

On the Significance of the Eclogite Facies in Alpine Metamorphism

With 3 figures

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Schlüsselwörter

Westalpen
Penninikum
Eklogit
Ophiolit
Krustentektonik

Zusammenfassung

Tiefemperatur-Eklogite sind charakteristische Gesteine, die bei Krustenabsenkungen unter Kontinentalrändern gebildet werden. Der Grad ihrer Bildung könnte die Geschwindigkeit der Krustenbewegung widerspiegeln. Eklogite sind Metamorphoseprodukte basaltischer Gesteine unter lokalen Bedingungen, wenn der Druck der fluiden Phase viel geringer ist, als der Belastungsdruck. Sie bilden sich entweder unter Reaktionen in festem Zustand oder an einem Intergranularfilm mit einem sehr niedrigen Wasser-Partial-Druck, möglicherweise unter Beteiligung gesättigter Lösungen im System NaCl-KCl-H₂O. Bei Eklogitbildung aus submarinen Laven ist zunächst eine Dehydrierung des basaltischen Materials notwendig. Wahrscheinlich erfolgt dies unter Bildung von Hydraten wie Lawsonit in der Glaukophan-Lawsonit-Fazies. Fortschreitende Metamorphose der Naß-Trocken-Vergesellschaftung muß zu einer Verringerung der Menge des Eklogits führen und zu einem ständigen Anwachsen des Verhältnisses von Amphibolit zu Eklogit.

Abstract

Low temperature eclogites are characteristic rocks formed during plate descent beneath continental margins. The degree of their formation may reflect velocity of plate motion. Eclogites are the product of metamorphism of basaltic rocks under local conditions where fluid pressures are much less than load pressures. Their formation involves either solid state reactions or reactions in fluid films with a very low partial pressure of water, possibly saturated solutions in the system NaCl-KCl-H₂O. Where submarine lavas are involved a preliminary step to eclogite formation must involve dehydration of the basaltic material, probably by formation of hydrates such as lawsonite in the glaucophane-lawsonite facies. Progressive metamorphism of the wet-dry assemblage must lead to reduction in the amount of eclogite and a steady increase in the ratio of amphibolite to eclogite.

Introduction

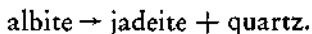
ESKOLA (1921) introduced the eclogite facies for rocks of basic composition and a dominant mineralogy of pyroxene (jadeite-diopside) and garnet (almandine-pyrope). GOLDSCHMIDT (1922) suggested that eclogite could be a major constituent of upper mantle of basaltic composition, and recently, particularly

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with the development of ideas of plate tectonics, there has been much interest in the question whether eclogites represent tectonically emplaced mantle or metamorphosed crustal material. Alternatively DOBRETSOV & SOBOLEV (1970) suggest that eclogites are intruded at depth during metamorphism. BEARTH (1959) has clearly demonstrated that some Alpine eclogites are metamorphosed submarine effusives and new oxygen isotope data supports the extension of this thesis to other occurrences. Workers on eclogites have been impressed by their association with rocks of glaucophane-lawsonite, greenschist and amphibolite facies, and COLEMAN et al. (1965) have suggested that the eclogite facies should be abolished.

As with many problems in modern petrology, a clearer understanding of the physico-chemical conditions involved would remove some of the difficulties in understanding transitions between eclogites and rocks of different facies. Up to the present time much experimental data has involved basalt-eclogite-amphibolite transitions near 1000°C . or above, so that the extrapolation required to cover the metamorphic conditions of recent mobile belts, with temperatures of perhaps $300\text{--}500^{\circ}\text{C}$., is very great. The state of confusion which has arisen is clearly illustrated by the different conclusions on the eclogite facies in two of the most recent texts of metamorphic petrology (WINKLER, 1967; TURNER, 1968).

YODER & TILLEY (1962) have shown that at temperatures near melting and with excess water, eclogites are unstable relative to amphibolites or basalts at pressures below 10 kb. GREEN & RINGWOOD (1967) studied the basalt-eclogite transition at high temperatures ($> 1000^{\circ}\text{C}$.) and proposed a phase boundary as in fig. 1. This suggests that, given favourable kinetic factors, eclogites could form in zeolite to greenschist facies conditions. ITO & KENNEDY (1970) have suggested a different boundary which projects into the high-pressure, low-temperature conditions of the glaucophane-lawsonite facies. In fact, their boundary is very close to that for the reaction:



Present field observations tend to support the ITO-KENNEDY boundary.

