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## **Sulfur Isotope Investigation of Sulfides and Rocks from the Main Basic Series of the Ivrea Zone**

By *Hartmut Heilmann* and *Günter Lensch* \*), Saarbrücken

### **Abstract**

In order to further study the arguments for or against the mantle-origin of the basites and ultrabasites of the Ivrea zone, 23 pure sulfide samples from former pyrrhotite deposits and 17 rock samples of peridotite, pyroxenite, and gabbro were investigated for their sulfur isotope composition. This investigation was supplemented by 45 chemical rock analyses in order to determine the character of the basic series.

The sulfur isotope distribution of the peridotites lies near the CDT standard. The average value of the basic rocks is  $+2.3^{\text{o}}/\text{oo}$   $\delta^{34}\text{S}$ . A systematic increase in heavy sulfur isotope from the bottom to top is visible within the series. This increase parallels a tholeiitic differentiation. The average value of the sulfide samples is  $+1.2^{\text{o}}/\text{oo}$   $\delta^{34}\text{S}$ . The stratigraphically deeper deposits also contain light sulfur, whereas the higher levels contain heavy sulfur.

From the results it can be concluded that the basites and sulfides of the Ivrea zone represent an almost undifferentiated mantle material. This corresponds with the current hypotheses of the Ivrea zone's origin.

### **I. Introduction**

There are many observations and considerations which indicate that in the Ivrea-zone a complete section across the earth's lower crust is accessible. This section begins with various-sized fragments of the peridotitic upper mantle, continues through a large series of metagabbros and degranitized metasediments representing the lower crust and finally extends to the normal sialic gneiss of the upper crust. Geophysical, geological and petrographical arguments backing this interpretation have been presented over the past few years by H. BERCKHEMER (1968), P. GIESE (1968), F. ROST (1968, 1971),

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G. LENSCH (1971, 1975, 1976), G. LENSCH and F. ROST (1972), K. R. MEHNERT (1975).

In this connection it would be interesting to present geochemical arguments for the origin of the metagabbros in the Ivrea zone. If these basites really come from the lower crust as well as from the transition zone into the upper mantle and are even genetically related to upper mantle mobilizations (G. LENSCH, 1976) then the sulfur isotopic composition should also support this supposition.

The pyrrhotite mineralization, which is found in peridotites and pyroxenites at different levels of the metagabbro body of the Ivrea zone, was investigated for its sulfur isotope composition. The study of the pure sulfur samples was completed by investigating the total sulfur in the basic rocks. For this reason a NW-SE profile was made in the Mastallone valley through the basic main body. These samples were also used to characterize the general geochemical composition of the metagabbros. The sample taking was concentrated in the Sesia and Mastallone valleys, supplemented by a few samples from the Strona valley (Fig. 1). In the Val d'Ossola and in the peridotite complex of Finero special problems occur which are in the process of being investigated but will not be treated in this paper.

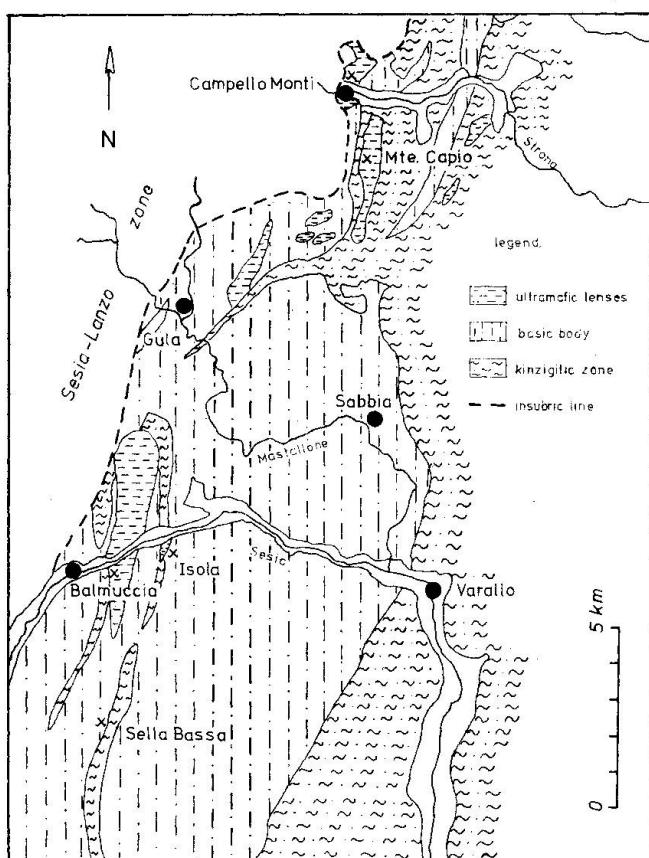


Fig. 1. Geological sketch-map of the middle part of the Ivrea zone.

