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# **The Stable Association Enstatite-Forsterite-Chlorite in Amphibolite Facies Ultramafics of the Lepontine Alps**

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With 2 text figures

## *Abstract*

Ultramafic rocks with the paragenesis forsterite-enstatite-chlorite-magnetite occur in the sillimanite and calcite-anorthite zones of the Lepontine Alps. Textural and chemical evidence indicates that this assemblage formed during the Alpine metamorphism. Some oxidation prior to or during the last recrystallization caused the silicates to be very magnesian (e. g. olivine  $\text{Fa}_{4.5}$ ). The paragenesis formed under conditions of low water activity in the amphibolite facies.

## **Geological Outline**

Ultramafic rocks are an important constituent of the metamorphic series of the Lepontine Alps. They have given rise to numerous studies and to various interpretations reflecting the change in geological thought during the past sixty years (GRUBENMANN 1908; HEZNER 1909; KÜNDIG 1926; P. NIGGLI 1936; DAL VESCO 1953; KNUP 1958; MÖCKEL 1968). The Lepontine ultramafics are frequently associated with metamorphic Mesozoic carbonate sediments and form lenses and bodies from a few meters to several kilometers in size. They generally show a marked schistosity and lineation completely in agreement with the surrounding marbles, schists and gneisses – a fact already well understood by GRUBENMANN (1908). Together with the accompanying rocks, the ultramafics were subject to strong Alpine deformation and to outlasting crystallization or recrystallization of various magnesian silicates, such as talc, anthophyllite, forsterite, and, in the zones of highest grade, enstatite.

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**Enstatite-Forsterite-Schists of Val Cama**

A typical example of enstatite-forsterite schist occur in Val Cama, Grisons (Eastern Lepontine Alps), in an area mapped and described by BRUGGMANN (1965). The grade of metamorphism in Val Cama is given by the occurrence of the parageneses anorthite-calcite (SCHWANDER and WENK 1967) and diopside-calcite-quartz in the adjacent marbles, and by the occurrence of predominant kyanite and locally of fibrolitic sillimanite in pelitic schists. Currently available experimental and calculated data on mineral equilibria indicate that the maximum temperature of metamorphism may have just exceeded 600°C. An estimate of pressure is much more uncertain – a value around four kb seems reasonable and not conflicting with estimates for the Western Bergell Alps (TROMMSDORFF 1968).

The ultramafic body at Val Cama forms a subvertical sheet about 100 m in thickness, accompanied on both sides by concordant marbles and calc-silicate rocks five to twenty meters in thickness. It outcrops over a length of more than two kilometers. Locally the ultramafics are inhomogeneous and

