁾ in his paper on the eruptive rocks of the young fold mountains of the Mediterranean. By means of a statistical and comparative study of all the available analyses he was able to show that, considered as a whole, the rocks of the peri-Adriatic province belong to two distinct differentiation series; the first represented by the „diorite—tonalite—quartz-diorite—granite“ line of descent and the second by the „shonkinite—syenite—quartz-syenite“ association. Both series occur together in the Bergell which serves therefore as a connecting link between the tonalitic region to the east and the Piedmont province to the west, where the syenitic line of descent is predominant. This Piedmont province forms a well-marked unit and the relationship between the various members is relatively close, so close in fact that NIGGLI²⁾ considers that Biella and Traversella may well represent differentiation products of the same magma. This is seen when we compare the NIGGLI values of the two igneous centres (see Table 2, p. 93).

Table 2

Traversella

	si	al	fm	c	alk	k	mg	c/fm	ti	p	Magma-type
1.	116	23,5	39	28	9,5	0,26	0,54	0,72	2,1	0,8	essexitegabbroid
2.	157	21,5	38	21	19,5	0,40	0,43	0,55	5,3	0,2	yogoitic
3.	164	26	35	22,5	16,5	0,35	0,40	0,65	4,4	0,8	dioritic-monzonitic
4.	198	28	32	20,5	19,5	0,34	0,38	0,65	7,7	0,8	qz. dioritic-opdalitic
5.	210	32	31	20,5	16,5	0,21	0,25	0,67	5,5	0,4	qz. dioritic
6.	484	48	7	7	38	0,51	0,47	1,00	1,2	0,7	aplite-granitic

Biella

A.	110	20	45	29,5	5,5	0,28	0,66	0,66	4,3	0,1	hornblendite-gabbroid
B.	195	27	30,5	19	23,5	0,57	0,46	0,62	6,0	0,2	normal syenitic
C.	206	32	26	16,5	25	0,50	0,45	0,63	1,4	0,8	„ „

¹⁾ P. NIGGLI, „Der Taveyannazsandstein und die Eruptivgesteine der jung-mediterranen Kettengebirge“, Schweiz. min. u. petr. Mitt., 2, 1922, p. 169.

²⁾ P. NIGGLI, op. cit.

In Traversella it is apparent from the analyses and petrographic characters, that, in addition to rock types whose characteristics link them definitely either with the tonalitic or syenitic lines of descent, others are present which occupy an intermediate position. Thus the monzonite from Riondella belongs to the pure potassic series and, as shown below, it agrees closely in composition with the type „yogoitic magma“, a characteristic member of the syenite line.

si	al	fm	c	alk	k	mg	
157	21,5	38	21	19,5	0,40	0,43	monzonite, Riondella.
145	23	37	21	19	0,50	0,55	Type yogoitic magma.

The quartz-diorite (so-called „porphyrite“ from Arissa) on the other hand is undoubtedly a member of the tonalitic series as shown by comparison with a typical member of the latter.

si	al	fm	c	alk	k	mg	
220	31	31	19	19	0,25	0,48	Type Quartz-dioritic magma.
210	32	31	20,5	16,5	0,21	0,25	Quartz-diorite, Traversella.

One of the quartz-poor dioritic types (Table 1, No. 3) does not agree exactly either with a monzonitic or dioritic magma-type but exhibits features which link it to both. The alk values of the

si	al	fm	c	alk	k	mg	
140	30	30	21	19	0,50	0,45	Type Monzonitic magma.
164	26	35	22,5	16,5	0,35	0,40	Quartz-bearing Diorite.
155	29	35	22	14	0,28	0,48	Type Dioritic magma

contrasted types are especially significant, while k shows an increase with respect to the dioritic magma and a decrease with respect to the monzonitic type. Probably, on the whole, rocks of this intermediate nature are predominant at Traversella. This is strange in view of the fact that, at Arissa, the chilled, marginal phase of the intrusion is a normal quartz-diorite belonging to the diorite—tonalite series. Such chilled, marginal parts are believed to represent the undivided magma; in this case it would appear that the potassic character of many of the Traversella rocks is one which has arisen through differentiation *in situ* of a quartz-dioritic magma. The available evidence is however insufficient either to confirm or invalidate the truth of this suggestion.

The same mixed type of differentiation which has been recognised at Traversella is more highly developed in the Bergell and occurs, in a lesser degree, at Adamello. Thus the Piedmont province with its mixed potassic and tonalitic character serves as a link between the true calc-alkaline province in the east and the strongly alkalic

(potassic) region in Italy. The tectonic relation of the mixed potassic province of Piedmont to the Alpine orogenic belt is similar to that of the closely related Yellowstone area of North America to the Cordilleran mountains.¹⁾

Finally it may be pointed out that Traversella, Banat and Elba all show pyrometasomatic contact phenomena with which was connected the deposition of ore minerals. All three intrusions are situated in analogous positions and all must have been intruded under similar tectonic conditions, a feature which may possess some underlying significance.

4. *Endomorphic contact effects*

Certain modifications of the normal igneous rock are seen where the latter borders on carbonate country rock. Such modifications may be either textural or mineralogical.

Textural modifications occur locally, especially in the neighbourhood of Castiglione, and consist of an abnormal coarseness of grain like that commonly developed in pegmatites. Mineralogical modifications are usually developed at the same time and it seems probable that the coarse grain results from the outward streaming of volatile components, carrying the ores, which would have the effect of keeping the marginal parts of the intrusion in a liquid state thus allowing of a long period of crystallization.

Mineralogical modifications are developed wherever the igneous body comes into contact with limestone and dolomite. For a distance of several feet inwards from the contact the normal quartz-diorite has suffered great change. It does not contain any quartz but shows a great enrichment in colourless diopside. This mineral may constitute up to some twenty-five per cent of the whole rock. The pyroxene is a normal diopside similar to that of the contact metamorphosed limestones and has a maximum extinction angle ($Z:c$) of 39° and an optic axial angle of 60° . It thus differs in a marked manner from the common augite described above (pages 88 and 89) from some of the more basic rocks within the mass. Accompanying the diopside is a rich development of sphene.

It is evident at once from the thin slices that the diopside is a true magmatic mineral and not of secondary formation. This state-

¹⁾ CONRAD BURRI, *Chemismus und provinzielle Verhältnisse der jungen Eruptivgesteine des pazifischen Ozeans und seiner Umrandung*. Schweiz. min. u. petr. Mitt., Bd. 6, 1926, pp. 160—167.

ment finds proof in the fact that, not uncommonly, the diopside of the enriched zone is enclosed within a euhedral crystal of hornblende and must have crystallized out from a liquid magma. The rock is now an unaltered igneous rock.

It is believed that the enrichment of the marginal zone of the igneous rock in lime and magnesia represents a reciprocal reaction between the magma and the bordering carbonate rocks. According to this conception lime and magnesia were introduced into the magma while, at the same time, silica and possibly alumina passed out into the aureole. ESKOLA has shown that in certain cases the enrichment of an igneous rock in lime along its contact with carbonate formations results, not from a direct interchange of material between the intrusive and the country rock, but by the later assimilation of a previously formed skarn¹⁾ by the igneous rock. In the case of the Traversella contact, however, such has not been the case, for not only are partially digested xenoliths of skarn totally absent but the igneous rock shows no sign of enrichment in iron, whereas the skarn rocks are usually rich in this mineral.

V. CONTACT METAMORPHISM OF THE SCHISTS

This problem will be treated in skeleton only, as it bears no direct relation to the main problem of pyrometasomatism and ore-genesis, although the hornfelses are of considerable interest.

The diorite is surrounded on all sides by a contact aureole consisting of hornfelsed schist, which varies greatly in width from point to point. On the extreme north-east side the appreciable metamorphic effect does not seem to extend to more than one hundred metres from the contact, whereas on the north between the main plutonic mass and the apophyses at Gias del Gallo it has a width of approximately two kilometres. At this point however, as indicated above (see p. 85), the whole area appears to be underlain by the igneous rock at no great depth.

When followed inwards from the unaltered schists towards the contact the rocks are seen to undergo gradual change. They become more compact as crystallization proceeds until at the immediate contact with the igneous mass typical hornfelses are produced. Microscopically the hornfelses exhibit great uniformity of texture and mineralogical composition. Cordierite-biotite-hornfelses are the commonest type. The biotite is the dark-red type typical of the hornfels

¹⁾ PENTTI ESKOLA, On Contact Phenomena between Gneiss and Limestone in Western Massachusetts. Jour. Geol., Vol. 30, 1922, p. 265, especially p. 290.

facies of metamorphism. It has two different modes of occurrence. First it may be present as aggregates of stout lathshaped individuals surrounding a central grain of rutile or magnetite. The more common mode however is as a sieve-like or diablatic intergrowth with alkali feldspar or cordierite. The biotite in this case forms swarms of extremely minute laths or rounded individuals having a parallel orientation throughout a considerable area. This diablatic texture is very characteristic for the entire aureole. Quartz, orthoclase, a little plagioclase (oligoclase) and finally cordierite constitute the remainder of the typical contact rocks. Very often the cordierite is perfectly fresh but quite often its presence may be marked only by pinite pseudomorphs. Green spinel in small grains is common in some of the rocks and one example of a cordierite-sillimanite-corundum-biotite-hornfels was observed from the actual contact between the eruptive mass and the country rock.

Many xenoliths of schist are found within the diorite and in such cases the metamorphism has been most intense. These included fragments have been altered to cordierite-biotite-spinel-hornfels, which may or may not contain sillimanite as an essential constituent. All the xenoliths show the same diablatic development of biotite. In the case of the hornfels of xenolithic origin it is doubtful whether transfer of material from the igneous rock has been entirely absent.

VI. CONTACT METAMORPHISM OF THE CARBONATE ROCKS (PYROMETASOMATISM)

In the case of the contact metamorphism of the schists the effect of the magma was simply that of a heat reservoir. Where the carbonate rocks come into contact with the intrusion there has been in addition active transfer of material from the magma to the country rocks and to a lesser degree the reverse reaction has also occurred. In both cases the original composition has been greatly modified. Such processes involving transfer of material at igneous contacts have been termed „pyrometasomatism“ by LINDGREN¹⁾ who defines this phenomenon as „metasomatism occurring at the contact of an igneous body and the surrounding rocks caused by the action of emanations issuing from the magma at high temperature.“

In the Traversella region carbonate rocks never occur in an unaltered state in direct contact with the igneous mass, a zone of calc-silicate rocks invariably intervening. Such calc-silicate rocks are

¹⁾ WALDEMAR LINDGREN, Mineral Deposits, 3rd. Edition, New York, 1928, p. 781.

found in two areas. They form disconnected bodies all along the north-west margin of the intrusion between Riondella and Castiglione and also constitute the predominant rock between the quartz-diorite stocks of Gias del Gallo—Montaju. The same types are developed in both localities.

Classification of Pyrometasomatic Rocks

The products of pyrometasomatic alteration of a rock depend on three variable factors: 1. the original composition of the rock which has undergone alteration, 2. the composition of the solutions causing alteration, 3. the physico-chemical conditions prevailing during alteration. A classification of pyrometasomatic rocks may be based on any or all of these factors. In the case with which we have to deal, however, the original rocks were of relatively uniform composition while we have no reason to believe that the magmatic solutions varied greatly; in fact, as will be shown later, there is considerable evidence that they did not. Hence any possible classification must be based on the physico-chemical conditions. These are known to have varied. Such a classification of metamorphic rocks based on the physico-chemical conditions of alteration is the three-fold zonal classification of GRUBENMANN.¹⁾ It is true that this is applied to products of regional metamorphism but at the same time there is no reason why it should not be applied to the case in question. The three zones, Kata-, Meso- and Epi-Zone do not necessarily imply depth, although depth may often be the controlling factor; they refer merely to three sets of physico-chemical conditions and the variation may just as easily be lateral as vertical. Each zone carries certain characteristic (typomorphic) minerals which are constantly absent in the other zones. When such typomorphic minerals are present in a contact aureole the various assemblages may be classified on the zonal principle. NIGGLI recognises that such contact metamorphic zones exist.²⁾

Among the metasomatic rocks of Traversella the author has observed the characteristic mineral assemblages of each zone, and so in the following account the rocks which owe their origin to the action of magmatic solutions on the carbonate rocks of the country will be classified according to the three zonal divisions.

¹⁾ U. GRUBENMANN, *Die kristallinen Schiefer*, II. Aufl., Berlin, 1910. — GRUBENMANN-NIGGLI, *Die Gesteinsmetamorphose I*, Berlin, 1924.

²⁾ GRUBENMANN-NIGGLI, *op. cit. supra*, p. 378.

The classification is as follows:

Kata-contact Rocks (high-temperature), diopside, garnet, olivine rocks etc.

Meso-contact Rocks (medium-temperature), mostly tremolite and hornblende types.

Epi-contact Rocks (low-temperature), predominantly composed of hydrous-silicates: chlorite, talc and serpentine, together with carbonates.

The meso-group above is of an artificial nature but it is convenient to group the amphibole rocks together.

1. Kata-contact Rocks

In this group hydrous silicates and amphiboles are absent and the typical minerals are the anhydrous silicates which may be found in igneous rocks, together with garnet. In some of the assemblages feldspar is present whereas in others it is absent so that we get a primary grouping on the basis of the presence or absence of feldspar. The following parageneses have all been observed:

Feldspar absent	{	diopside diopside-garnet garnet diopside-spinel olivine (forsterite).
Feldspar present	{	diopside-garnet-plagioclase diopside-plagioclase diopside-plagioclase-orthoclase.