The other major difficulty involves the influence of water pressure on eclogite stability. This was discussed by ESSENE & FYFE (1967) and later by FRY & FYFE (1969) who showed by thermodynamic arguments based on YODER & TILLEY's data that if water is in excess amphibolite is more stable than eclogite under any reasonable crustal conditions. This is confirmed by experimental work of ESSENE, HENSON & GREEN (1970). FRY & FYFE show that an eclogite facies, in the sense of a P-T field in which eclogite is the most stable assemblage for basic rocks of normal water content, must lie in upper mantle conditions. Otherwise, eclogites represent dry, low PH_2O metamorphism inside the P-T fields of other accepted facies. Equilibrium apparent between eclogite minerals and assemblages of, say, glaucophane-schist or amphibolite facies is real, the mineral proportions reflecting the water content at any given site. In this context an additional point should be stressed. For most rock compositions amphibole bearing assemblages are stable to lower water pressures than other hydrous assemblages. Thus, not only are assemblages in equilibrium with eclogite likely to be amphibole bearing, but reactions which would produce eclogite by dehydration such as:

peridotite + amphibolite \rightarrow serpentine + eclogite
 are not possible. This is strictly correct only when both assemblages are at the same pressure and temperature, that is, under isobaric isothermal conditions.

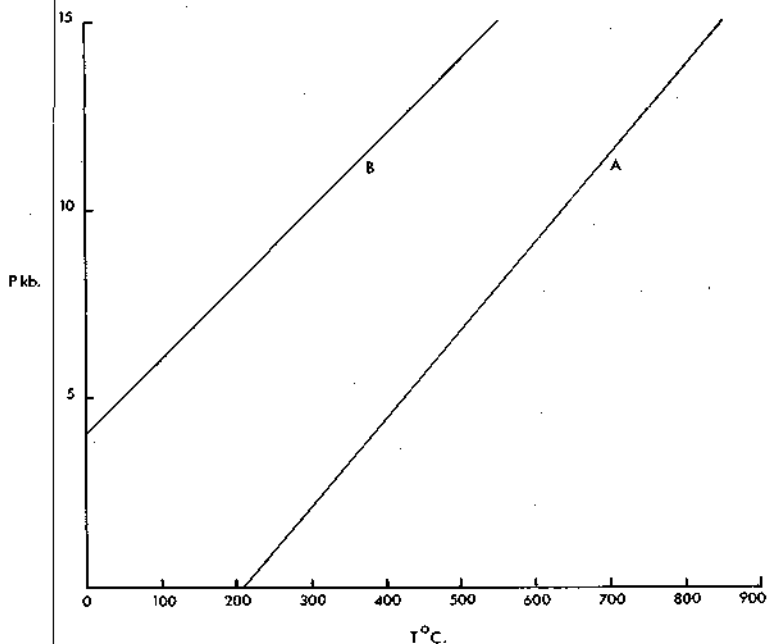


Fig. 1: Field boundary between eclogite and basalt:
 A as proposed by GREEN and RINGWOOD (1967),
 B as proposed by ITO and KENNEDY (1970).

Low and Medium Grade Metamorphism

Several authors have pointed out changes in eclogite mineral composition with changing grade (see BANNO, 1970). At lower temperatures garnets tend increasingly to almandine composition, so much so that it is doubtful whether at very low grade a bimineralic omphacite-garnet rock can have a basaltic bulk composition.

This hypothesis is difficult to verify because most minerals known to occur with omphacite and garnet at low grade are hydrates. So it may be that where, for example, eclogite and glaucophane schist coexist, their combined bulk composition is basaltic though neither this eclogite nor this glaucophane schist has itself a basaltic composition. Two points about such eclogites should be noted. Firstly, they do not disprove the possibility of an anhydrous, bimineralic eclogite of basaltic composition at the same P-T conditions. Secondly, the presence of hydrous minerals in a rock is not itself evidence of excess water or high P_{H_2O} . On the contrary, where eclogite is present the hydrous phases are

likely to be at their low P_{H_2O} limit of stability, thus providing a buffered P_{H_2O} of very low value, with P_{H_2O} increasing with temperature.