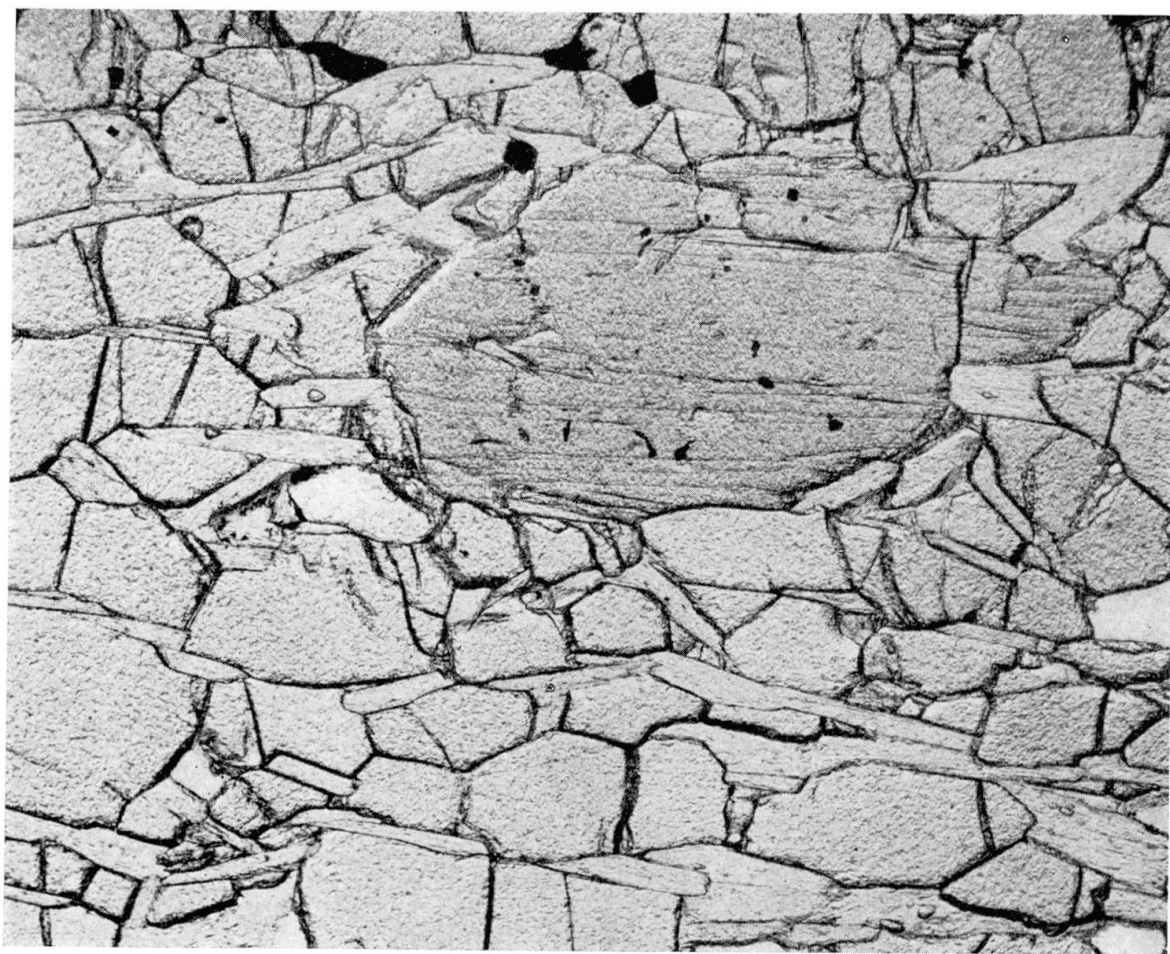


Fig. 1. Magnetite-chlorite-enstatite-forsterite schist, Val Cama. Specimen Mg 7. Magnification  $\times 48$ .

rich in hydrous phases such as talc, anthophyllite and tremolite, and these often occur in zoned veins cross-cutting the body. However, most of the ultramafic sheet is composed of magnetite-chlorite-enstatite-forsterite schist.

#### Petrography and Structural Analysis

One specimen of magnetite-chlorite-enstatite-forsterite schist, from Promegn, Val Cama, Switzerland (Coord. [Swiss net] 736.1/125.5; specimen Mg 7e), was studied in detail. The rock consists of a fine-grained, dark green matrix and of enstatite porphyroblasts forming slender prisms several cm in length oriented parallel to the foliation. In the matrix the dominant constituent is forsterite, forming a perfect mosaic of slightly elongated grains 0.5 to 1 mm in cross-section (Fig. 1). The marked schistosity of the rock is accentuated by evenly distributed colorless flakes of chlorite, strongly oriented parallel to the s-plane. Magnetite forms (up to 5 mm) xenomorphic and small idiomorphic grains evenly distributed over the rock. As a component of the matrix, the