Feldspar-free types.

Diopside, diopside-garnet, and garnet rocks. These are the typical skarn rocks so widely developed in the Western States of America and in Europe in connection with ore deposits of contact metamorphic origin. In the Traversella region they are the most common products of the metasomatism of the carbonate rocks and have a wide spread distribution both at Riondella—Castiglione and in the northern group of mines at Gias del Gallo—Montaju. While the monomineralic members are by no means rare the predominant representative is a mixture of approximately equal parts of diopside and garnet. Such a rock forms the main type between the small diorite stocks at Gias del Gallo and Montaju and is the source of the crystallized minerals for which Traversella is justly famous.

Diopside rocks. It is characteristic that the pyroxene rocks attain a greater degree of purity than the corresponding garnet members of the series, for whereas in the garnet rocks small amounts of diopside, apatite and occasionally calcite usually occur, the pyroxene rocks often consist of pure diopside.

Megascopically they vary in colour from light-green to practically colourless. In the greenish varieties the texture is granular and porous but in the lighter-coloured types it is massive and compact, the pyroxene tending to form columnar crystals. Under the microscope the mineralogical characters of all are uniform but great variation in texture is observed (Plate I, Fig. 3).

The diopside is colourless, the common cleavage parallel to (110) being well marked; at the same time there is a prominent parting parallel to (100) and (010). The mean R.I. was found to be 1.685. The optic axial angle was found to vary between 59° and 61° while the extinction angle ($Z:c$) = 39° . Twinning is commonly present on (100). In one or two cases a faint suggestion of zonal structure was observed but this was too indistinct to allow of optical determinations within the different zones. The optic sign is positive.

The predominant texture is crystalloblastic, the pyroxene seldom showing crystallographic outlines except where it projects into a cavity or in the rare cases where it borders on a small patch of carbonate. Owing to the simultaneous formation in a solid medium the crystals possess a rounded form but the grain size varies greatly from point to point even within the same slice; thus in one slice a fine-grained mosaic of colourless grains of diopside may be seen to border on a patch of coarser individuals which may reach a diameter of 0.5 mm. Another striking variation is seen in the development of long prismatic crystals which give a transition to the nematoblastic type of texture. These prismatic crystals may occur scattered among the rounded grains or again they may increase in importance until they constitute the main part of the rock. They commonly adopt a radial or sub-radial grouping which imparts a most characteristic appearance to the slice. The best example of such a habit is seen in the case of the analysed rock which consists of from 50 to 60 per cent of such prismatic crystals arranged in sub-radial groups and set in a porphyroblastic manner in a groundmass of small rounded grains of diopside.

The diopside rocks are often porous, showing cavities which appear to form at the junction of several grains. Such pores may be empty or they may contain late-formed minerals. In some cases garnet was the cavity-filling, thus giving a transition to the diopside-garnet mixtures. The garnet was found in most cases to be associated with a certain amount of fine lamellar talc. In other cases the pore filling consisted of calcite in which were embedded sporadic grains of garnet, sphene or apatite. Less commonly quartz takes the place

of the carbonate mineral. Spheue is usually an important accessory although in the analysed specimen it was absent. When garnet is present it occurs invariably within the pores and has the appearance of being posterior in formation to the main mass of the rock.

Below is given an analysis of a pure diopside rock from the quarry above Riondella, and for comparison two analyses of diopside.

	1.	A.	B.	C.		NIGGLI Values	
						1.	C.
SiO ₂	54,19	54,30	54,77	55,60			
TiO ₂	0,00	—	—	—	si	97	100
Al ₂ O ₃	0,11	—	—	—	al	tr	—
Fe ₂ O ₃	0,51	—	0,17	—	fm	51	50
FeO	1,37	1,11	0,89	—	c	48	50
MnO	0,10	—	0,11	—	alk	0,5	—
MgO	18,14	18,33	18,46	18,50	k	0,33	—
CaO	25,16	25,00	26,33	25,90	mg	0,95	1,00
Na ₂ O	0,24	—	—	—	ti	0,00	—
K ₂ O	0,23	—	—	—	p	tr.	—
H ₂ O+	0,14	—	—	—	c/fm	0,94	1,00
H ₂ O-	0,03	—	—	—			
CO ₂	0,00	—	—	—			
P ₂ O ₅	0,05	—	—	—			
Total	100,27	98,74	100,73	100,00			

1. Diopside-rock, Riondella, Traversella, Piedmont, Italy. Anal. S. PARKER.
- A. Diopside (malacolite), Rezbanya. Quoted from DOELTER, *Handbuch der Mineralchemie*.
- B. Diopside, Black Lake. NIGGLI, *Lehrbuch der Mineralogie*, Bd. 2, 2. Aufl., 1926, p. 269.
- C. Theoretical values for pure $[\text{SiO}_4 \cdot \text{SiO}_2]_{\text{Ca/Mg}}$ molecule.

The Traversella rock exhibits a remarkable degree of purity, the analysis corresponding very closely not only with the actual mineral analyses quoted but also with the theoretical values for pure diopside molecule. It may be regarded rather as a massive mineral than a rock and indicates that the original calcareous rock from which it is derived must have contained very little admixture of aluminous and ferruginous impurities. One conspicuous feature of the analysis is the entire absence of titanium, for as a rule the metasomatic rocks of the region show a considerable amount of spheue. The projection point of the analysis is shown on the triangular diagram for the system CaO-MgO-Al₂O₃ (Fig. 3, p. 109).

At this point may be mentioned the occurrence in the quarry above Riondella of a peculiar rock which consists entirely of colourless diopside and green spinel, together with light-green amphibole

which is seen to be forming as an alteration product of the pyroxene. The spinel which is dark-green in colour seems to be a pleonaste and builds aggregates of small octahedral grains among the crystalloblastic diopside. A few grains of apatite constitute the only additional component. The pleonaste forms not more than 5 to 7 per cent of the rock.

Garnet rocks. Rocks in which garnet forms the chief component seldom attain the same degree of purity as those containing predominant pyroxene; and whereas the latter may be free from all impurities, as was seen in the case of the analysed specimen, the former usually carry a certain amount of intermixed pyroxene.

In the field the rocks are heavy and compact, pale to dark brown in colour with a greasy lustre. Usually they are coated on weathered surfaces with a skin of iron oxide which testifies to the high iron content. Very often they have a slight greenish tinge due to the presence of diopside. This latter mineral is not evenly distributed throughout the rock but tends to be segregated in patches. The porous structure seen in the diopside rocks is here much more pronounced and the patchy occurrence of the diopside is partly due to its localization within the pores.

Microscopically the rocks show rounded or irregular interlocking crystals of light brown isotropic garnet. Optical anomalies were only observed in one case where they indicated the rhombic dodecahedron. In their absence it is difficult to determine the boundaries of the individual crystals. The pores which appear to have formed at the junction of several grains may at times attain a considerable size, and crystals which project into the cavities often show great perfection of crystalline form. As in the case of the diopside rocks these pores may either be empty or else have fillings of certain late-formed minerals. The common fillings include calcite, orthoclase, quartz, diopside, apatite and sphene. In addition, apatite is commonly found dispersed throughout the rock independent of the cavities, in which case it must have been of early formation. The rounded nature of the grains suggests strongly that the apatite is sedimentary and has passed unaltered through the metasomatic changes which have affected the rock. Calcite and quartz are the commonest cavity fillings, less often feldspar. All three contain embedded grains of colourless diopside and sphene. The latter is a most important accessory in all the garnet rocks. Calcite and quartz have been observed to occupy the same cavity but along their junction no wollastonite has formed,

but it is extremely likely that some at least enters into the garnet. This would tend to diminish the amount of diopside calculated. The analysis is plotted on the triangular diagram (p. 109).

Diopside-garnet mixtures. Rocks in which diopside and garnet are present in roughly equal proportions are most common but they do not differ in any marked respect from those types in which one mineral or the other predominates. It was observed however that each of the components showed a tendency to become segregated into separate patches rather than to form uniformly dispersed mixtures. In consequence there are produced streaks and patches of garnet-rich material within a diopside base and *vice versa*. Microscopical examination of the diopside-garnet mixtures shows that no definite order of formation can be made out, the diopside and garnet appearing to have formed contemporaneously. This is in direct contrast to the types in which one mineral or the other predominates and in which a definite order of formation can be established.

Olivine rocks. NOVARESE was the first to point out the importance of forsterite within the contact aureole. The forsterite seems to occur both as a product of normal contact metamorphism and as a pyrometasomatic mineral. A good example of the latter is seen at Gias del Gallo where forsterite-magnetite veins are found cutting the calc-silicate rocks of the country and also as an impregnation in carbonate rocks. This forsterite-magnetite paragenesis is of great interest but owing to the fact that the veins invariably carry ore it will be better to leave the discussion until the ore section (p. 120).

From the evidence afforded by microscopical study the forsterite, in such cases, cannot be due to recrystallization of original siliceous impurities, and active transfer of material from the magma must be postulated to account for its development.

Felspar-bearing Assemblages. Calc-silicate rocks in which basic plagioclase occurs as an essential constituent are found here and there throughout the aureole, but are very subordinate in amount to the plagioclase-free rocks. Nothing in their geological relations, moreover, gives any clue to the nature of the original rock type from which they have formed, for nowhere can they be traced into an unaltered sediment. One feature which all the members of this group have in common is that they are invariably confined to the immediate contact of the igneous rock, and separate the latter from the felspar-free assemblages described above. There is however no doubt that

they represent altered sediments and not altered igneous rock. They occur chiefly in small isolated outcrops between Riondella and Castiglione as well as in the quarry at the former locality.

Plagioclase-diopside rocks. Such types are whitish-green in colour, highly compact and free from pores. Their general appearance serves to distinguish them instantly from the diopside rocks although, in colour, the two are rather similar.

Under the microscope may be distinguished plagioclase, diopside, sphene, apatite and rare calcite. The pyroxene resembles that of the diopside rocks both in colour and in optical properties. The optic axial angle is 60° and the extinction 38° . Twinning is common on (100). The plagioclase is homogeneous throughout and shows no sign of zoning; the common twinning is on the combined Carlsbad-Pericline law. Determinations by various methods carried out on a large number of individuals gave a range in composition from An 89 per cent to An 95 per cent. Reddish-brown sphene is always present and at times reaches a considerable concentration. The texture is granoblastic to diablastic, generally somewhat coarse-grained, the individual crystals having a mean diameter of from 1.5 to 2 mm in exceptional cases. Variation is the rule however and the grain size may change rapidly even within the same slice. All the components are rounded and never show development of crystal faces. Locally a rather ill-defined diablastic texture makes its appearance, in which case several small unorientated grains of one mineral are enclosed within a large plate of the second. Either plagioclase or diopside may form the host but it is common to find grains of diopside within a crystal of plagioclase (Plate I, Fig. 4). Another common feature is the enclosure of several grains of diopside within a larger plate of the same mineral. Sphene forms large patches in all the slices and is much more common in this group than in any of the other calc-silicate rocks.

In addition to plagioclase, orthoclase may also enter into the composition of these rocks in considerable proportion. The orthoclase forms large untwinned plates which enclose rounded grains of diopside and small tabular crystals of anorthite in a poikiloblastic manner. The orthoclase types are invariably fine-grained apart from the large orthoclase plates. One example from Casa del Las shows a pseudo-augen structure in which the „eyes“ are lens-shaped crystals of orthoclase which enclose small grains of diopside and laths of anorthite set in a fine-grained mass of diopside, anorthite and sphene.

An analysis gave the following result:

	1.	A.	NIGGLI Values	
SiO ₂	50,93	57,24	si	150
Al ₂ O ₃	17,05	12,30	al	25
Fe ₂ O ₃	0,88	1,77	fm	24
FeO	4,13	2,95	c	40
MnO	0,21	0,09	alk	11
MgO	3,54	4,80	k	0,62
CaO	14,75	10,31	mg	0,55
Na ₂ O	1,77	2,78	ti	1,65
K ₂ O	4,27	5,41	p	0,60
H ₂ O ⁺	1,01	0,18	c/fm	1,66
H ₂ O ⁻	0,11	0,06		
CO ₂	0,17	0,35		
TiO ₂	0,87	0,65		
P ₂ O ₅	0,56	0,90		
Total	100,25	99,78		

1. Orthoclase-bearing Plagioclase-diopside rock, Traversella. Anal. S. PARKER.
- A. Plagioclase-pyroxene Hornfels, Christiania region. Anal. DITTRICH, quoted from V. M. GOLDSCHMIDT, „Die Kontaktmetamorphose im Kristianiagebiet“, 1911, p. 188.

The mineralogical composition places this rock among GOLDSCHMIDT's¹⁾ hornfelses of Class 7 (biotite-poor plagioclase-pyroxene-hornfels).

For comparison with the Traversella rock is quoted an analysis of such a biotite-poor plagioclase-pyroxene-hornfels (p. 106, No. A). It is obvious that the two analyses, although being of the same general character, show certain differences. The Traversella rock is richer in lime, alumina and ferrous iron, but poorer in silica, ferric iron and total alkalis. Both agree in the predominance of potash over soda, a relation which is very characteristic of argillaceous sediments. According to GOLDSCHMIDT the hornfelses of Class 7 may contain alkali feldspar in addition to plagioclase. Those rocks which contain alkali feldspar commonly show a more acid plagioclase. This is evident from the calculation of the approximate mineral composition of the analysed rock.