## II. The pyrrhotite deposits of the basic main body of the Ivrea zone and their sulfur isotope composition

Apart from the few gold-bearing quartz-pyrite veins which run from the Monte Rosa gold-province along the Insubric line, partly extending into the Ivrea zone, the rock character and ore mineralization change abruptly at this dislocation zone. The ophiolitic rocks of the Piemont trough and the gneisses of the Monte Rosa, northwest of the Insubric line, contain ore mineralizations primarily in the form of pyrite, chalcopyrite, arsenopyrite and gold. In contrast, the peridotitic and pyroxenitic lenses and the gabbros southeast of this line contain primarily pyrrhotite, pentlandite, and some chalcopyrite with traces of cubanite and valeriite.

The investigated sulfide samples are primary mineralizations which belong to a magmatic differentiation. Replacements occur seldom, if at all. The pentlandite content of pyrrhotite varies in the different deposits. Because the mining has been abandoned now for over 30 years, only dump stocks were available for sample taking. This, of course, has the consequence, that only an approximate  $\delta^{34}\text{S}$ -value of the particular deposits could be determined. The ore mineralization of these deposits has been thoroughly discussed by H. F. HUTTENLOCHER (1934, 1942) and M. BERTOLANI (1952, 1964). For this paper, only the mining districts of Monte Capio, Campello Monti, Balmuccia, Isola and Sella Bassa were investigated (Fig. 1). Samples from the former Gula mine will not be discussed. The ore paragenesis there deviates from the above mentioned deposits in that it shows a younger mobilization and replacement. This process could explain the shift in the isotopic composition towards light sulfur isotope ( $\delta^{34}\text{S}$ -values up to  $-11.3\text{‰}$ ). Note: Sample preparation and measuring techniques are not described here. Precise procedural descriptions are given by H. NIELSEN (1963, 1968), W. RICKE (1964) and A. SCHNEIDER (1970).

### 1. Monte Capio (Alpe Laghetto) deposit

#### Geological setting

The galleries lie about 2000 meters above sea level between the Strona and Mastallone valleys. The ore-bearing rock is peridotite. There are numerous peridotite lenses here which appear at different levels and in various sizes along the Insubric line.

#### Ore mineralization

The Monte Capio ore is composed of pyrrhotite with large quantities of pentlandite. Chalcopyrite, cubanite, and valleriite occur as accessories.

The sulfide distribution varies considerably even within small areas. Finely distributed sulfide varies from small veins and droplets to large, nest-like concentrations of 0.5 cm in diameter. In these larger ore concentrations the pyrrhotite grains display a distinctly parallel developed lamellar structure ( $\alpha$ - and  $\beta$ -lamellae, D. L. SCHOLTZ, 1936). They are so numerous that it is difficult to distinguish lamellae from matrix.

#### Sulfur isotopes

Three hand specimens were available for the investigation of the sulfide's sulfur isotopes. Six individual samples were taken from the samples 3710 and 3713 in order to investigate the variation of S-isotope distribution within a small area and the possible difference between coarse and fine-grained particles.

The  $\delta^{34}\text{S}$ -values from the samples 3710/1 and 3710/2, which contain the nest-like sulfide concentrations, have a slightly positive  $\delta^{34}\text{S}$ -value of  $+1.1\text{‰}$  to  $+1.3\text{‰}$ . The sample 3712 represents the very finely distributed sulfide from small veins and droplets. Its  $\delta^{34}\text{S}$ -value of merely  $+0.3\text{‰}$  lies clearly below all other samples. The samples 3713/1-4 were separated from one hand specimen, composed of numerous compact sulfide nests. The  $\delta^{34}\text{S}$ -values from these four samples show a very uniform composition, varying only  $0.3\text{‰}$  between  $+0.9\text{‰}$  and  $+1.2\text{‰}$   $\delta^{34}\text{S}$  (see table 1).