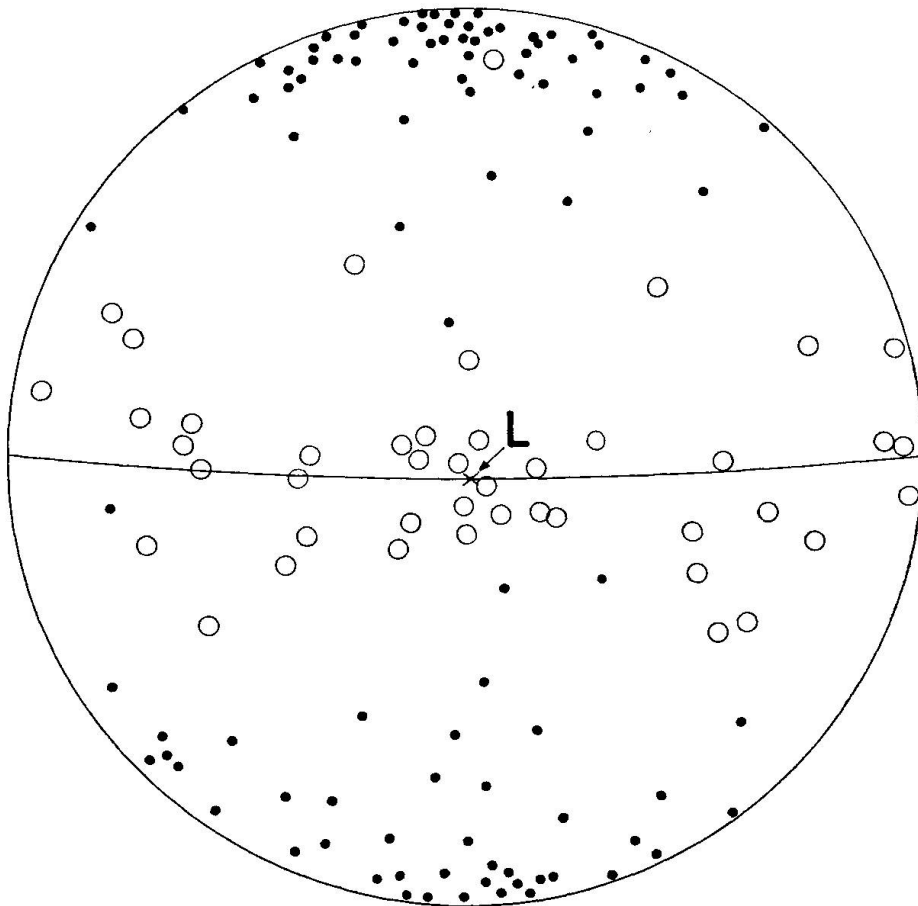


Fig. 2. Orientation diagram for  $\{001\}$  of 100 chlorites (dots) and for  $[001]$  of 50 enstatites. The great circle corresponds to the macroscopic schistosity of the rock and L marks the lineation. Specimen Mg 7, Val Cama.

enstatite is generally free of inclusions. The porphyroblastic enstatite, however, contains numerous inclusions of magnetite and forsterite aligned parallel to the foliation. Some of the large enstatites show slight undulatory extinction and occasionally ruptures filled with minor recrystallized granules. The grains of the matrix mosaic are absolutely undeformed.

An orientation diagram (Fig. 2) for (001) of the chlorites is consistent with the macroscopic foliation of the rock. In the same diagram, enstatite [001]-axes show a preferred orientation parallel to the macroscopic lineation and spread out on a great circle parallel to the s-plane. There is no detectable difference in orientation for small or large enstatite grains. Since the lineation and foliation of the ultramafic schists are in complete agreement with the structural properties of the accompanying metamorphic Mesozoic rocks, all the constituents of the matrix mosaic must have crystallized postkinematically during the Alpine metamorphism. The large enstatites are believed to have attained their shape and orientation by Alpine recrystallization.

#### Chemical Composition of Rock and Minerals

Aside from a high ratio of  $\text{Fe}_2\text{O}_3$  to  $\text{FeO}$ , the composition of Mg 7e (Table 1) is comparable to typical harzburgites in the literature. Notable features are the low contents of  $\text{CaO}$  and alkalis. The high  $\text{NiO}$  and  $\text{Cr}_2\text{O}_3$  helps confirm the ultimate igneous origin of the rock. Reduction of some of the  $\text{Fe}_2\text{O}_3$  suffices to bring normative olivine and orthopyroxene compositions into line with other harzburgites, and, at the same time, reduces total normative orthopyroxene considerably (Table 1).

Table 1. *Chemical Analysis and Norm of Magnetite-Chlorite-Enstatite-Forsterite-Schist, Promegn, Val Cama, Specimen Mg 7e*

| Weight %                |         | C.I.P.W. norms |          |                         |
|-------------------------|---------|----------------|----------|-------------------------|
|                         |         |                | Mg 7e    | Mg 7e,<br>all Fe as FeO |
| $\text{SiO}_2$          | 43.56   |                |          |                         |
| $\text{TiO}_2$          | 0.00    |                |          |                         |
| $\text{Al}_2\text{O}_3$ | 1.65    | Co             | 1.57     | 1.57                    |
| $\text{Cr}_2\text{O}_3$ | 0.52    | Or             | 0.06     | 0.06                    |
| $\text{Fe}_2\text{O}_3$ | 4.91    | Ab             | 0.25     | 0.25                    |
| $\text{FeO}$            | 4.23    | An             | 0.05     | 0.05                    |
| $\text{MnO}$            | 0.11    | Hy {           | En 31.10 | 20.42                   |
| $\text{NiO}$            | 0.40    |                | Fs 1.18  | 3.05                    |
| $\text{MgO}$            | 44.01   | Ol {           | Fo 55.01 | 62.50                   |
| $\text{CaO}$            | 0.01    |                | Fa 2.31  | 10.27                   |
| $\text{Na}_2\text{O}$   | 0.03    | Mt             | 7.12     | 0.00                    |
| $\text{K}_2\text{O}$    | 0.008   | Cm             | 0.77     | 0.77                    |
| $\text{H}_2\text{O}^+$  | 1.12    | Total          | 99.43    | 98.94                   |
| $\text{H}_2\text{O}^-$  | 0.01    |                |          |                         |
| Total                   | 100.628 |                |          |                         |