At low grades important restrictions are placed on the precursors of eclogite. BRYHNI et al. (1970) have suggested that in certain high grade metamorphic regimes, partial melting may give conditions appropriate to eclogite formation: $P_{load} = P_{fluid} = P_{melt} \gg P_{H_2O}$. At low to moderate grades such a process is not applicable. In combination with the statement above, that dehydration to eclogite by another solid assemblage is impossible, this leads to an important conclusion. It appears that at low grades eclogite can only form from another anhydrous assemblage, which must usually mean an igneous basaltic assemblage.

In general, hydrous assemblages contain more water at lower metamorphic grades, and with prograde reactions release water. Where eclogite is present the following situation exists:

1. For a given overall water content, the lower the grade, the greater is the bulk ratio of eclogitic to hydrous material. For a given proportion of eclogite, the lower the grade, the greater is the overall water content. Thus basalts which metamorphosed at low grades may give a mixture of eclogite and a hydrous assemblage, may at higher grades give no eclogite at all.

2. Prograde reactions releasing water from hydrates enable some eclogite to be hydrated. So, with increasing grade, progressively less unaltered eclogite will remain. It should be stressed that partial alteration of eclogite to amphibolite or greenschist is not indicative of retrograde metamorphism. On the contrary, it could be typical of prograde metamorphism.

Mechanism of Basalt Dehydration

As common amphibolites of basaltic composition contain about 2% water, to totally or partially form an eclogite assemblage requires that the water content of a rock is of the order of 1% or less. There is probably little difficulty in achieving such low water contents in gabbros if these are buried and suffer only slight fracturing during loading or if such rocks are introduced during deep metamorphism. The transformation of gabbroic rocks to eclogites in a glaucophane schist facies terrain necessitates very small diffusion coefficients for water; diffusion coefficients of the same order of magnitude as those in solids themselves.

It is now certain that some of the precursors to eclogites are submarine volcanics. In many cases these rocks have spilitic affinities and the work of VOGEL & GARLICK (1970) has clearly shown that some eclogites have suffered extensive oxygen isotope exchange with light meteoric waters. It is difficult to see how submarine effusives could be buried with less than 2% water. If they are to form eclogites, they must first be dehydrated and then rendered impermeable to water.

Submarine volcanics, particularly pillow lavas, will have a significant glass content and will be mixed with muds, carbonates and cherts and other fine-grained reactive materials. There are thus four low strength materials capable of facile deformation. Excess water will be expelled by compaction and the

residue will be taken up by the formation of hydrates. Such hydrates will tend to nucleate and grow most easily at reactive sites such as provided by silica gel, fine muds and glass. Thus a glassy pillow rim may be the site of low grade mineral formation while the more crystalline core may remain intact. At the same time as water moves to reactive sites the elements may also tend to move, particularly if residual fluids are saline. Potassium, an element often very low in eclogites, may migrate to clay mineral sites to generate mica.

It is perhaps reasonable to suggest that if a large fraction of dry basalt is to survive, burial and deformation should be rapid. Otherwise it is difficult to see how, in a submarine environment, it is possible to avoid a degree of hydration sufficient to preclude eclogite formation. Motion of the same order as that observed on some continental margins (10 cms./year) would be suitable. In such circumstances rocks will remain cold and hence reaction rates will be even more sensitive to fine rock structures. Thus hydrate formation at sites at a distance from dry basalt is a preliminary process in the formation of eclogite from basic lava complexes.

Lawsonite Precursors

In rocks of the Täschtal (Zermatt) a conspicuous feature of some meta-lavas is the presence of white pseudomorphs which in shape resemble lawsonite porphyroblasts in glaucophane schists (Figs. 2 and 3). These pseudomorphs are apparently widely distributed (BEARTH, pers. comm.) within the Inner Zone of the Pennine Alps (BEARTH, 1966) in which Täschtal lies. In Täschtal they consist of aggregates or intergrowths of zoisite or clinozoisite, usually with small amounts of mica, but more rarely kyanite. Chemically, replacement of lawsonite by an epidote mineral must release alumina and water, which could lead to mica metasomatism, by alkali fixation at these sites.