Table 1. Sulfur isotope distribution in the Monte Capio deposit

Sample No.	Description	$\delta^{34}\text{S}$ -value
3710/1	pyrrhotite in amphibole-peridotite, nest-like concentrations in hand-specimen ( $13 \times 4$ cm)	$+1.1\text{‰}$
3710/2	nest-like concentrations in hand-specimen ( $13 \times 4$ cm)	$+1.3\text{‰}$
3712	very fine grained pyrrhotite from amphibole-peridotite	$+0.3\text{‰}$
3713/1	different separated sulfide-nests in amphibole-peridotite from a hand-specimen, 12 cm in diameter	$+1.1\text{‰}$
3713/2	amphibole-peridotite from a hand-specimen, 12 cm in diameter	$+1.2\text{‰}$
3713/3	total-rock sulfur from amphibole-peridotite	$+0.9\text{‰}$
3713/4	total-rock sulfur from amphibole-peridotite	$+0.9\text{‰}$
3722	total-rock sulfur from amphibole-peridotite	$0.0\text{‰}$
2589	total-rock sulfur from peridotite	$+0.3\text{‰}$

It is possible that the original sulfur isotope distribution still exists in the fine sulfide veins and droplets. A  $\delta^{34}\text{S}$ -value of  $+0.3\text{‰}$  coincides with the cosmic average value, which is presumed to be about  $+0.2\text{‰}$  on the CDT-scale. On the other hand, large, compact ore-nests with a  $\delta^{34}\text{S}$ -value of  $+0.9\text{‰}$  to  $+1.3\text{‰}$  show an obvious concentration of heavy  $^{34}\text{S}$ -isotope. The over all average value of all pyrrhotite samples of the Monte Capio deposits indicates, with  $+0.9\text{‰}$   $\delta^{34}\text{S}$ , a slight concentration of heavy sulfur compared with the CDT-standard. With  $1.0\text{‰}$ , the deposit has a very narrow

spread. To what extent this value is representative for these deposits cannot be exactly determined due to the limited number of samples. However, because of the uniformity of the entire complex, a wide deviation is hardly to be expected.

The sulfur isotope distribution of total sulfur in the rocks was investigated in two peridotites. The values of  $0.0^{\text{o}}/\text{oo}$  for sample 3722 and  $+0.3^{\text{o}}/\text{oo}$  for 2589 are similar to the values for the finely distributed sulfide, which are either close to the CDT-standard or correlate with it. Consequently, a light fractionation of the juvenile sulfur causing a concentration of heavier  $^{34}\text{S}$ -isotopes occurs only in large sulfide nests.

## 2. Campello Monti (Upper Strona Valley)

### Geological setting

The deposits lie above the village of Campello Monti at the upper end of the Strona valley. Ore mineralization is found in pyroxenitic and peridotitic rocks in the immediate vicinity of the Insubric line. These are connected with gabbros, norite, and high metamorphic paragneiss (stronalite) in the southeast.

### Ore mineralization

The ore appears in a droplet form but also in large ore particles that extend into their surroundings in a nestlike form. Pyrrhotite with numerous lamellae and flameshaped, imbedded pentlandite is the main mineral. Small amounts of bravoite were found on some slides.

### Sulfur isotopes

Seven sulfide samples were investigated for their sulfur isotope composition (see table 2). Except for one sample (3714), which produced a negative  $\delta^{34}\text{S}$ -value of  $-0.3^{\text{o}}/\text{oo}$ , all the other isotope values are positive, lying between  $+0.5^{\text{o}}/\text{oo}$  and  $+1.3^{\text{o}}/\text{oo}$   $\delta^{34}\text{S}$ . These deposits, like Monte Capio's ore, appear to

Table 2. Sulfur isotope distribution in the Campello Monti deposit

Sample No.	Description	$\delta^{34}\text{S}$ -value
3708		$+0.9^{\text{o}}/\text{oo}$
3709/1		$+1.2^{\text{o}}/\text{oo}$
3709/2	fine veinlets of pyrrhotite	$+0.5^{\text{o}}/\text{oo}$
3714/1	with pentlandite in peridotites	$-0.3^{\text{o}}/\text{oo}$
3714/2		$+0.8^{\text{o}}/\text{oo}$
L 82		$+0.6^{\text{o}}/\text{oo}$
L 83		$+0.8^{\text{o}}/\text{oo}$
2589		$+0.3^{\text{o}}/\text{oo}$
3719	total-rock sulfur from peridotites	$+0.8^{\text{o}}/\text{oo}$
3720		$+0.4^{\text{o}}/\text{oo}$
3723		$+0.2^{\text{o}}/\text{oo}$

have a very homogenous isotope distribution with a slight concentration of heavy  $^{34}\text{S}$ -isotope. The deposit's average S-isotope composition lies at  $+0.7^{\text{o}}/\text{oo}$   $\delta^{34}\text{S}$ .