Orthoclase		25
Albite		14
Anorthite		26
Diopside	{ CaO . SiO ₂	16
	{ MgO . SiO ₂	8
	{ FeO . SiO ₂	7
Sphene		2
Apatite		1
Rest		1

¹⁾ V. M. GOLDSCHMIDT, „Die Kontaktmetamorphose im Kristianiagebiet“, 1911, pp. 186—192.

The calculated plagioclase is here seen to contain about 65 per cent anorthite molecule: it is probable however that the acid composition of the calculated plagioclase results from the presence of a certain amount of free albite.

Plagioclase-diopside-garnet rocks. The incoming of garnet in appreciable quantity causes the plagioclase-diopside rocks to pass into Class 8 hornfelses of GOLDSCHMIDT, a type which is uncommon both in the Christiania region and at Traversella.²⁾

The rocks are light-green in colour with numerous streaks and patches of light brown garnet and agree in their characters with the garnet-free types. The garnet however forms irregular patches which enclose the other minerals in a poikiloblastic manner, and shows no optic anomalies. Numerous small, irregular or rounded crystals of reddish-brown sphene are scattered through all the slices in considerable quantity.

The plagioclase forms small untwinned or simply twinned, water-clear grains. Small amounts of green hornblende may be present as alteration products of the pyroxene, and very often accessory sulphides are seen. An analysis of this rock is as follows:

SiO ₂	42,47	NIGGLI Values	
Al ₂ O ₃	18,62	si	95
Fe ₂ O ₃	4,61	al	22
FeO	2,81	fm	21,5
MnO	0,26	c	55
MgO	3,01	alk	1,5
CaO	25,07	k	0,42
Na ₂ O	0,47	mg	0,43
K ₂ O	0,49	ti	1,9
H ₂ O +	0,62	p	0,36
H ₂ O -	0,06	c/fm	2,5
CO ₂	0,13		
TiO ₂	1,27		
P ₂ O ₅	0,45		
S	tr		
Total	100,34		

Diopside-plagioclase-garnet rock, Traversella. Anal. S. PARKER.

Compared with the analysis of the garnet-free plagioclase-diopside rock this type shows a great decrease in silica, ferrous iron and alkalis, combined with increase in lime, ferric iron and alumina.

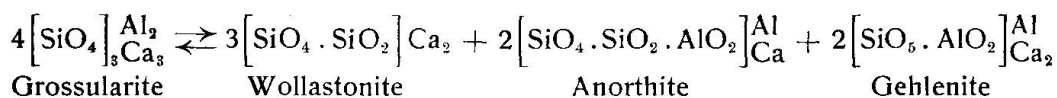
The ferric iron probably enters into the garnet molecule along with some alumina. The most striking feature of the analysis however

²⁾ V. M. GOLDSCHMIDT, op. cit., pp. 192—193.

is the low content of total alkalis combined with the richness in alumina. In addition, the molecular percentage of soda is greater than that of potash; both features are unusual in argillaceous sediments. TiO_2 is present in considerable amount. The following represents the approximate mineral composition. It must be regarded as being very approximate, for the nature of the actual molecules present is unknown and, in the absence of analyses of the minerals, the distribution of the oxides may only be guessed.

Orthoclase	2,5
Albite	3,5
Anorthite	28,0
Andradite	14,0
Grossularite	13,0
Diopside	26,0
Sphene	3,0
Apatite	1,0
Gehlenite	9,0

It was found necessary to introduce gehlenite into the calculation although it has not been identified in the slice. Its presence may have been overlooked if it is present in occult form, in which case it might be due to the following reaction:



Wollastonite could not exist as such in the presence of active ferric oxide but would react with the latter to form andradite.

Conditions of formation of the kata-contact rocks. From the above descriptions and analyses it is seen that the kata-contact rocks of the Traversella aureole consist predominantly of five oxides (CaO , MgO , Al_2O_3 , Fe_2O_3 and SiO_2) which are contained in three minerals (diopside, garnet and anorthite). They may thus be represented on a triangular diagram for the system CaO , MgO , Al_2O_3 , SiO_2 in which lime, magnesia and alumina are located at the three corners of the triangle and silica is considered as a free component, i.e. always present in sufficient quantity to satisfy all the oxides and forming a possible phase in all assemblages. Ferric iron replaces alumina in garnet and so the two may be taken together. In the same manner ferrous iron is added to magnesia which it replaces in isomorphous manner in diopside.¹⁾ The diopside may then contain slight ad-

¹⁾ This is permissible, for in a physico-chemical system the addition of a component capable of replacing one of the others in isomorphous manner does not cause the separation of a new phase but simply enters into one of the molecules already present.

mixture of hedenbergite and the garnet belongs to the mixcrystal series andradite-grossularite. All the alkalis go towards the formation of feldspar and allowance is made for them by subtracting the molecular values from alumina.

Consideration of the diagram shows that all the projection points are strictly localized within one part of the triangle; they all fall

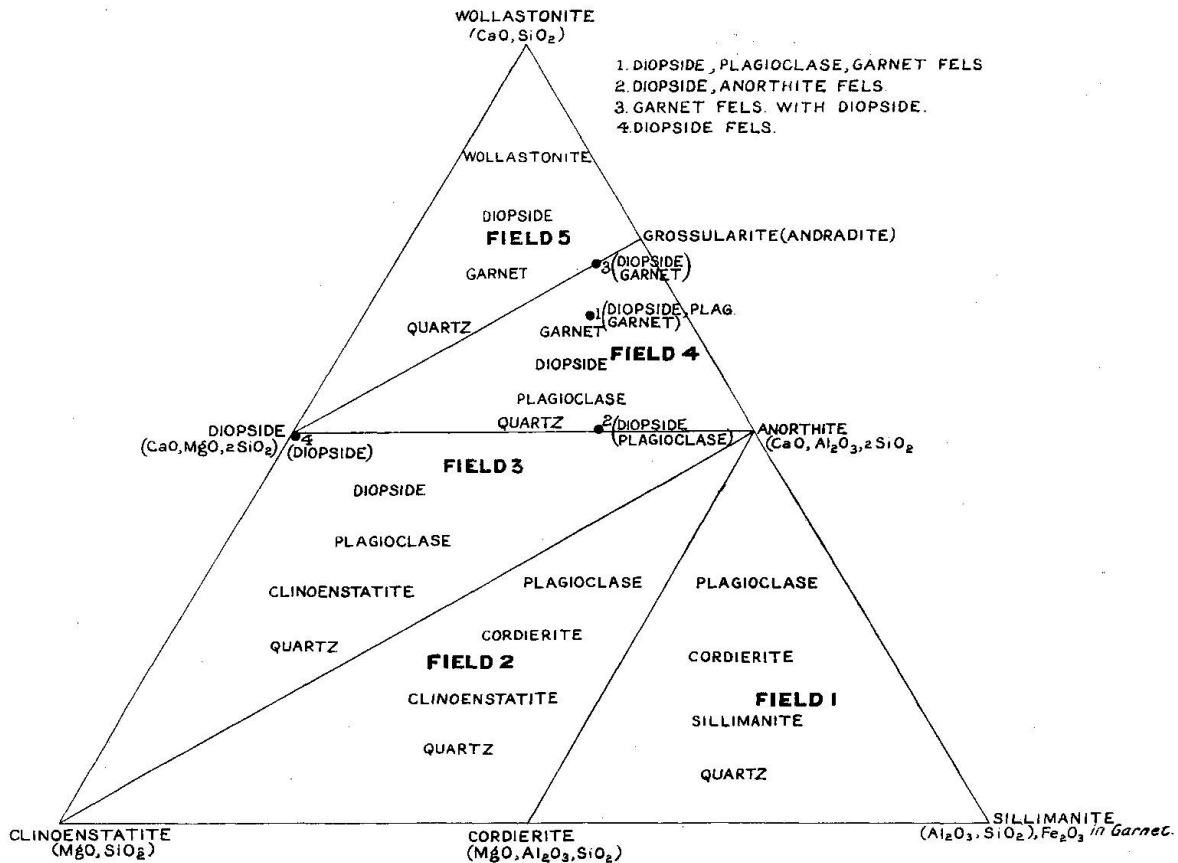


Fig. 3.

Diagram of the system $\text{CaO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$, in which there is isomorphous replacement of MgO by FeO and of Al_2O_3 by Fe_2O_3 .

Points (1, 2, 3, 4) represent plotted analyses.

within Field 4 or on its boundary curves. Moreover the chemical and mineralogical compositions are in perfect equilibrium. Such factors have an important bearing on the discussion of the origin of calc-silicate aureoles. Even at the present day there is considerable discussion as to whether those calc-silicates which commonly accompany contact ore-deposits owe their origin to recrystallization of original siliceous impurities or whether there has been active transfer of silica etc. from the magma to the country rocks. UGLOW¹⁾ in a series of

¹⁾ W. L. UGLOW, Econ. Geol., Vol. 8, 1913, and Vol. 9, 1914.

papers urged the recrystallization theory and amassed a great deal of data in support of his contention. More recently however WINCHELL and others,¹⁾ especially LINDGREN, have reaffirmed the introduction theory.

Transfer from the magma to the country rocks has undoubtedly been operative at Traversella. Thus none of the assemblages contain quartz except as a very minor accessory of late origin, moreover carbonate does not appear in its place. Had the calc silicates arisen by recrystallization of original impurities the limestone must have contained exactly sufficient silica to form the new minerals, otherwise either an excess of silica or unaltered carbonate should remain. It is conceivable that excess carbonate could have been removed but this would necessitate drastic volume changes of which there is no evidence.²⁾ It is not possible to assume that in every case exactly sufficient silica was present in the limestone, and so the major proportion must have been introduced. In addition iron is present in the calc-silicate bodies in an amount which prohibits its being regarded as an original impurity, for no such iron rich sediments are known from outside the aureole. Finally the whole country was subjected to regional metamorphism prior to the intrusion of the eruptive body responsible for the contact metamorphism, and had impurities been present in any amount they must have produced pure calc-silicate rocks. As pointed out above, however, the limestones beyond the aureole contain only scattered silicates.

Chemical nature of the metamorphosing solutions. The felspar-free and the felspar-bearing assemblages will be treated separately.

Diopside-garnet assemblages have been produced by the reaction of carbonate rocks (varying between the limits, limestone to dolomite) with solutions introduced from the magma. Chemical and microscopical study have brought out the following facts:

- I. Pyroxene and garnet tend to be segregated into patches.
- II. Accessory garnet in diopside rocks and accessory diopside in garnet rocks are of later formation than the chief mineral.
- III. The garnet is andradite with generally only a little grossularite molecule, i. e. ferric iron predominates greatly over alumina.
- IV. The pyroxene is almost pure diopside, hedenbergite molecule is subordinate, other ferrous iron silicates are absent.

¹⁾ A. N. WINCHELL, Petrographic studies of limestone alterations at Bingham., Trans. Am. Ins. Min. Eng. 70, 1924, p. 884, see also many references in LINDGREN, Mineral Deposits, p. 784. — E. V. SHANNON, Proc. U. S. Nat. Mus., 66, 1924, pp. 1—86.

²⁾ W. LINDGREN, Volume changes in Metamorphism, Jour. Geol., 26, 1918, p. 542.

Silica and ferric iron have obviously come from the magma and must have formed the main constituents of the magmatic solutions. As the country rocks consisted of carbonates varying from limestone through dolomitic limestones to dolomite, all the lime and magnesia now locked up in the calc silicates could have been derived from these country rocks. The small amounts of alumina could also have been present as impurities in the unaltered limestones. Sulphides are present in considerable amount and this indicates introduction of sulphur and ferrous iron. A striking feature of the Traversella aureole, and one which imparts to it a certain individuality, is a poverty in ferrous iron silicates. Most contact ore deposits have hedenbergite as the main pyroxene, but although ferrous iron was an important constituent of the solutions at Traversella, as indicated by the large amounts of sulphide ore, it failed to enter into the calc silicates. This can only mean that the ferrous iron was present in the solutions in some highly inactive state, possibly as a sulphide. The solutions consisted therefore of silica, ferric iron and inactive ferrous iron.

The ratio of CaO to MgO in the original carbonate rocks seems to have played an important part both in the nature of the minerals formed and in the order of their separation. In limestones containing only a small amount of dolomite the composition would be suitable for the formation of andradite without the elimination of any constituent. The lime was therefore first satisfied with silica and ferric iron from the solutions and produced garnet. At the same time dolomite was concentrated but owing to the operation of the Law of Mass Action could not form diopside until it attained a certain minimum concentration.¹⁾ This concentration was only reached at a late stage and so the diopside formed later than the garnet, being localized within the pores between the garnet crystals. No wollastonite could form as ferric iron was present and the tendency is for the newly formed silicates to take up as many constituents from the magmatic solutions as possible.

In the case of dolomite-rich limestones on the other hand, although the solutions in contact were rich in ferric iron this did not take part in the reactions as magnesia-ferric iron garnet can not form and andradite could therefore only be produced by elimination of vast quantities of MgO. The ratio MgO:CaO was however exactly that required for the production of diopside. Thus diopside crystallized

¹⁾ V. M. GOLDSCHMIDT, *Der Stoffwechsel der Erde*, Vidensk. Skrift. I. Math.-naturw. Kl., 1922, No. 11, p. 22. — U. GRUBNMANN und P. NIGGLI, *Die Gesteinsmetamorphose*, p. 153.

and the excess of lime over the diopside ratio underwent concentration until it reached its minimum concentration when it united with silica and ferric iron to produce garnet. This accessory garnet is later than most of the diopside, a fact verified by observation (p. 111). Finally when dolomite and calcite were present in roughly equal amounts both diopside and garnet could form simultaneously. These facts are in agreement with the observed orders of separation of the minerals. It is a fact of some significance that in diopside rocks which contain no ferric iron bound to silica, magnetite is common, but has never been observed in garnet rocks which contain ferric silicates. Wollastonite has not been found in the Traversella aureole and this is to be explained by the content of ferric iron in the emanations. The calcite could not react with silica and ignore the iron when the ratio of the oxides was suitable for the formation of a molecule containing all the constituents introduced.