Lawsonite in eclogite has been recorded, together with zoisite alteration or pseudomorph formation, by WATSON (see WYLLIE, 1967, p. 263) and DIXON (1969). GREEN et al. (1968) have interpreted pseudomorphs of clinozoisite and paragonite as after lawsonite in a Colombian eclogite from which fresh lawsonite is absent. The authors believe that such an interpretation applies to pseudomorph-bearing eclogites and glaucophane-garnet rocks of the Pennine Alps.

This, together with the association of eclogites and glaucophane-lawsonite rocks in California, Urals, etc. leads the authors to believe that frequently the formation of eclogite from basalt occurs at temperatures of perhaps 300 to 400° C. where pressures are appropriate to glaucophane-lawsonite formation (5—10 kb.). With increasing temperature these hydrates break down and as progressive metamorphism takes place the amount of eclogite is reduced in the heterogeneous rock assemblage.

As an example of the role played by hydrates in eclogitic metamorphism lawsonite is superb. It is distinctive in composition, and is recognizable both as a fresh mineral and when pseudomorphed because of its porphyroblastic habit. Its stability field of pressure and temperature is not only known, but

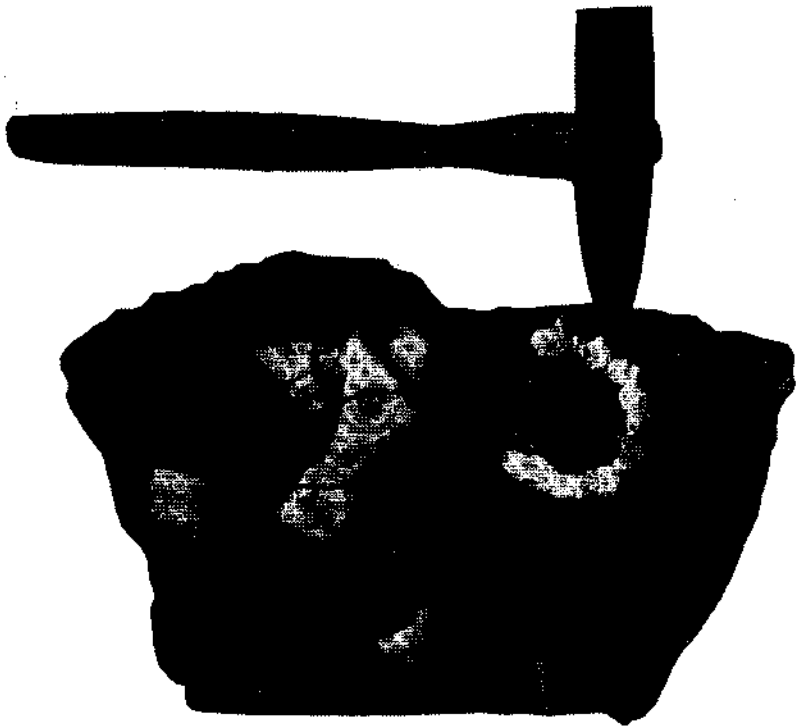


Fig. 2. Lawsonite porphyroblasts in chloritic glaucophane schist from the Franciscan of California ($\times 1$).

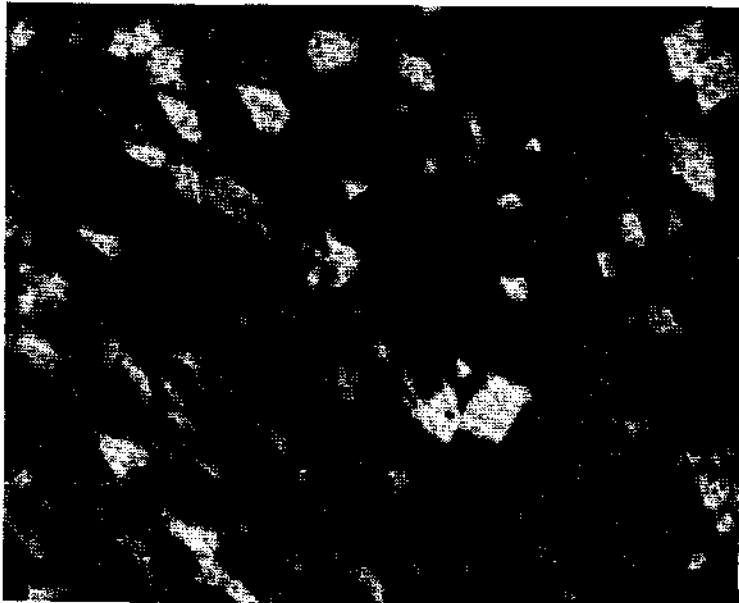


Fig. 3. Pseudomorphs of clinozoisite in garnetiferous glaucophane schist from Täschental, Switzerland ($\times 1$).