The rock-sulfur investigation of Campello Monti's sulfidebearing amphibole-peridotite also yielded a slight predominance in  $^{34}\text{S}$ -isotope, from  $+0.2^{\text{o}}/\text{oo}$  to  $+0.8^{\text{o}}/\text{oo}$ . Here again the relationships appear similar to the described deposits at Monte Capio, in that the sulfide always exhibits a heavier sulfur than the mother rock.

### 3. The Sesia Valley pyrrhotite deposits

(Balmuccia, Sella Bassa, Isola)

#### **Geological setting**

The Balmuccia and Isola deposits are located in the middle of the Sesia valley. The rocks of these two deposits are bronzitite and pyroxenite lenses enclosed in gabbros.

A melanocratic gabbro forms the bedrock at the Sella Bassa deposit in the mountains at the southern side of the valley.

#### **Ore mineralization**

The sulfide ore consists mainly of pyrrhotite and pentlandite with small amounts of chalcopyrite. Two kinds of replacements can be observed from investigated polished sections of Balmuccia and Isola.

a) The sulfides in the strongly mineralized samples are clearly replaced by silicates. These extend lath-like into the sulfides so that only a strongly pinnate border remains. Even large grains with yet undisturbed cores are strongly pinnated at the edges and have halos of finegrained ore formed closely around it, which undoubtedly represent the original grain size.

b) Another type of replacement was observed in samples with little ore content, where the silicates are clearly replaced by sulfides. Here the sulfide is concentrated around the silicate-grain border, splitting it apart.

The ore of the former Sella Bassa mine does not show the above-mentioned types of replacement. The ore consists of a concentrated pyrrhotite ore with a considerable amount of pentlandite.

#### **Sulfur isotopes**

#### **Balmuccia**

The three investigated pyrrhotite samples display a notably homogeneous sulfur isotope composition. The samples show a spread of only  $0.3^{\text{o}}/\text{oo}$ , between  $+1.3^{\text{o}}/\text{oo}$  and  $+1.6^{\text{o}}/\text{oo}$   $\delta^{34}\text{S}$  (see table 3).

Table 3. Sulfur isotope distribution in the Val Sesia deposits

Sample No.	Description	$\delta^{34}\text{S}$ -value
3704	pyrrhotite in pyroxenite from the	+1.3 $^{\text{o}}/\text{oo}$
3705	Balmuccia ore deposit	+1.6 $^{\text{o}}/\text{oo}$
L 81		+1.3 $^{\text{o}}/\text{oo}$
3703/1	pyrrhotite from massive ore in	+1.7 $^{\text{o}}/\text{oo}$
3703/3	melagabbro from the Sella Bassa	+1.4 $^{\text{o}}/\text{oo}$
3703/4	ore deposit	+1.5 $^{\text{o}}/\text{oo}$
3703/6		+1.5 $^{\text{o}}/\text{oo}$
3706	pyrrhotite replacing silicates from	+2.9 $^{\text{o}}/\text{oo}$
3707	the Isola ore deposit	+2.7 $^{\text{o}}/\text{oo}$

### Sella Bassa

Only one large hand specimen was available, from which four samples from different parts were taken and investigated. The results corroborated those from the Balmuccia deposit. Positive values between +1.4 $^{\text{o}}/\text{oo}$  and +1.7 $^{\text{o}}/\text{oo}$   $\delta^{34}\text{S}$  were also measured here. The ore from this deposit again appears to come from a very homogeneous source according to its S-isotope composition.

### Isola

The Isola sulfur from further down in the valley, coming from sulfides in a pyroxenite lense, is isotopically heavier. The samples show the highest  $\delta^{34}\text{S}$ -values of +2.7 and +2.9 $^{\text{o}}/\text{oo}$  of all the deposits investigated here.

This distinct shift in  $\delta^{34}\text{S}$ -values toward the heavier sulfur isotope can possibly be explained by the abovementioned replacements. An argument against this possible explanation is that similar replacements occur at Balmuccia without a distinct shift in the sulfur isotope composition.