Felspar-bearing assemblages, as may be seen from the triangular diagram, have their formation controlled by the available lime and alumina. Anorthite will form in any rock of this series in which the proportion of lime falls below the curve joining diopside and garnet, provided that sufficient alumina is present. Rocks containing the proper proportion of lime cannot fail to have been present and therefore alumina must have been the controlling factor. The question therefore arises as to the source of this alumina, whether it represents an original impurity or has been introduced from a magmatic source. The possibility of a sedimentary origin is ever present, for the analysis of one of the felspar-bearing rocks is directly comparable with a hornfelsed sediment from Christiania about whose origin there is no doubt (see p. 106). From the point of view of composition alone there is nothing against a purely sedimentary origin for the alumina, but, however, it does not explain the strict localization of this rock group to the *immediate contact* against the intrusive mass. This localization may be best explained by assuming transfer of alumina from the magma to the limestones adjacent to it, a transfer however, itself essentially localized. It has been pointed out above (p. 95) that along the contact zone the igneous body has been enriched in lime and magnesia derived from the country rocks by diffusion. This must represent a reciprocal reaction and it is highly probable that the transfer of lime and magnesia from the country rocks to the magma was compensated by introduction of alumina and locally alkalis from the magma to the limestones immediately adjacent to the contact. Transfer of alumina appears to have been totally re-

stricted to this reciprocal reaction; the main pyrometasomatic solutions, producing ore deposition and skarn formation, were practically free from that oxide.

2. *Meso-contact Rocks*

When dealing with rocks belonging to the lower grades of metamorphism it is important to remember that there are two possible modes of origin. The silicates may arise as a result of building-up processes such as in the case of the formation of tremolite in a dolomite rock when silica is introduced. At the same time however the characteristic minerals of the lower grades of metamorphism may equally well arise by the breaking down of some previously formed assemblage of higher grade.¹⁾ The formation of lower grade assemblages from those of higher grade has been termed *diaphthoresis* by BECKE²⁾ who shows that any group of minerals when subjected to new external conditions react to form an assemblage in equilibrium with the new conditions. The reaction is subject to a certain lag effect but might be expected to be most complete under the influence of chemically active solutions such as exist in a contact aureole like that at Traversella.

The meso-zone is characterised by conditions intermediate between those of the kata- and epi-zones and very often the mineral assemblages show mixtures of the typical minerals of both. For the purposes of the present paper it has been found convenient to group all the amphibole rocks together as members of the meso-zone.

Tremolite rocks are the most common and widespread members of the group, some of them being due apparently to the metamorphism of dolomites and some to diaphthoretic changes in diopside rocks.

It is well known that with increasing distance from an intrusion tremolite forms in preference to diopside, the transition point lying, according to BECKE, in the neighbourhood of 550° C. at 200 atmospheres pressure. Many authors have noted the presence of tremolite in the outer zones of contact aureoles where temperature conditions have been lower. Typical tremolite rocks are found at Traversella outside the zones of diopside and garnet and so far as can

¹⁾ The terms „*anamorphic*“ and „*katamorphic*“ have been used for such building-up and breaking-down processes but it was thought better to avoid them in this place as they might cause confusion with the term „kata-zone“.

²⁾ F. BECKE, Über Diaphthorite, Vortrag Wiener Min. Gesellsch., T.M.P.M., 28, 1909, p. 369.

be made out these have never been anything else than tremolite and must owe their origin not to the breaking down of diopside but to direct metamorphism of dolomitic limestones. Temperature seems to have been the controlling factor and it was noted in these cases that pyrrhotite was constantly absent although replacement by pyrite was quite common. Such rocks are compact, white or light-grey in colour and under the microscope are seen to consist of radial groups of elongated prisms and needles of colourless tremolite. The texture is nematoblastic and carbonate may be present in greater or less amount giving all transitions between tremolite limestones and pure tremolite rocks.

In the second type of tremolite rock the amphibole has formed by the breaking down of diopside under the influence of the ore solutions. Alteration commences in the interspaces between the grains of pyroxene and spreads outwards in a radial manner. The end product is a compact, very fine-grained nematoblastic to fibroblastic aggregate of tremolite needles and prisms in which may be embedded residual grains of partially replaced diopside. All stages in the alteration may be followed, and it is characteristic for these rocks that the tremolite forms closely knitted webs and sheaf-like aggregates rather than radial groups (Plate I, Fig. 5).

Another type of amphibole rock is seen at Riondella where diopside is breaking down into a pale green amphibole with weak pleochroism. This is the mineral traversellite and in hand specimen it may be distinguished by a peculiar greyish-green mottled appearance.

This breaking down of the diopside illustrates the progressive change in the nature of the solutions. It is evident that the temperature must have been lower, while at the same time a high content of active water and carbon dioxide is indicated. The change from diopside to tremolite liberates Ca but all carbonates are noticeably scarce or absent so that the excess lime must have been removed in solution.

3. *Epi-contact Rocks*

In the low grade assemblages which characterise this group it is fortunately extremely easy to distinguish the products of breaking-down processes from those of constructive metamorphism. Both are intimately connected with ore deposition but it is convenient to consider the ores in a separate section (p. 120). At the same time the essential unity of the operations must not be lost sight of, for the diaphthoretic changes were produced by the same solutions which

deposited the ore minerals. The formation of hydrous silicates has taken place quite independent of the nature of the original rock and though the end products are similar the actual alteration has been effected in different ways.

Two main classes may be distinguished:

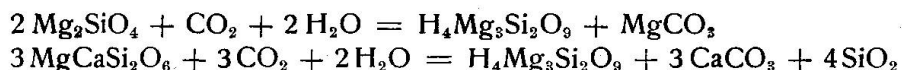
- a) Secondary hydrous silicate rocks; chlorite, talc, serpentine assemblages formed by breaking down of higher grade rocks (diopside, olivine, garnet etc.).
- b) Primary hydrous silicate rocks; chlorite, talc, serpentine assemblages produced by constructive changes in dolomitic limestones under the influence of the mineralizing solutions.

Secondary hydrous silicate rocks have a wide distribution throughout the region but are found especially at Castiglione and Montaju where they form the main gangue for the ore. Their distribution is sporadic, that is to say they show no zonal relation to the igneous contact but occur within the zones of higher grade in an irregular manner. NOVARESE described stratified, yellowish, greenish and dark coloured serpentine bodies formed by the alteration of calc silicate rocks, and considered that much of the serpentine was derived from olivine. Subsequent work has shown, however, that all the calc silicates have contributed to the serpentine formation the colour and texture of the resulting product depending to a great extent upon the nature of the original mineral. In many cases may be observed residual grains of anhydrous silicates (among which may be mentioned olivine, diopside, garnet and tremolite) embedded in the colourless serpentine. As stated above, the texture of the serpentine depends to some extent upon the original mineral but this is by no means a sure guide as the same rock may produce a variety of different textures. Generally the serpentine forms webs of fine fibres which pseudomorph the calc silicates and may preserve in a very perfect manner details of cleavage etc. Again the pseudomorphing mineral may be antigorite in small lamellar plates. The most common variety is light green in colour and forms at the expense of diopside and olivine, while most of the darker types appear to have been derived from garnet rocks containing appreciable amounts of iron. In one or two cases the serpentine was found to consist of a deep yellow, isotropic variety (webskyite?) which formed eyes surrounded by the colourless type. Carbonates are only sparsely developed in all such rocks.

Tremolite may be mentioned as a further source of serpentine, the alteration being well illustrated by the occurrences at Gias del

Gallo where, along either side of the olivine-magnetite veins, the tremolite has been altered to serpentine which pseudomorphs the primary mineral with preservation of texture (Plate II, Fig. 6).

The formation of serpentine proceeds according to the following reactions:

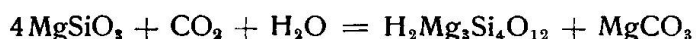


It is seen that in both cases carbonates are produced as end products of the reactions and silica also in the case of the formation from diopside. Both silica and carbonates however are conspicuously absent from the serpentines of the region, the natural inference being that these products must have been removed in solution. This peculiarity is of more than passing interest for, as will be shown later, the outermost rocks of the aureole show an introduction of silica and carbonate some of which at least may have been derived from this source.

Most of the serpentines contain small amounts of chlorite and talc in addition to the dominant hydrous silicate, and in one case the minerals were found to be present in roughly equal proportions. Pure talc and talc-chlorite rocks are also known and are seen to be secondary after tremolite and diopside. Relatively large plates of talc and chlorite are seen to cut across and replace prisms of tremolite. Often the two hydrous silicates form parallel intergrowths. The chlorite is green with strong pleochroism in green and light yellow, optically negative and with low polarization colours, although there is no trace of Berlin blue so common in pennine. Serpentine is also a constituent and one case was observed in which a mesh structure consisted of eyes of talc surrounded by colourless serpentine.

The close association of these hydrous silicate rocks with ore minerals, together with their localization within the contact aureole, makes it evident that they are due to the action of magmatic solutions. Various authors ¹⁾ have urged the importance of such magmatic emanations in the genesis of hydrous silicate minerals.

Talc may be formed from any magnesian mineral when acted upon by hydrothermal solutions containing carbon dioxide as follows:



¹⁾ G. P. MERRILL, *Geol. Mag.*, 1899, p. 354. — A. W. G. BLEECK, *Zeitschr. für prakt. Geol.*, 15, 1907, p. 391. — V. NOVARESE, *Boll. Soc. Geol. d'Italia*, 1902, p. 36.

The nature of the carbonate formed depends upon the original mineral and may be $MgCO_3$, $CaCO_3$ or $FeCO_3$. LINDGREN believes²⁾ that solutions active near igneous contacts are most potent to effect the change and that moderately high temperature is an important factor.

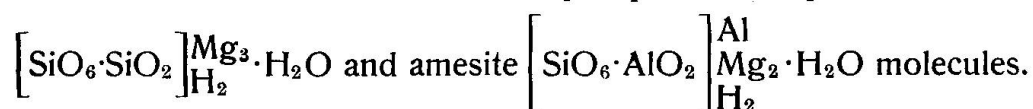
Primary hydrous silicate rocks. These are always localised outside the zone of calc-silicate development, the change in the nature of the physico-chemical conditions being of lateral nature instead of temporal as was the case with the diaphoretic hydrous silicate assemblages. The rocks are all ore-bearing and are best described as chlorite and chlorite-talc limestones. A greenish-white patchy appearance is evident in hand specimen and depends on the irregular development of the hydrous minerals which at times may increase in proportion so as to constitute the bulk of the rock. In many of the specimens two stages of metamorphism are present, first normal contact metamorphism and second metasomatism. The carbonates form a coarse to medium-grained aggregate of interlocking crystals of calcite and dolomite due to recrystallization. At the same time the siliceous impurities have reacted with the dolomite to form forsterite which is present as small rounded grains between the carbonate crystals. During the later mineralization these crystals of forsterite have suffered serpentinization, but invariably residual grains are present in the centres of the pseudomorphs. The typical mesh structure is well developed.

The greater part of the rock however consists of a lepidoblastic web of lath-shaped chlorite crystals associated with very fine-grained serpentine and iron ores. The chlorite laths form a closely interwoven plexus with polygonal interspaces filled with fine-grained serpentine of primary origin or else unaltered carbonate (Plate I, Fig. 6). The resemblance of this texture to the intersertal one commonly found in basalts is most striking. No term exists for this texture in metamorphic rocks and so in accordance with the GRUBENMANN nomenclature it may be called „intersioblastic“.

The chlorite is colourless and the shape of the crystals may only be made out in polarized light. The optic axial angle is small and varies within narrow limits. It never rises above three to five degrees and in the majority of cases the mineral is almost but never quite uniaxial. The extinction $Z:c = 2-3^\circ$, the optical sign is positive and the sign of elongation negative. The polarization colours are in general a dark greyish-brown and give a patchy appearance;

²⁾ W. LINDGREN, Mineral Deposits, 3rd. Edit., New York, 1928, p. 433.

no trace of the ultra blue common in many chlorites is to be seen. From the above optical characters the mineral appears to be of abnormal composition but agrees best with the clinochlore group of the orthochlorites which consist of equal parts of serpentine



Sometimes the laths spring from a common centre and produce a radial grouping which is however not so common as the intersio-blastic type described above. The term „primary hydrous silicate“ is used here because it is quite certain that the chlorite is forming from the component oxides and is not an alteration product of some earlier silicate.