Analysts: A. G. LOOMIS, R. N. JACK, and J. HAMPEL.

Table 2. *Microprobe Analyses of Olivine, Orthopyroxene, Chlorite and Magnetite in Specimen Mg 7e*

|                                | Olivine            | Orthopyroxene     | Chlorite            | Magnetite           |
|--------------------------------|--------------------|-------------------|---------------------|---------------------|
| SiO <sub>2</sub>               | 41.3               | 57.9              | 33.17               | 0.00                |
| TiO <sub>2</sub>               | 0.00               | 0.00              | 0.00                | 0.09                |
| Al <sub>2</sub> O <sub>3</sub> | 0.00               | 0.05              | 13.68               | 0.50                |
| Cr <sub>2</sub> O <sub>3</sub> | 0.00               | 0.01              | 1.35                | 7.8                 |
| V <sub>2</sub> O <sub>3</sub>  | 0.00               | 0.00              | 0.00                | 0.25                |
| Fe <sub>2</sub> O <sub>3</sub> |                    |                   | 1.37                | 61.79 <sup>3)</sup> |
| FeO                            | 4.46 <sup>1)</sup> | 3.4 <sup>1)</sup> | 1.29                | 24.03 <sup>3)</sup> |
| MgO                            | 53.3               | 38.1              | 36.19               | 3.9                 |
| NiO                            | 0.41               | 0.065             | 0.22                | 0.82                |
| MnO                            | 0.10               | 0.17              | 0.01                | 0.18                |
| CaO                            | 0.00               | 0.03              | 0.00                | 0.00                |
| H <sub>2</sub> O <sup>+</sup>  |                    |                   | 12.33 <sup>2)</sup> |                     |
| Total                          | 99.57              | 99.725            | 99.61               | 99.36               |

*Atomic proportions:*

| Basis:           | 4 oxygens | 3 oxygens | 36 (O + OH) | 32 oxygens |
|------------------|-----------|-----------|-------------|------------|
| Si               | 0.994     | 0.988     | 6.285       | 0.000      |
| Ti               | 0.000     | 0.000     | 0.000       | 0.020      |
| Al               | 0.000     | 0.001     | 3.056       | 0.176      |
| Cr               | 0.000     | 0.000     | 0.202       | 1.843      |
| V                | 0.000     | 0.000     | 0.000       | 0.060      |
| Fe <sup>3+</sup> |           |           | 0.195       | 13.901     |
| Fe <sup>2+</sup> | 0.090     | 0.048     | 0.204       | 6.008      |
| Mg               | 1.912     | 0.970     | 10.220      | 1.738      |
| Ni               | 0.008     | 0.001     | 0.033       | 0.198      |
| Mn               | 0.002     | 0.002     | 0.002       | 0.046      |
| Ca               | 0.000     | 0.001     | 0.000       | 0.000      |
|                  |           |           | OH 15.582   |            |

*Optical properties:*

|                  |         |             |   |               |
|------------------|---------|-------------|---|---------------|
| n <sub>α</sub>   | 1.643   | 1.656       | ω | 1.579 ± 0.001 |
| n <sub>β</sub>   | 1.661   | 1.660       |   |               |
| n <sub>γ</sub>   | 1.679   | 1.666       |   |               |
| Δγ               | 0.036   | 0.010       |   | 0.004 ± 0.001 |
| 2 V <sub>γ</sub> | 88 ± 1° | 70.3 ± 0.5° |   | 10°–15°       |

<sup>1)</sup> Total iron. There may be finite amounts of Fe<sub>2</sub>O<sub>3</sub> in all three silicates in view of the presence of magnetite.