### III. Geochemical characteristics and sulfur isotope distribution of the metagabbros of the Ivrea zone

The deeper part of the Ivrea zone consists of a continuous series of banded, steep dipping gabbroic rocks reaching to 8 km in thickness. This series includes pyroxenites, melanocratic norites, and gabbros, which become in part garnetiferous, normal gabbros, and biotite bearing diorites. The above described ore mineralizations are mostly bound to the deeper part of this series (Fig. 1). From bottom (at the external side, towards NW) to top (at the internal side, towards SE), a decrease in metamorphism and an increase in sialic elements is observed. This increase, which may reflect a magmatic differentiation, clearly becomes evident by the development of the colour index (Table 4 and Fig. 4).

In order to characterize this differentiation more precisely, 45 rock analyses

were carried out. The analyses were performed on rocks from the Mastallone, Sesia, Strona, Sessera and Ossola valleys and the region around Finero, at the northeastern part of the Ivrea zone (H. HEILMANN, 1976).

When using the proposals of T. N. IRVINE and W. R. A. BARAGAR (1971) for a chemical classification of igneous rocks, the plot alkalis versus silica reveals that the series is subalcaline. The FAM-diagram (Fig. 2) shows clearly, that the members of the main basic series of the Ivrea zone are arranged in a distinct tholeiitic trend.

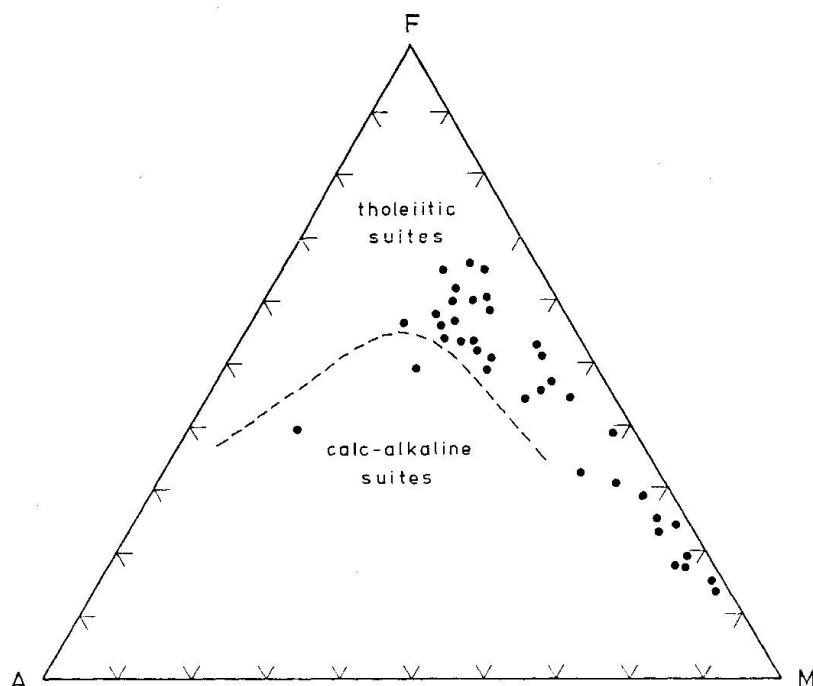


Fig. 2. Plot F A M for the basites and ultra-basites of the Ivrea zone.

Eleven samples were taken from the Mastallone Valley to investigate the sulfur isotope composition of total sulfur in the gabbroic series. This Valley reveals a cross sectional profile of the basic rock body. The samples were systematically taken from the lying wall (Insubric line) in the northwest to the roof (the transition zone of kinzigite at Varallo) in the southeast.

The eleven samples of the profile consisted of nine gabbros, one garnet-bearing pyroxenite, and one biotite-diorite. A slight retrograde alteration of the primary paragenesis is present in all samples. The primary mineral paragenesis of the rock sequence shows a clear correlation to the stratigraphic position. This is especially pronounced in garnet and biotite, with garnet limited to the profile's deeper part and biotite favoured in the roof. A correlation with the stratigraphic position is also found in plagioclase. It is manifested from bottom to top by a constant increase in feldspar and consequently by a decrease in the Colour Index.

The table 4 shows the sulfur isotope composition of the Mastallone-profile rocks.