A second product of this mineralization phase is a chlorite-talc limestone, and the original rock in this case seems to have been richer in dolomite. The texture is rather different from that of chlorite marble both in the fabric and arrangement of the components. The chlorite forms laths similar to those in the talc-free types which, however, are no longer aggregated into a felted mass but occur separately as porphyroblasts. In addition the chlorite itself shows certain peculiarities. The optical characters are similar to those of the chlorite described above but here the terminations of the laths are isotropic, only the central portions showing the greyish-brown colours. In other cases the centre of the lath is isotropic and the margins not, or else combinations of the two characters may be present. This pseudozoned nature is very characteristic for the chlorites in limestone at Traversella. DOELTER¹⁾ quotes an old analysis which shows that the chlorite is not normal but is a so-called „talcchlorite“. It is relatively poor in alumina. The dolomite crystals possess a peculiar granular appearance together with high interference phenomena which is quite abnormal. Examination with the highest power objectives shows however that each dolomite crystal is completely pseudomorphed by an aggregate of fine lamellar talc. This alteration has left the calcite unaffected so that it occurs as small islands within the fine talc aggregates (Plate II, Figs. 1, 2 and 3). Here and there the material of the aggregates collects to form a stout flake of talc which may be moulded on to a chlorite lath, and merges on the free side into the normal aggregate. Calcite of late crystallization is also present but is readily distinguished. In another case the development of talc was accompanied by deposition of later silica containing small

¹⁾ DOELTER, Handbuch der Mineralchemie, Vol. II, 2, 1917, pp. 648–649.

but perfect spherulites of chlorite and masses of magnetite. An endless variety of textures may be seen in the chlorite marbles including spherulites showing brush-extinction.

In the case of this group of chlorite and talc limestones there is no question as to the primary origin of the hydrous minerals; they have not formed from pre-existing anhydrous minerals. The talc and chlorite must have arisen from the carbonates originally present under the influence of silica-bearing, watery solutions. The introduction of silica from without is indicated by the fact that all original siliceous impurities reacted during normal contact metamorphism to produce olivine and so could not be available later for the formation of talc and chlorite. Moreover the silica must have been in a highly soluble state to produce the fine lamellar talc aggregates, and it would be almost impossible to bring sedimentary silica into such a state. Silica possessing the necessary qualities would most probably be a component of a magmatic residue, and as iron ores were deposited at the same time as the silica was introduced it is evident that both were of magmatic origin. Hence the ore solutions are seen to have carried water, silica and ferric iron together with some sulphide.

The artificial formation of a hydrous magnesian silicate has been carried out using $MgCl_2$ and H_2SiO_3 and also by the use of a solution of Na_2SiO_3 on $MgCO_3$. In the latter case the reaction is reversible, the magnesian silicate forming only at high temperature (200°). The formation of talc from dolomite is not impossible in the laboratory. Its formation under the influence of siliceous magmatic solutions acting upon dolomite has been described by WILSON from Canada¹⁾ and the process seems to be analogous to that at Traversella. LINDGREN²⁾ also considers such an origin as he states, „Talc is thus a product of the later stages of pyrometasomatism but the magnesia is chiefly, at least, derived from the rocks in which it occurs.“

The magmatic solutions which produced these changes at Traversella possessed the same chemical characters as those to which the calc silicates of the inner contact are due. No oxides have been introduced in either case so far as it is possible to judge, except SiO_2 , H_2O , Fe_2O_3 and inactive FeO . The different products are due only to differences in the physico-chemical conditions.

1) M. E. WILSON, „Talc Deposits of Canada“, Mem. 2, Econ. Geol. Ser., Geol. Survey Canada, 1926.

2) W. LINDGREN, Mineral Deposits, 3rd. Edit., New York, 1928, p. 434.

VII. THE ORE DEPOSITS

Introduction

The structural and morphological characters of the ore bodies have already been fully described by former investigators¹⁾ and require little mention here. In former papers on the district, however, less attention was paid to the processes involved in ore deposition, and so in the present section the problem discussed will be that of the genesis of the deposits.

The structure of the ore bodies is relatively simple. They form tabular, steeply dipping, vein-like masses which show conformity with the surrounding rocks. As pointed out above (p. 82) this conformable nature is due to the fact that they are replacement masses in carbonate or calc-silicate rocks. Both the schists and the igneous rocks have remained unaffected by the mineralization, the only ore observed in these being a small patch of pyrrhotite replacing biotite in a hornfels from Castiglione.

Magnetite is the predominant ore mineral and may occur in comparatively pure masses although it is more often associated with more or less sulphide (pyrite, pyrrhotite or chalcopyrite). The sulphides may become enriched so as to form a purely sulphidic ore and any one of the individual sulphides may constitute the chief ore mineral. Numerous other minerals have also been reported from time to time and include galena, zinc-blende, scheelite, molybdenite, apophyllite, epidote and arsenite.²⁾ Arsenite has not been observed either by MÜLLER or the author,³⁾ and the others occur only sporadically as scattered grains and nests within the oxide or sulphide ores.

Classification

Ore deposition appears to have extended over a considerable interval of time as indicated by the various parageneses, some ore being roughly contemporaneous with the calc silicate formation. The main mineralization, however, was later and with it were associated the hydrothermal phenomena which led to the breaking down of the

¹⁾ F. MÜLLER, *Zeitschr. für prakt. Geol.*, Bd. 20, 1912, p. 209, see also the bibliography given in this work.

²⁾ For a list of references to papers on the minerals of Traversella, see L. COLOMBA, *Mem. R. Acc. Sc. Torino*, 63, 1913, p. 272, and 66, 1915, No. 3, p. 7.

³⁾ It must be pointed out that arsenite does occur in the late-formed veins which cut the igneous rock and the crystalline schists, but appears to be absent from the metasomatic ores.

previously formed silicates. At the same time much ore was deposited in the unaltered carbonate rocks and this deposition was accompanied by the formation of new hydrous minerals. On the basis of these observations the ores may be classified as follows:

Hydrous silicates absent	{	forsterite—magnetite. calc-silicates—ore (oxide or sulphide).
Hydrous silicates present	{	associated with breaking-down processes: no carbonate present: serpentine—talc—chlorite—ore. associated with building-up processes: carbonate—chlorite—talc—serpentine—ore.

Both NOVARESE and MÜLLER distinguish a northern group of mines at Gias del Gallo-Montaju and a southern group at Traversella (including Riondella and Castiglione) which they discuss separately. This division will not be employed here as the whole problem is treated from the point of view of mineral paragenesis. It may be pointed out however that the division was to some extent justified as in the northern group the ores are predominantly oxidic whereas at Traversella sulphides appear in quantity. Sulphides however are not entirely absent from Gias del Gallo.

Observed Paragenesis

1. Forsterite—magnetite. This association occurs in its most typical development at Gias del Gallo and Montaju where it exhibits features which separate it from all other ores of the region.

The ore is found mainly in calc-silicate rocks (especially tremolite types) and to a less extent in carbonate rocks. In both cases it is free from sulphide and in no case has sulphide been found associated with *olivine*. In a carbonate rock from Gias del Gallo the carbonate has been recrystallized to a mosaic of clear grains while at the same time magnetite and olivine have developed. These two minerals occur in bands separated by areas of calcite and dolomite containing only scattered olivine grains. The olivine is almost pure forsterite and is intergrown with rounded and irregular crystals of magnetite, the two forming a crystalloblastic mosaic of even grain. When examined in thin slice and in polished sections in reflected light the relations of forsterite to magnetite are invariably those of mutual interference during growth. There is no trace of the magnetite having replaced the silicate. Within the ore bands carbonate is absent and the contemporaneous formation of olivine and magnetite seems to be beyond question. It appears in this case that the ore-bearing solutions were the actual cause of the metamorphism

and that they must have carried silica in addition to iron. Analogous phenomena have been described from the Philipsburg Quadrangle, Montana, by CALKINS¹⁾ who finds that magnetite replaces carbonate while at the same time an intermediate zone of olivine forms. At Philipsburg the olivine and ore are not intergrown to the same extent as at Traversella but nevertheless both occurrences must indicate the operation of similar factors. CALKINS assumes in the case of the Montana deposit that the ore solutions contained silica in addition to iron and that the olivine formation was contemporaneous with the ore deposition, conclusions which have also been reached in regard to Traversella. That the olivine is in both cases forsterite free from the fayalite molecule indicates that ferrous iron must have existed in some form which prohibited its reaction with silica to form the iron-olivine.

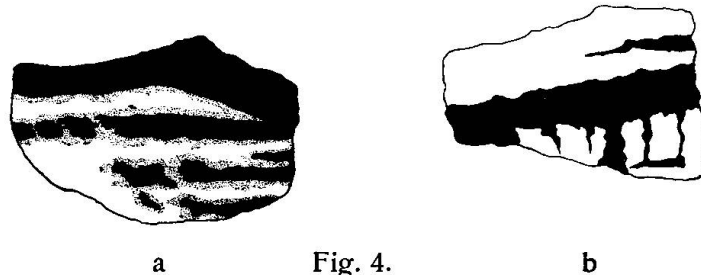


Fig. 4. Veins of olivine—magnetite (black) in calc-silicate rock (White). In (a) the vein is separated from the calc-silicate rock by a narrow zone of serpentine (stippled).

A second and more characteristic mode of occurrence is that of veins and stringers of olivine-magnetite within a calc-silicate rock, usually a tremolite variety. These veins are limited to a maximum breadth of a few centimetres. They seem to follow the joint system of the rock in which they occur, and the main veins which fill the major joints give off small secondaries along the less perfect right angle joints. The effect is to produce an imperfect type of network, Fig. 4 b. The banded nature of the veins becomes even more apparent when examined microscopically. The vein fillings consist of an intergrowth of olivine and magnetite. The olivine, which is again a forsterite, is perfectly fresh and forms rounded grains within the ore. Passing outwards from the ore towards the tremolite of the country rock there intervenes on either side a band of colourless serpentine (Fig. 4 a and Plate II, Fig. 6) which is seen to replace the tremolite and preserves in perfect detail the texture of the amphibole rock.

¹⁾ W. H. EMMONS and F. C. CALKINS, Prof. Paper 78, U. S. G. S., 1913.

The solutions which deposited the ore and gave rise to the olivine were rich in volatile matter which was liberated on the crystallization of magnetite and olivine, and penetrating outwards into the surrounding rocks altered the tremolite of the latter into serpentine. This association of the ore deposition with the evolution of a water-rich residual solution seems to be the most characteristic feature of the Traversella mineralization. The discussion of the genesis of these olivine-magnetite veins will be left over until later when the whole problem of the mineralization of the region will be treated.

2. Calc-silicate—ore. The common ore minerals (see p. 120) are of fairly widespread occurrence in the calc-silicate rocks but only in exceptional cases become concentrated to form workable ore bodies, and although of great genetic importance are of little or no economic value. The accessory ore minerals present are generally sulphides; magnetite is not usually associated with the calc silicates although it does form an ore body in a diopside rock at Gias del Gallo. In the cases where magnetite forms an accessory in the skarns it is associated with diopside, tremolite and olivine, but *never with garnet*. Commonly garnet, diopside and tremolite rocks all contain small amounts of sulphide, either pyrite, or pyrrhotite, but chalcocopyrite is comparatively rare. The sulphides occur in the interspaces between the silicates and in all cases seem to be the last-formed constituents. As one would expect in such cases the ore tends to replace the earlier minerals, a feature which is well seen in the diopside-tremolite rocks at Castiglione. Here the mineral pyrrhotite replaces diopside along cracks and cleavages while at the same time the sulphide contains long prismatic crystals of tremolite. The ore in this case seems to replace diopside while the diopside is undergoing alteration to tremolite. The latter was nowhere seen to have been itself replaced by pyrrhotite. In this paragenesis no hydrous silicate is present. In the garnet-diopside assemblages pyrite was found to replace garnet and any residual carbonate, leaving the diopside unaffected. In all cases examined, the sulphide although exhibiting replacing relations towards the silicates was only very slightly later than them and undoubtedly belonged to the same period in the evolution of the magmatic solutions.

The relations shown by magnetite to diopside and tremolite, where it occurs in association with these minerals, vary greatly. It may occupy interspaces between the silicate minerals, and the diopside in this case forms crystal faces against the ore; or else the oxide may

penetrate along cracks and cleavage planes in the diopside and tremolite. In both cases the ore deposition is again contemporaneous with the development of the skarn minerals. Finally in certain cases the silicates and ore are intergrown in such a manner as to leave no doubt at all as to the simultaneous crystallization (Plate II, Figs. 4 and 5). In one specimen from the northern group of mines, magnetite occurs in a diopside rock. The ore forms small rounded or partially idiomorphic crystals distributed throughout the rock without regard to cleavage or other structural features. A rough banded appearance is present and the magnetite crystals occur wholly within the diopside

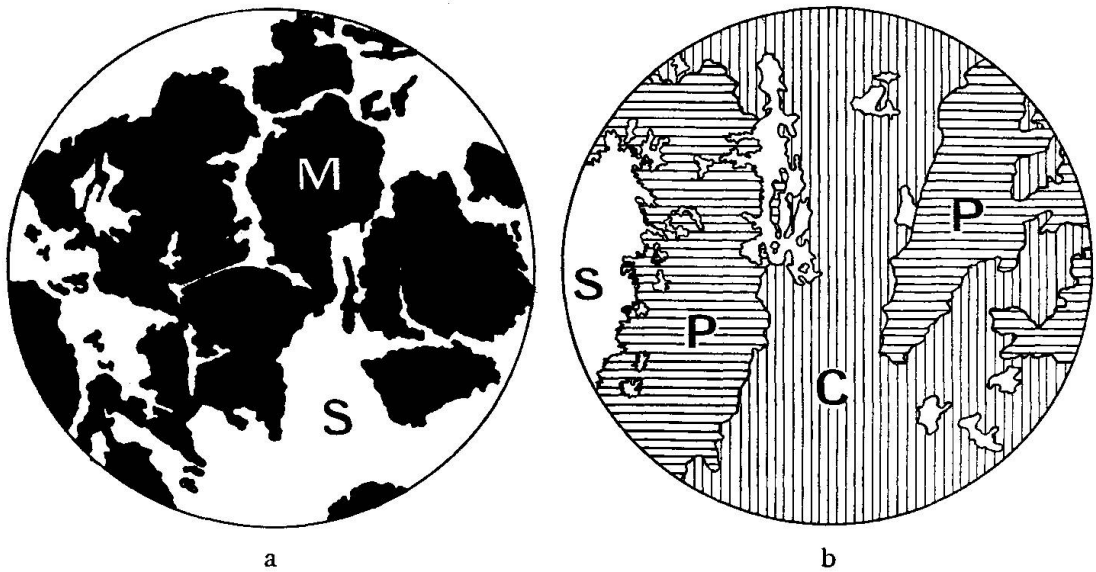


Fig. 5. Photo-micrographic tracings of polished sections in reflected light.
 a) Magnetite (M) in serpentine (S). The hydrous silicate penetrates cracks in the ore.
 b) Fringed junction between Serpentine (S) and Pyrrhotite (P). Chalcopyrite (C) is replacing Pyrrhotite.

grains and intimately intergrown with them. This produces a sieve-like texture in which diopside forms the host mineral. Such a type of magnetite-pyroxene intergrowth is by no means uncommon.