restricted to unusual conditions (hence its use as a determinative mineral of the glaucophane-lawsonite facies). Lawsonite is also one of the most water rich metamorphic minerals. Its breakdown in eclogite therefore leads to alteration of a large quantity of eclogitic minerals, perhaps in some cases destroying them completely by prograde metamorphism in a chemically closed system.

Mechanism of Eclogite Formation

From what has been said above, the simplest method of forming eclogites is to transform dry basalts or gabbros to eclogites in the solid state. If solid state reactions of this type occur, we would expect that the textures observed would be those resulting from the shortest possible diffusion paths. A plagioclase-pyroxene rock would be converted to a garnet-omphacite rock by the shortest possible exchange distances. We would anticipate that there would be a simple textural relationship between parent material and product. This is often seen, particularly in coronitic gabbros (see, for example, MILLER, 1970). It is of note that GREEN & RINGWOOD (1967) and ITO & KENNEDY (1970) were able to study the solid state reaction over a considerable temperature range (800—1300° C.) in times which vary by less than a power of ten. This suggests quite a low activation energy for the process and given geological times reaction as low as 300° C. might be possible. There are no data yet available to substantiate this point.

But there are other eclogites in the Alps whose textures have all the appearance of normal hydrothermal growth, for example large radiating groups of omphacite or mineral layering and non-random development of minerals. Such textures if not widespread could also be inherited from special igneous textures but they are often very normal in terms of wet metamorphic crystallization. Is it possible that fluids with low P_{H_2O} are present; fluids whose partial pressure of water is lower than that in equilibrium with amphiboles appropriate to the P-T regime?

From the submarine volcanic nature of some rocks transformed to eclogite, mentioned above, it is not unreasonable to suppose that salts in the NaCl-KCl system are likely to be trapped in such rocks. The presence of saline materials in fluid inclusions in rocks appears to be very common. At very high load pressures most hydrate forming reactions will not reduce P_{H_2O} below that of saturated salt solutions. Hence, such solutions may remain in the rocks, possibly as films on grain boundaries. They could be critical in catalyzing the basalt-eclogite reaction, as well as creating some of the observed textures.

The critical question to answer is whether or not the partial pressure of water in equilibrium with solid NaCl + KCl is lower than that in equilibrium with eclogite-amphibolite assemblages. Thermodynamic calculations we have performed using the data for tremolite stability indicate that it is a "touch and go" situation. At temperatures above 600° C. saline fluids are likely, below they might exist. All the data needed to perform an exact calculation are not available but the results are interesting. There could be a very strong case for searching for fluid inclusions in the minerals of low temperature eclogites. It is perhaps worth noting that the presence of such salt-solution films could be ubiquitous in

metamorphic rocks, particularly in rocks containing phases such as micas, chlorites, etc. Such films could have profound effects on the mechanical properties of metamorphic rocks.

The Significance of the Eclogite Facies

There is little doubt that eclogites can form from dry rocks within the P-T fields where wet rocks of otherwise identical composition would be glaucophane-lawsonite, greenschist or amphibolite rocks. We already recognize the necessity to distinguish silica deficient or excess assemblages. Clearly we must do the same with water, possibly recognizing degrees of deficiency.

As for the eclogite facies, it may still be too soon to restrict this facies to the upper mantle. If facies are to be treated as mutually exclusive P-T fields, each defined by stability of a different mineral assemblage in rocks with excess water, then clearly the eclogite facies must be consigned to mantle conditions. In this sense it does not exist as a metamorphic facies.