Table 4. Sulfur isotope distribution and Colour Index of gabbroic rocks from the Mastallone profile

Sample No.	Locality	Description	$\delta^{34}\text{S}$ -value	C.I.
415	Gula	garnetiferous gabbro	+1.5 $^{\circ}/_{\text{oo}}$	84
413	Gula	garnetiferous gabbro	+1.9 $^{\circ}/_{\text{oo}}$	80
418	Voi	garnetiferous gabbro	+2.1 $^{\circ}/_{\text{oo}}$	64
421	Voi	garnetiferous gabbro	+2.3 $^{\circ}/_{\text{oo}}$	59
422	Valbella	garnetiferous pyroxenite	+2.5 $^{\circ}/_{\text{oo}}$	81
426	Cravagliana	gabbro	+2.5 $^{\circ}/_{\text{oo}}$	53
429	Cravagliana	gabbro	+2.3 $^{\circ}/_{\text{oo}}$	65
430	Cravagliana	gabbro	+2.7 $^{\circ}/_{\text{oo}}$	28
433	SE Cravagliana	gabbro	+1.9 $^{\circ}/_{\text{oo}}$	16
434	NW Sabbia	gabbro-diorite	+2.8 $^{\circ}/_{\text{oo}}$	23
436	Sabbia	biotite-diorite	+3.1 $^{\circ}/_{\text{oo}}$	26

#### IV. Discussion and conclusions

The 23 investigated samples of pure nickeliferous pyrrhotite from five former deposits, connected with ultramafic lenses along the Insubric line, show:

a) All  $\delta^{34}\text{S}$ -values lie close to the CDT standard with a slight tendency towards the heavy  $^{34}\text{S}$ -isotope. These results correspond with most investigations of sulfides from the crust/mantle region. The average S-isotope value in this investigation of pure nickel-bearing pyrrhotites of the Ivrea zone is +1.2 $^{\circ}/_{\text{oo}}$   $\delta^{34}\text{S}$ . In comparison with investigations of great intrusions with presumably similar magma sources, for instance, the Muskox intrusion (A. SASAKI, 1969) with an average value of +5.1 $^{\circ}/_{\text{oo}}$   $\delta^{34}\text{S}$  and Sudbury (H. P. SCHWARCZ, 1973) with +2.1 $^{\circ}/_{\text{oo}}$   $\delta^{34}\text{S}$ , the Ivrea zone's sulfide sulfur is somewhat lighter. The homogeneity of the sulfur isotope distribution in the Ivrea sulfides is noteworthy, having a spread of only 3.2 $^{\circ}/_{\text{oo}}$  over the five investigated deposits.

b) Putting the deposits in stratigraphic order, that is, assuming Monte Cipio and Campello Monti are the underlying bed leaning towards the Insubric line, whereas Balmuccia, Sella Bassa, and Isola lie further southeast forming the roof, the following results (see Fig. 3): Going from bottom to top there is a slight but constant increase in heavy  $^{34}\text{S}$ -isotope. This increase takes place in three stages. The deepest level with the highest concentration of the light  $^{32}\text{S}$ -isotope is found at Monte Cipio and Campello Monti. The middle level is found at Sella Bassa and Balmuccia with an average  $\delta^{34}\text{S}$ -value of +1.5 $^{\circ}/_{\text{oo}}$ . The Isola deposit is the highest level, lying the furthest southeast and having the heaviest sulfur. This increase in heavy sulfur parallels the tholeiitic differentiation process of the country rock.

A similar manifestation was found by H. G. THODE, J. MONSTER, and H. B. DUNFORD (1961) in the intrusives at Sudbury, Ontario and Stillwater,

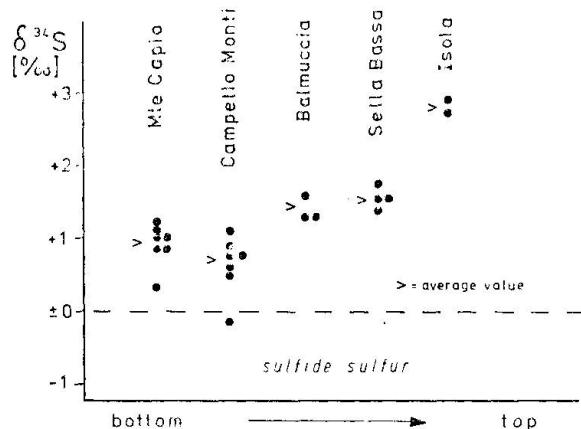


Fig. 3. Variation of  $\delta^{34}\text{S}$  of pure sulfides relative to the stratigraphic position.