Similar intergrowths of magnetite and tremolite also occur and give rise to structures resembling the ophitic structure of dolerites, Plate II, Fig. 5. In such cases the magnetite is penetrated in an ophitic manner by long columnar prisms of tremolite, the latter also forming intimate intergrowths with the ore.

3. Hydrous silicate—ore (mineralization connected with breaking-down processes). Apart from the development of ore in the carbonate rocks, an association of magnetite and sulphide with serpentine, talc and chlorite is the most common ore paragenesis and forms workable ore-bodies. It resembles the carbonate-ore-hydrous

silicate paragenesis in the presence of hydrated minerals but, whereas in the one case the hydrous silicates were the result of the breaking down of anhydrous silicates, in the other case they were due to building up from dolomitic limestones under the influence of the ore solutions.

The ore minerals are magnetite, pyrite, pyrrhotite and chalcopyrite. These vary greatly in amount and relative proportions from point to point; only locally do pure oxide or pure sulphide ores occur. Broadly speaking the Gias del Gallo—Montaju group carries an oxide ore, whereas at Traversella itself sulphidic and mixed ores

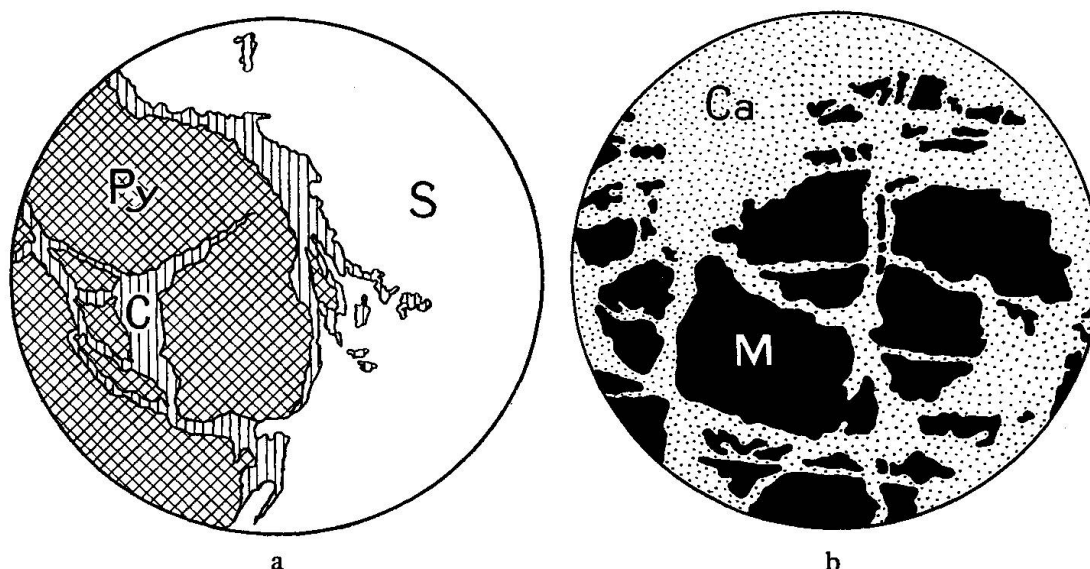


Fig. 6. Photo-micrographic tracings of polished sections in reflected light.
a) Pyrite (Py) replaced by Chalcopyrite (C). — b) Magnetite (M) veined by Calcite (Ca).

predominate. The sulphides are rarely quite free from oxide, but the latter may be quite free from sulphides, and may become enriched to form the chief ore. Pyrite and pyrrhotite never occur together in the same body.

The following parageneses have been observed:

	1.	2.	3.	4.	5.
hydrous silicates	x	x	x	x	x
magnetite	x	x	o	o	x
pyrite	x	o	x	o	o
pyrrhotite	o	x	o	x	o
chalcopyrite	x	x	x	x	o

Ores containing predominant magnetite are the most common and form heavy, greenish-black masses which have a granular texture due to the habit of the ore mineral. Examination of polished sections in reflected light shows that the magnetite forms rounded or irregular

grains of large size indicative of replacement, Fig. 5 a. The hydrous mineral is partly later than the oxide mineral and in the latter case it penetrates along cleavages and cracks in the magnetite and defines the octahedral cleavage system. Occasionally a rude tendency towards the development of crystal outlines may be seen. Again the ore and silicate may be intergrown in the most complicated manner, the one fringing out into the other in a way which suggests the simultaneous deposition of ore and hydration of the silicates of the original rock.

In mixed sulphide-oxide ores the former are of later formation. Pyrrhotite may penetrate between grains of magnetite, at the same time spreading laterally along cracks until eventually only small isolated fragments of magnetite may be seen embedded in the sulphide. Typically the pyrrhotite serves as a kind of groundmass separating grains of magnetite. Chalcopyrite becomes important locally and is almost invariably present in small amount in the mixed ores. It is the latest ore mineral to form and veins both the magnetite and the other sulphides or forms a groundmass in which the relics of these minerals are embedded.

Pyrite behaves differently from pyrrhotite. It occurs in large irregular patches and not as an intimate intermixture with magnetite. Very often pyrite veins the oxide ore and thus indicates its subsequent deposition.

The most perfect „fringed junctions“ between ore and serpentine are seen in the case of pyrrhotite (Fig. 5 b). The hydrous silicate along its junction with the sulphide shows an intimate interfingering which produces a feather-like structure. In this the „hairs“ of serpentine are curved backwards as if movement had occurred, a feature which may be explained as due to the volume changes during hydration.

Chalcopyrite as mentioned above is later than all the other ore minerals and veins them along cracks, Fig. 6 a.

Summing up the evidence derived from the microscopical study of this group of ores it may be stated that the hydration, which produced the serpentine, etc., took place towards the end of the ore deposition period: it was definitely later than the deposition of most of the ore and certainly earlier than the formation of some. The time relations between pyrite and pyrrhotite cannot be judged with absolute certainty as the two never appear together in the same paragenesis, but as they occupy similar places in the ore sequence it is reasonable to assume that they are temperature equivalents of one

another or that the sulphur content had some influence. The sequence of ore minerals is:

- | | |
|------------------|------------------|
| 1. Magnetite | |
| 2. Pyrrhotite. | 2. Pyrite. |
| 3. Chalcopyrite. | 3. Chalcopyrite. |

4. Hydrous silicate—Ore—Carbonate (mineralization connected with building-up processes).

The main ore bodies of economic importance at Traversella are those in which the ore is associated with carbonates (calcite and dolomite) and „primary“ hydrous silicates. As is the general rule with deposits of this type the ore has been concentrated into stock-like masses within the carbonate and exhibits characteristic irregular boundaries and form. Mineralization has been most intense just below the hanging wall of crystalline schists where the solutions must have been trapped and held for some time.

Mineralogically the masses consist of magnetite, pyrite and chalcopyrite but *nowhere has the author observed pyrrhotite within the carbonate-ore-hydrous silicate paragenesis and no mention of its occurrence is to be found in the existing literature.*

Both calcite and dolomite are present and vary in relative proportion from point to point. The recrystallization of these into large individuals is characteristic and falls into line with our knowledge of similar deposits of contact metamorphic origin. The grain size varies considerably, however, and seemingly without regularity, so that all transitions may be seen between very coarse-grained textures and those of moderate to fine grain. The dolomite crystals have a stronger tendency towards the development of idioblastic form.

Within the carbonate masses the ore may show a rude banding but this is not always apparent and in the majority of cases it is quite structureless and massive. The chief metallic mineral is magnetite which forms small rounded grains and irregular patches. Again relatively coarse-grained aggregates may be present in which the individual crystals reach a size of from 0.5 to 1 cm. and have perfectly developed crystal faces showing the forms (111) and (110). Usually however fine-grained impregnations without crystal form prevail.

From the examination of thin slices and polished sections it is evident that the ore is replacing calcite and dolomite, while at the same time chlorite and talc with subordinate serpentine are forming at the expense of the dolomite. Wherever ore is deposited in carbonate these hydrous minerals are found to develop and the two

processes must be closely connected. The lath-shaped crystals of chlorite may be seen to penetrate magnetite and pyrite in an ophitic manner similar to that in which plagioclase laths penetrate augite in dolerites. It is impossible in such cases to conceive how the chlorite could be all of later formation than the ore, and the only conclusion to be drawn is that the two processes have in part been contemporaneous. The hydrous mineral phase seems to have set in before the end of ore deposition but slightly later than the main mineralization.

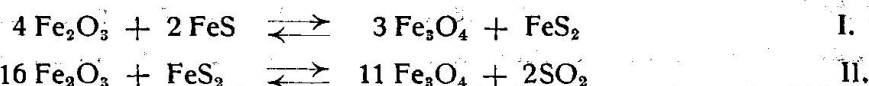
The replacement of calcite and dolomite by magnetite and sulphides is very well shown, the ore replacing the individual crystals around the peripheries and at the same time penetrating along the cleavages. Part of the carbonate is however of later crystallization than the ore.

Pyrite is associated with magnetite and also forms pure masses of sulphide ore, in which case it contains chalcopyrite in varying amount. The iron sulphide, in almost all cases where it occurs alone, tends to form crystal faces and the individual crystals may attain considerable size. The beautifully developed crystals from this source are famous and are to be found in most mineral collections. The sulphide may show replacing relations towards the carbonates which it penetrates in a manner similar to magnetite. Pyrite in addition fills cracks in the oxide ore and is of somewhat later formation. Chalcopyrite is less common than pyrite and is to be regarded as an impurity. Locally it becomes enriched to form a medium-grade copper ore, however, but not in workable quantity. At Castiglione the average copper content of the ore bodies is about 2 per cent. As in all other parageneses chalcopyrite is the last formed ore mineral. It never shows crystal form and builds narrow veins and lenses in the carbonate and in the accompanying ores.

The latest phase in the ore deposition consists of the crystallization of considerable quantities of carbonate (mostly calcite). This has been introduced from some external source and replaces all the earlier components. Magnetite and the sulphides are replaced by calcite which cuts through them in veins and imparts a peculiar shattered appearance to the ore. This is illustrated in Fig. 6 b, p. 125, which is a photographic tracing of magnetite replaced by calcite. The original unity of the central magnetite crystal cannot be mistaken. The replacement may also take place along cleavages, in which case a notched or step-like appearance is imparted to the boundaries of the isolated parts of the crystal. Cavities are occasionally seen and are lined with needle-shaped crystals of quartz.

The origin of the late-formed carbonate is obscure and it may be of magmatic derivation but at the same time the changes involved in the breaking-down of the calc-silicate rocks of the inner zones must have produced much carbonate (mostly calcite) which was carried away in solution. It seems most probable that the late-formed carbonate which penetrates the ores came from this source.

The absence of ferrous iron from the silicates is remarkable when we consider that the magnetite contains this oxide in addition to ferric iron. It must be assumed that ferrous iron was present but in some state which allowed it to react with Fe_2O_3 to form magnetite but at the same time prohibited its reaction with silica and magnesia to form hedenbergite. The constant presence of sulphides of iron suggest that the ferrous iron entered as a sulphide and reacted with ferric iron giving rise to magnetite. The reaction would be as follows:



The absence of pyrrhotite from the outer zones of mineralization probably depends on the fact that there the temperature was lower and pyrite formed in preference to pyrrhotite. In equation¹⁾ I. rise of temperature causes the reaction to proceed towards the left side of the equation, and pyrrhotite forms instead of pyrite.

The absence of pyrite and pyrrhotite in the same paragenesis must depend on the establishment of complete equilibrium in equation I.

VIII. TIME AND PHYSICAL CONDITIONS OF TRANSFER

The problem here presented is one which must be solved by a consideration of all the data available from examples of pyrometasomatic mineral deposits.²⁾

From an examination of the work on contact ore deposition it would seem that pyrometasomatic deposits may be classified into two main groups:

1. Deposits in which only the country rocks have suffered introduction of material.
2. Deposits in which both the eruptive rock and the country rock have been affected by transfer leading to secondary silicate formation.