<sup>2)</sup> F and Cl were not detected at the 0.1 and 0.01% levels respectively. SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, FeO, MgO and H<sub>2</sub>O<sup>+</sup> by A. G. LOOMIS.

<sup>3)</sup> FeO and Fe<sub>2</sub>O<sub>3</sub> calculated from total iron on the basis of a stoichiometric spinel with minor ulvöspinel substitution.

Microprobe analyses of the constituent minerals of Mg 7e (Table 2) revealed their homogeneous nature, the only exception being the small magnetites present as inclusions in the orthopyroxene. Olivine (Fa 4.5) and orthopyroxene (Of 4.8) compositions lie outside the range shown by igneous ultramafics, whether layered, orogenic or xenolithic. Their magnesian compositions are a response to metamorphism under relatively oxidizing conditions. As a result, the relative proportions of NiO and FeO (or MgO) deviate from the rather

well defined trend characteristic of terrestrial olivines of igneous origin (e. g., WHITE 1966; FORBES and BANNO 1966; SMITH 1966; MOORE and EVANS 1967).

The orthopyroxene is perhaps notable for its low contents of  $\text{CaO}$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Cr}_2\text{O}_3$ . The partitioning of Ni between olivine and orthopyroxene suggests an equilibration temperature of  $1310^\circ\text{C}$  (HÄKLI 1968) a value drastically inconsistent with geological evidence<sup>1</sup>). The chlorite possesses an even lower Fe/Mg-ratio than olivine or orthopyroxene, and is a Cr-Al-variety, both elements being derived presumably from the original accessory chromite. The remaining Cr is present in a very Ti-poor magnetite, along with some of the Ni formerly present in silicate or sulphide phases.

### Conclusions

Textural relationships argue strongly that the constituent phases of the enstatite-olivine rocks of Val Cama, as typified by specimen Mg 7, attained equilibrium during the last main metamorphic episode, the Alpine metamorphism. The chemical data, in addition, are consistent with a thorough phase of reequilibration at a late stage in the metamorphic history of the rock. As indicated by the parageneses kyanite-sillimanite-muscovite and diopside-calcite-anorthite in associated pelites and marbles respectively, the grade of metamorphism corresponds to medium amphibolite facies. Enstatite and forsterite together with magnetite and chlorite occur frequently in similar ultramafic rocks in the same metamorphic zone of the Lepontine region<sup>2</sup>). In this case, it is clear that orthopyroxene is not indicative of PT conditions of the severity of granulite facies or pyroxene hornfels facies. Interestingly, enstatite is a possible phase in O'HARA'S (1967) chlorite-amphibole-peridotite "facies", which he equates with parts of the amphibolite facies. The same holds for the chlorite-peridotite "facies" of ROST (1968). However, the designation "peridotite facies" seems unnecessary and possibly even confusing.

The stability at about  $600^\circ$  to  $650^\circ\text{C}$  of the pair enstatite-forsterite as opposed to anthophyllite-forsterite or talc-forsterite, requires the activity of  $\text{H}_2\text{O}$  to be less than about 0.25 of the activity of pure  $\text{H}_2\text{O}$  (GREENWOOD 1967). These conditions are still capable of stabilizing magnesian chlorite, since the latter can go to approximately  $780^\circ\text{C}$  at four kb water pressure (FAWCETT and YODER, 1966).  $\text{H}_2\text{O}$ -activity was not uniformly low during the meta-

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<sup>1</sup>) Possibly the calibration of this thermometer is incorrect, and the dependence of K on Mg/Fe underestimated. For the exchange equilibrium between olivine and orthopyroxene  $\Delta H$  and  $\Delta G$  are apparently both large and opposite in sign, hence  $\Delta S$  would be unusually large.

<sup>2</sup>) For instance Alpe Arami, Val Gorduno (not including garnet bearing ultramafics); Corno di Gesero, west of Bellinzona; Val Agro, Verzasca; Val di Moleno; Cima Caneto, Centovalli.



morphism of the ultramafic rocks. Zoned anthophyllite-talc veins at Val Cama and other localities in the Lepontine Alps (TROMMSDORFF, ms) point to local gradients in  $H_2O$ -activity. It seems unlikely that the enstatite-forsterite rocks of the Lepontine formed by simple progressive metamorphism of serpentinite, unless the latter was rich in carbonates. Metamorphism of a dry protolith, or alternatively crystallization under conditions of high  $CO_2$ -activity (from the surrounding marbles) was much more probable.

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