Montana, were the  $\delta^{34}\text{S}$ -value increases from the basic underlying bed to the acidic roof. R. K. WANLESS et al. (1960) reported a strongly metamorphosed area with a comparable trend in sulfur isotopes at Yellowknife, Canada. Also A. P. VINOGRADOW (1958) found similar fluctuations in the isotopic composition of sulfides in acid and basic igneous rocks. New and very detailed investigations in Sudbury (Southrange) by H. P. SCHWARCZ (1973), however, reveal an opposite trend, namely that the amount of heavy sulfur increases with the deposits depth. Further investigations on the pyrrhotite deposits in the Ivrea zone are already under way, in order to pursue this notable trend more precisely and to verify it with additional samples.

On the basis of petrographical and chemical investigations of the metagabbros, the main basic body of the Ivrea zone, which contains the above described ore mineralization, represents a differentiated tholeiitic series. Within this series, the garnetiferous gabbros from Gula near the Insubric line contain the lightest sulfur with  $+1.5\text{‰}$   $\delta^{34}\text{S}$ . Moving away from the Insubric line towards SE, the levels become stratigraphically higher, in the same way a continually increasing concentration of heavy isotope in the rocks is observed (Fig. 4). The maximum amount of heavy sulfur is found at Sabbia near the Mastallone valley exit, where the basite series ends and the kinzigit begins. This profile's spread is only  $1.6\text{‰}$ , but there is a distinct trend towards a concentration of  $^{34}\text{S}$ -isotope. A similar effect of the concentration of heavy sulfur-isotope in the highest levels has also been discovered by W. G. SMITHERINGALE and M. L. JENSEN (1962) among Triassic rocks of the eastern USA, that likewise stem from a tholeiitic magma from the crust/mantle region. Other investigations from rocks of basic sills from Palisades, N.Y., Leitch, Ontario, and Insizwa, S. A. by M. SHIMA, W. H. GROSS and H. G. THODE (1963) show a similar manifestation. For example, the Palisade's sill displays a distinct increase in  $\delta^{34}\text{S}$  from the lower to the upper contact.

It should be mentioned here that gabbros from the Sessera valley yielded clearly higher  $\delta^{34}\text{S}$ -values ranging up to  $+5\text{‰}$   $\delta^{34}\text{S}$ . Likewise, some samples from

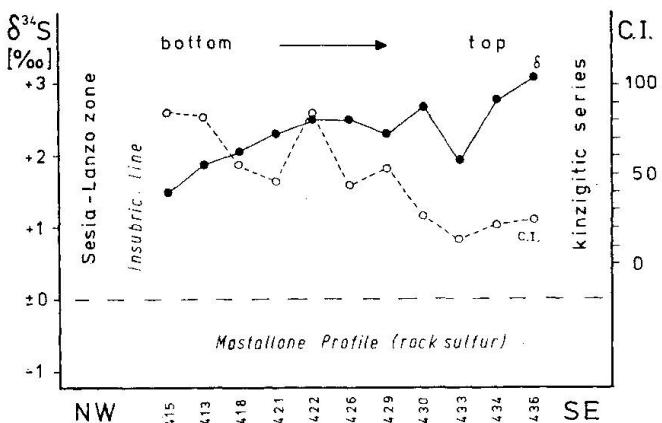


Fig. 4. Variation of  $\delta^{34}\text{S}$  and Colour Index of rocks relative to the stratigraphic position.

the Finero ultramafic complex deviate strongly and reveal a considerable inhomogeneity because the  $\delta^{34}\text{S}$ -values scatter between  $+2.9^{\circ}/\text{oo}$  and  $-14.7^{\circ}/\text{oo}$ . The origin and significance of these observations is presently being investigated by the authors.

In the gabbros with an average  $\delta^{34}\text{S}$ -value of  $+2.3^{\circ}/\text{oo}$  there exists a slight isotope fractionization to the favour of heavy sulfur. The gabbros differ from the peridotitic rocks near the Insubric line whose  $\delta^{34}\text{S}$ -values partly coincide with the presumed cosmic composition. Therefore, these peridotites may be considered as undifferentiated parts of the upper mantle. The basic rocks on the other hand, may be directly derived from a mobilization in the upper mantle which has produced a slightly differentiated gabbro complex.

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