¹⁾ C. W. CARSTENS, Der unterordovicische Vulkanhorizont in dem Trondhjemgebiet etc. Diss. Zürich 1923. Norsk geologisk tidsskr., Bd. VII, H. 3, p. 59.

²⁾ For a complete list of references to literature see W. LINDGREN, Mineral Deposits, 3rd Edit., New York, 1928, pp. 781—839.

There has been much discussion as to the sequence of events and some authors have been so influenced by the particular type of deposit which they themselves have encountered as to deny the importance of the others. SPURR,¹⁾ influenced by his studies in Mexico, has even gone so far as to deny the importance of pyrometasomatism as a factor in ore deposition and considers that the residual magmas carrying ore were introduced along fissures from some deep seated source. In his opinion these mineralizing solutions are more closely related to the vein-dykes than to metamorphism. LINDGREN²⁾ however, who possesses undoubtedly the most extensive knowledge of this type of deposit, has recently attacked the attitude adopted by SPURR. He says in this respect, „This view is assuredly wrong. The phenomena of contact metamorphism are well established, and the metasomatic rocks having notable addition of substance cannot be separated from those of pure metamorphism.“ However it must be noted that UMPLEBY states that in the Mackay Region, Idaho,³⁾ the metamorphosing solutions were influenced by faults and joints, especially within the intrusion which along such lines has been altered to garnet with concomitant deposition of ores.

Other authors have observed a lapse of time between normal contact metamorphism and metasomatism. In the Christiania region the metasomatism was later than the contact metamorphism but both were prior to the consolidation of the magma. At Philipsburg both processes seem to have occurred simultaneously and the same is true at Ely, Nevada. At White Knob, Idaho,⁴⁾ two stages are recognised and are separated by a time interval, the metasomatism being later than the crystallization of the magma.

At Traversella the igneous rock is not garnetized and is free from calc silicates except at the immediate contact where there has been a development of diopside due to transfer of lime and magnesia from the adjacent carbonate rocks. This transfer is of the nature of a reciprocal reaction and took place before consolidation of the diorite as the diopside has separated from a liquid magma. Again at Traversella the marginal portions of the intrusion, where they border

¹⁾ SPURR, GARREY and FENNER, *Econ. Geol.*, Vol. VII, No. 5, 1912, p. 444. — SPURR, *op. cit.*, p. 485, and *The Ore Magmas*, Vol. II, New York, 1923, Chapter XIV.

²⁾ W. LINDGREN, *Mineral Deposits*, 3rd. Edit., New York, 1928, p. 791.

³⁾ J. B. UMPLEBY, *Geology and ore deposits of the Mackay Region, Idaho*, U. S. G. S., Prof. Paper 97, 1917.

⁴⁾ W. H. EMMONS and F. C. CALKINS, U. S. G. S., Prof. Paper 78, 1913. — A. C. SPENCER, U. S. G. S., Prof. Paper 96, 1917.

on altered carbonate rocks, occasionally show abnormally coarse grain, which suggests that the contact portion of the diorite was kept liquid by outward streaming of the volatile components. From the available facts it seems that at Traversella the transfer took place before final consolidation of the magma and possibly later than the normal contact metamorphism.

The differences in the times of transfer in different deposits as indicated by the alteration or non-alteration of the igneous rock must depend on the behaviour of the volatile components.¹⁾ The whole process of pyrometasomatism depends on the fact that magmas

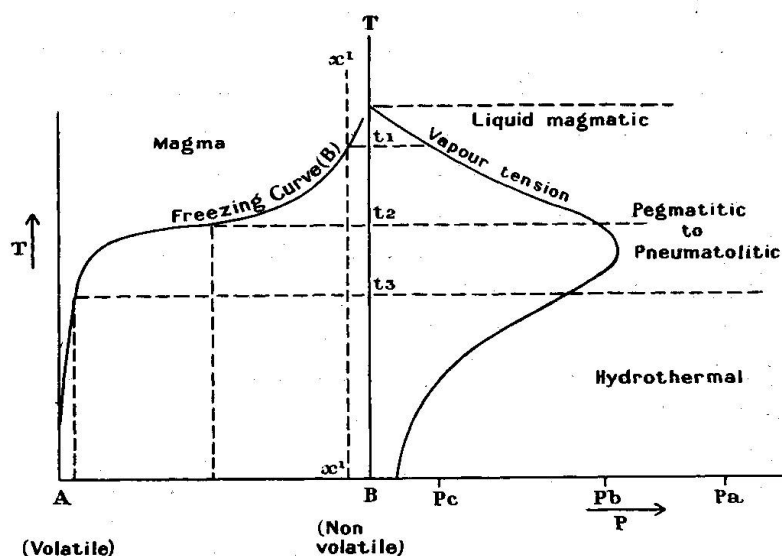


Fig. 7. T—X and P—T Diagram for a system containing one volatile and one refractory Component. After NIGGLI.

contain small amounts of volatile components. Now as crystallization of the non-volatile components proceeds, the vapour pressure instead of decreasing begins to rise, reaches a maximum under certain conditions and only then starts to fall. The process is illustrated in Fig. 7, p. 131. This shows in simplified form a binary system in which A is a volatile component, and B a refractory one. The right hand side of the diagram shows the temperature-pressure conditions, the

¹⁾ P. NIGGLI, Die leichtflüchtigen Bestandteile im Magma, Leipzig, 1920. — U. GRUBENMANN und P. NIGGLI, Die Gesteinsmetamorphose I, p. 272. — P. NIGGLI, Versuch einer natürlichen Klassifikation etc., Abhandl. z. prakt. Geol., Bd. 1, Halle, 1925. — P. NIGGLI, Ore deposits of magmatic origin. London, 1929. — P. NIGGLI and G. W. MOREY, Die hydrothermale Silikatbildung, Zeitschrift für anorg. Chemie, 83, 1913. — G. W. MOREY, The Development of Pressure as a Result of Crystallization, Journ. Wash. Ac. Sc., Vol. 12, 1922, p. 219.

left side conditions representing temperature-composition. The original composition of the magma is represented by x^1 . As cooling proceeds B starts to crystallize and separates out along the freeing curve the magma being enriched in the volatile component. At this point a very small lowering of the temperature causes a great change in the composition of the magma. In the vicinity of t_2 the magmatic period comes to an end and there remains a small amount of magma very rich in volatile matter and containing dissolved refractory material. This is the pegmatite phase which, as cooling continues, gradually passes over into the hydrothermal condition. At the same time it is seen that as crystallization proceeds the vapour tension rises and attains its maximum about the pegmatitic to pneumatolitic stage afterwards gradually decreasing through the hydrothermal field. The presence or absence of transfer from magma to country rock depends on the inner and outer pressure conditions. If the outer pressure is high, corresponding to a great depth of cover on the intrusion, critical phenomena cannot develop. The residual solutions escape along joints, etc., and give rise to pegmatites mostly within the igneous body. If however the outer pressure is such that at some point it is equalled by the inner pressure then critical phenomena set in. The pressure is no longer sufficient to retain the volatile components in solution and they therefore separate as a fluid phase. This fluid is intermediate between liquid and gas and may contain considerable amounts of the refractory components. It will pass from points of higher pressure to points of lower, that is outwards into the country rock. (It is important that the critical temperature of the volatile component should be lower than the freezing point of the refractory constituent.) The fluid having the properties of a gas as well as of a liquid can permeate the carbonate rocks and so produce the alteration.

Thus the period of metasomatism depends both on the inner conditions of crystallization and on the outer pressure. If the outer pressure remains higher than the maximum inner vapour pressure, introduction of material from the magma to the country rocks will not occur except as mutual reaction along the contact and in joints, etc. Such conditions are represented by P_a in Fig. 7. If however the outer pressure lies near P_b the inner pressure will come to equal the outer only after a considerable part of the magma has crystallized, and hence the confined „fluid“ phase will tend to escape by joints, in which case the eruptive rock itself may undergo alteration such as garnetization. Finally the outer pressure may be so low that

streaming off of the fluid phase will commence as soon as crystallization begins. In this case the transfer will be prior to consolidation of the igneous rock which will itself be unaltered. This is seen in the case of Traversella and is shown in Fig. 7 as Pc. In certain cases such as Clifton Morenci, Arizona, the liquor must have been in the hydrothermal stage before transfer commenced. At Traversella however the solutions show all stages from the pneumatolitic to the hydrothermal.

This discussion makes it evident that the variations seen in pyrometasomatic deposits are all due mainly to variations in the physical conditions of crystallization of the magma.

IX. ORE GENESIS

It has been indicated in the previous section how the mineralizing solutions gained access to the carbonate rocks and it now remains to consider their nature and behaviour in the country rocks.

From a study of the silicates and ores it was possible to deduce that the solutions contained silica, ferric iron and inactive ferrous iron, while in the majority of the ore deposits vast quantities of water must have accompanied deposition. The main points of importance with regard to the ore parageneses may be summarized as follows:

1. Magnetite is associated in veins with olivine (forsterite).
2. Halogen minerals are absent.
3. Sulphides in greater or less amount are present.
4. Pyrrhotite does not occur in the carbonate paragenesis.
5. Pyrrhotite and pyrite never occur together.
6. Ferrous iron was inactive and did not form silicates.
7. At a late stage in the ore deposition great amounts of water were liberated.

In the descriptive portion of the paper it was shown that the solutions possessed the same chemical characters from the commencement to the end of the transfer stage and that towards the end of the period of ore deposition large quantities of water were liberated as shown by the development of hydrous silicates. The liberation of the water seems to depend on the crystallization of the ore minerals and calc silicates. This is shown most clearly by the olivine-magnetite vein at Gias del Gallo (Plate I, Fig. 4) as well as by the relations of ore and hydrous silicates.

It has been established for many contact ore deposits that the ore was brought in as a halogen compound which reacted with the

carbonate and deposited the ore minerals. The reactions are supposed to proceed as follows:



The CaCl_2 being soluble may be carried away in solution and leave no trace unless it enters into scapolite, so that the absence of chlor-minerals does not necessarily indicate the absence of the halogen compound. In the case of fluorine the problem is different. It would be to a great extent immediately fixed as fluorite and in consequence its absence is significant. It must always be remembered however that the process depends on the Law of Mass Action and it is possible that the concentration of fluorite never reached the minimum necessary to allow of deposition. In such a case however it could not possibly be sufficient to account for the ore. As mentioned above halogen minerals are almost entirely absent from the Traversella rocks and so the main part of the ore at least cannot have been introduced in combination with chlorine or fluorine. This being the case some other form of iron compound must be looked for. The presence of water in the same solutions and depending on the separation of iron for its liberation suggests that the ore must have come in as a hydrate or at least as some hydrous compound.

Recently GEIJER has discussed the possibility of such iron-water compounds playing an important part in pyrometasomatic ore deposition. It is commonly assumed that silica can be transported by watery solutions and there seems to be no reason why iron should not. This author says¹⁾: „Certainly it is contrary to our established ideas of mineral deposition to imagine that iron can be carried in a gaseous water solution. Yet this possibility deserves serious consideration even if the evidence for it is largely negative.“ The whole question depends on the behaviour of the volatile components in the magma under conditions of varying temperature and pressure. For instance at high pressure water may be dissolved in the magma even though the temperature is far above the critical temperature of the volatile substance. The work of NIGGLI and others has shown that the effect of constituents dissolved in watery solutions is to raise the critical point of the latter and so produce a solution in the strict sense of the word. Thus under conditions of high temperature, and pressure greater than that of the vapour pressure of the solution, critical phenomena cannot set in. However by crystallization of the

¹⁾ P. GEIJER, *Econ. Geol.*, Vol. 20, 1925, pp. 687—690.

refractory constituents the vapour pressure rises until at some point it comes to equal the vapour pressure. At this point a phase is split off which has the properties of a fluid; it is neither liquid nor gas, but rather a liquid with the viscosity and penetrable powers of a gas. At high temperature such a fluid may consist of water containing a good proportion of iron and silica. The temperature must be in the region of 400—600° C., i. e. above the critical temperature of water. Thus though it is not easy to conceive of iron being carried away in a gaseous state it is quite easy to imagine it forming a considerable concentration in such a fluid. FOSHAG also considers the possibility of iron being carried in watery solutions.¹⁾ He believes that the

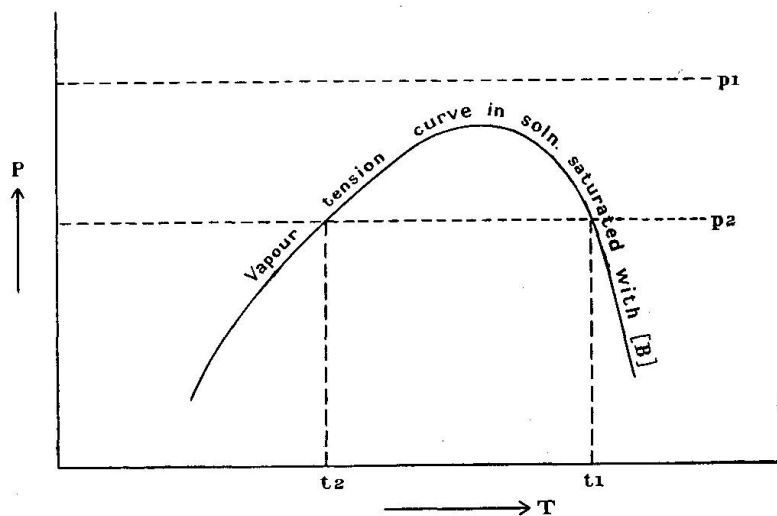


Fig. 8. P—T Diagram for a system containing one volatile Component (A) and one refractory Component (C). After MOREY and NIGGLI.

main function of mineralizers is not to transport the material but to keep the solutions in a liquid state. The iron may thus be carried as a silicate. At Traversella we have excellent proof that the iron was united in some way with water, but there does not seem to be any reason to suppose that it was carried as a silicate in the way which FOSHAG suggests.

The function of the mineralizers is not merely to keep solutions in a liquid state but the whole process of separation of a fluid phase depends on their presence. Without such volatile components no fluid phase could separate and in consequence any pyrometasomatism would be impossible.

The most characteristic feature of the entire Traversella ore deposition is the development of the late-formed water solutions. The

¹⁾ Econ. Geol., Vol. 21, 1926, pp. 194—197.

whole process involved may be brought into line with our modern knowledge of systems containing a volatile component.

The diagram, Fig. 8, p. 135, shows the vapour pressure curve of a magma. If p_1 represents the outer pressure (i. e. outer pressure always exceeds vapour pressure) the vapour pressure curve reaches a maximum and then decreases gradually. p_2 on the other hand represents the probable conditions at Traversella (vapour pressure curve cuts the outer pressure curve). As the temperature falls the

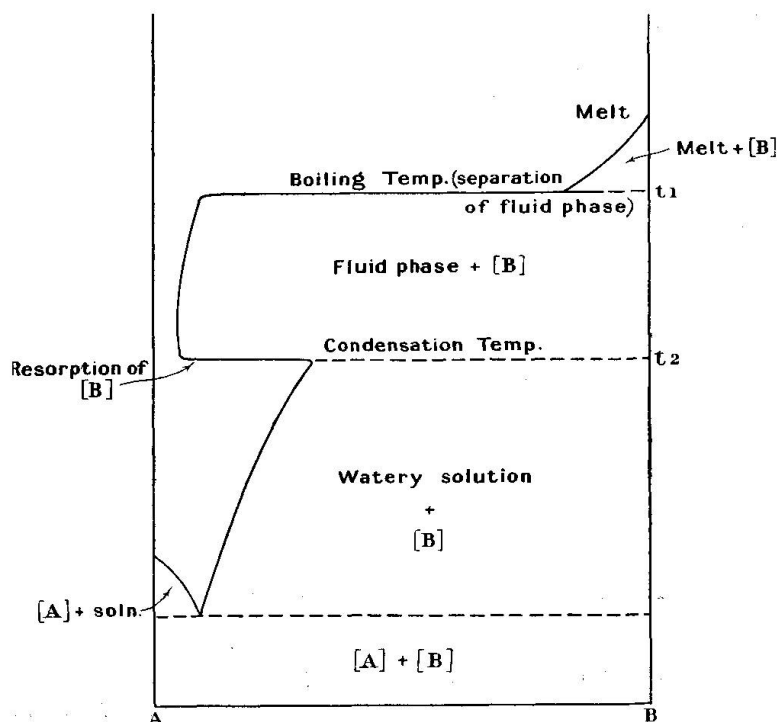


Fig. 9. T—X Diagram for the same system as in Fig. 8 under pressure equivalent to p_2 . After NIGGLI.

vapour pressure increases until at t_1 it equals the outer pressure. At this point a fluid phase is split off consisting chiefly of water with a proportion of refractory material. This is also shown in Fig. 9. This fluid penetrates into the carbonate rocks and the refractory component is deposited, with consequent enrichment in the volatile matter. During the separation of the refractory component from the fluid, B and fluid may coexist together, Fig. 9. The temperature will remain practically constant during the deposition of the non-volatile component but when the fluid has separated out the maximum amount of refractory matter and has become greatly enriched in the volatile component, the temperature will again decrease, vapour pressure will fall until at t_2 it becomes equal to the outer pressure. At this point, Fig. 8 and Fig. 9, condensation commences while some of B is

resorbed. The temperature will here remain constant for a short time but finally B will commence to separate out from a watery solution. At this stage B and liquid water co-exist. The observed facts at Traversella agree very well with this case. The formation of calcsilicates and deposition of ores in such rocks represent the fluid phase. Liquid water was not present. As the iron was deposited however and the temperature fell, the pressure gradually decreased until at a certain point condensation commenced and immense quantities of water were liberated which altered the calc silicates to hydrous silicates, while at the same time the little remaining iron separated from water solution. This explains the development of hydrous minerals prior to the deposition of a small part of the ore.

The olivine-magnetite veins show rather special features and in some ways have a superficial resemblance to the eulysites of Scandinavia described by VON ECKERMANN¹⁾ and CARSTENS.²⁾ At Traversella however the olivine is forsterite and not fayalite as in the case of the eulysites. ECKERMANN regards the latter as intrusive veins possessing the characters of pegmatites, but CARSTENS has shown them to be of contact metamorphic or metasomatic nature. The fact that the magnetite-olivine at Gias del Gallo forms veins must be due to local conditions of pressure which were seemingly too high to allow of re-impregnation of the calc-silicate rocks by later solutions. These were therefore forced to penetrate along joints and cracks. The formation of the forsterite is difficult to explain as one would have expected diopside. In the opinion of the author the olivine has crystallized from the iron-bearing solutions which contained some additional magnesia of magmatic origin and a rather low silica content. It is not possible to prove this but the presence of magnesian olivine must be explained either as due to introduction of MgO and removal of CaO or else removal of CaO without introduction of magnesia. In the latter case great volume changes would be expected whereas diopside or tremolite could have formed without removal of a constituent. It seems most probable that magnesia has been introduced locally. At the same time the development of serpentine along the margins of the veins attests to the late separation of the watery liquid as in the more normal deposits of the region, and attests to the similarity of the processes involved.

1) H. VON ECKERMANN, Geol. Foren. Stockh. Forhandl., 1922, pp. 203—410.

2) C. W. CARSTENS, *ibid.*, Bd. 46, 1924, pp. 248—253.

X. ACKNOWLEDGEMENTS

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Plate I



Fig. 1.

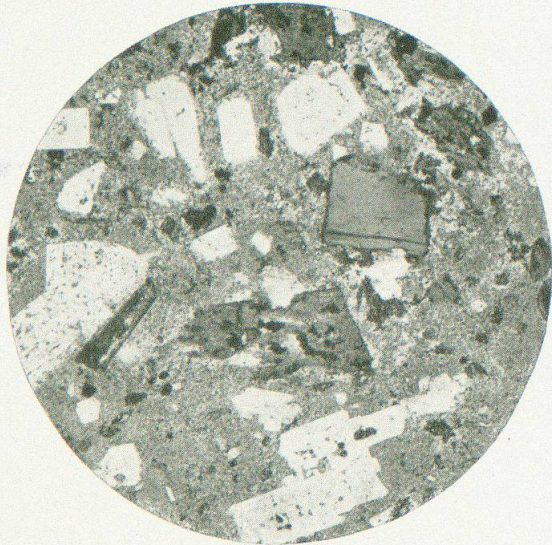


Fig. 2.

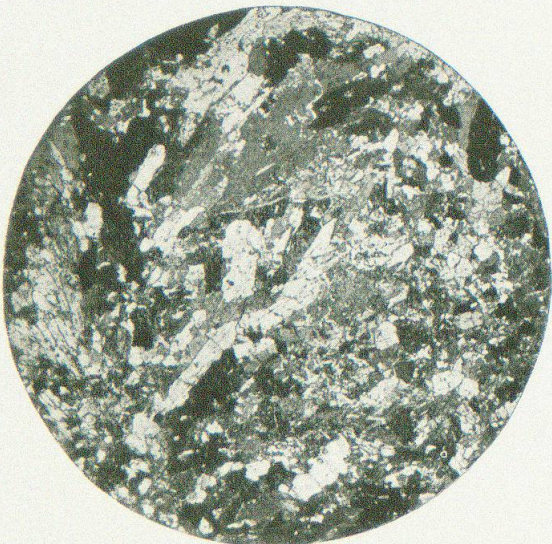


Fig. 3.



Fig. 4.



Fig 5.

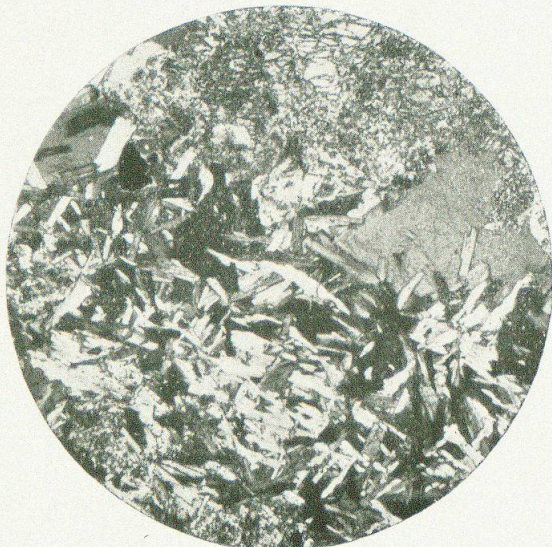


Fig. 6.

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Plate II



Fig. 1.



Fig. 2.

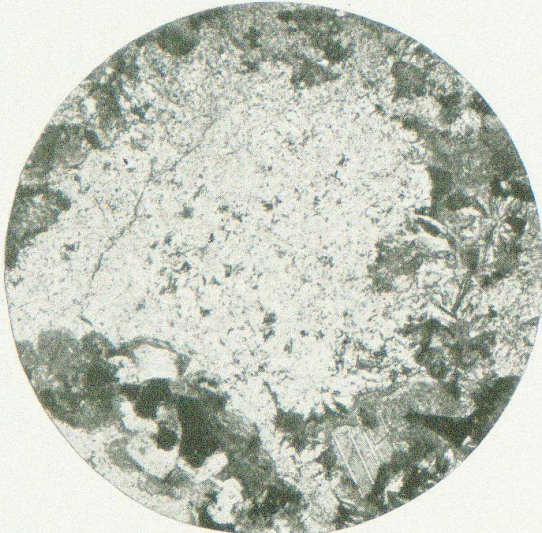


Fig. 3.

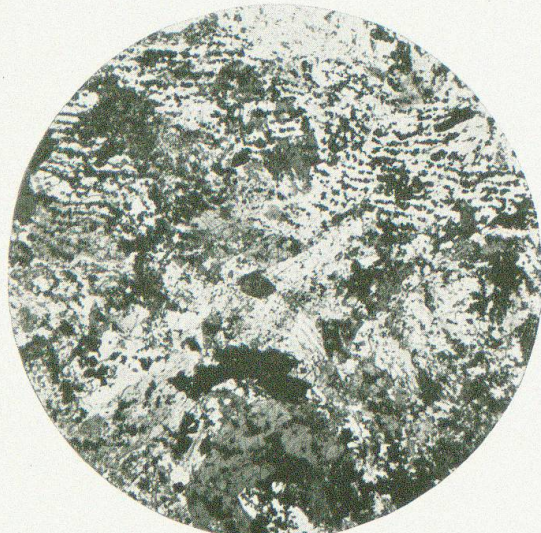


Fig. 4.



Fig. 5.



Fig. 6.

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EXPLANATION OF PLATES

Plate I

- Fig. 1. Quartz-diorite showing the enclosure the biotite by idiomorphic hornblende. Ordinary light. $\times 24$.
- Fig. 2. Biotite-hornblende-porphyrite. Ordinary light. $\times 24$.
- Fig. 3. Diopside rock showing the characteristic bladed forms of the diopside crystals and the variation in texture in different parts of the same slice. Crossed Nicols. $\times 24$.
- Fig. 4. Plagioclase-diopside rock. A large crystal of plagioclase encloses grains of diopside in poikiloblastic manner. Crossed Nicols. $\times 13$.
- Fig. 5. Diopside (highly refracting mineral) breaking down into an aggregate of fine needles of tremolite. Ordinary light. $\times 24$.
- Fig. 6. Chlorite rock. Shows an aggregate of small lath-shaped crystals of chlorite developing from carbonate. The interspaces are filled with fine grained serpentine or carbonate. In the upper part of the field is seen an early formed crystal of forsterite which is breaking down into serpentine. Penetration of the carbonate by chlorite laths indicates the primary nature of the hydrous silicate. Crossed Nicols. $\times 13$.

Plate II

- Fig. 1. Chlorite and talc developing in a carbonate rock under the influence of the ore solutions. The highly refracting mineral is residual carbonate and the greyish interstitial mass between the colourless chlorite crystals, and in which the residual carbonate is embedded consists of a very fine-grained aggregate of talc. The dark patches are magnetite. Ordinary light. $\times 13$.
- Fig. 2. Same as Fig. 1. Crossed Nicols. $\times 13$.
- Fig. 3. Showing replacement of carbonate rock by an aggregate of talc, due to the action of silica-bearing ore solutions. Crossed Nicols. $\times 13$.
- Fig. 4. Intergrowth of diopside and magnetite. This shows the banded nature of some of the ore which is developed without regard to cleavage or other structures in the pyroxene. Crossed Nicols. $\times 13$.
- Fig. 5. Pyrrhotite developed in diopside-tremolite rock. The sulphide (black) is intergrown with blades of tremolite. Ordinary light. $\times 24$.
- Fig. 6. Forsterite—magnetite vein in tremolite rock. The ore vein (black) is separated from the tremolite (greyish mineral aggregate at right) by a narrow zone of colourless serpentine developed at the expense of the calc-silicate. Ordinary light. $\times 10.5$.
-