However, within certain types of metamorphic terrain eclogites have widespread distribution, though each outcrop may be small. Eclogites are easily recognized and (pace GREEN & RINGWOOD, 1967) represent, these authors believe, elevated pressures. They may be sufficiently indicative of certain plate tectonic phenomena, and resulting types of metamorphic terrains, to justify retaining the eclogite facies as a high pressure facies defined by dry rocks. Presence or absence of eclogite may be recording the velocity of plate motion. But in the end nomenclature is of little significance as long as it serves and does not restrict our developing understanding of metamorphism.

A k n o w l e d g e m e n t. The writers wish to express their deep gratitude to Prof. P. BEARTH for introducing them to the Zermatt area and freely providing from his store of knowledge, while they naturally accept responsibility for any misconceptions in this paper.

References

- BANNO, S. (1970): Classification of eclogites in terms of physical conditions of their origin: in, Phase transformations and the Earth's interior. Special volume of Physics of the Earth and Planetary Interiors. p. 405—421. North Holland publishing Comp. Amsterdam.
- BEARTH, P. (1959): Über Eklogite, glaukophanschiefer und metamorphe Pillow-laven. SMPM, 39, 267—286, Zürich.
- BEARTH, P. (1966): Zur mineralfaziellen Stellung der Glaukophangesteine der Westalpen. SMPM, 46, 13—23, Zürich.
- BRYHNI, I., GREEN, D. H., HEIER, K. S., & FYFE, W. S. (1970): On the occurrence of eclogite in Western Norway. *Contr. Mineral. and Petrol.* 26, 12—19, Springer-Verlag.
- COLEMAN, R. G., LEE, D. E., BEATTY, L. B., & BRANNOCK, W. W. (1965): Eclogites and eclogites: their differences and similarities. *Bull. Geol. Soc. Am.*, 76, 483—508, New York.
- DIXON, J. E. (1969): Unpublished Ph. D. thesis, Cambridge University.
- DOBRETSOV, N. L., & SOBOLEV, N. V. (1970): Eclogites from metamorphic complexes of the U. S. S. R.: in, Phase transformations and the Earth's interior. Special volume of Physics of the Earth and Planetary Interiors. p. 462—470.

- ESKOLA, P. (1921): On the eclogites of Norway. Videnskap. Skrift. I Mat.-Naturv. Kl., 1. Bd., Nr. 8, 1—118, Kristiania.
- ESSENE, E. J., & FYFE, W. S. (1967): Omphacite in Californian metamorphic rocks. *Contr. Mineral. and Petrol.* 15, 1—23, Springer-Verlag.
- ESSENE, E. J., HENSEN, B. J., & GREEN, D. H. (1970): Experimental study of amphibolite and eclogite stability: in, *Phase transformations and the Earth's interior. Special volume of Physics of the Earth and Planetary Interiors.* p. 378—384.
- FRY, N., & FYFE, W. S. (1969): Eclogites and water pressure. *Contr. Mineral. and Petrol.* 24, 1—6, Springer-Verlag.
- GOLDSCHMIDT, V. M. (1922): Über die Massenverteilung im Erdinnern, verglichen mit der Struktur gewisser Meteoriten. *Naturwissenschaften*, 42, S. 1—3, Berlin.
- GREEN, D. H., & RINGWOOD, A. E. (1967): An experimental investigation of the gabbro to eclogite transformation and its petrological implications. *Geochim. Cosmochim. Acta*, 31, 767—833, London.
- GREEN, D. H., LOCKWOOD, J. P., & KISS, E. (1968): Eclogite and almandine-jadeite-quartz rock from the Guajiva Peninsula, Columbia, South America. *Amer. Min.* 53, 1320—1335, Menasha.
- ITO, K., & KENNEDY, G. C. (1970): The basalt-eclogite transition and the structure of the upper mantle. *Abstracts Geol. Soc. Am. Annual meeting*, 586, Boulder.
- MILLER, C. (1970): Petrology of some eclogites and metagabbros of the Ötztal Alps, Tirol, Austria. *Contr. Mineral. and Petrol.*, 28, 42—56, Springer-Verlag.
- TURNER, F. J. (1968): *Metamorphic Petrology*. McGraw-Hill Book Co., New York etc.
- VOGEL, D. E., & GARLICK, G. D. (1970): Oxygen-isotope ratios in metamorphic eclogites. *Contr. Mineral. and Petrol.*, 28, 183—191, Springer-Verlag.
- WINKLER, H. G. F. (1967): *Die Genese der Metamorphen Gesteine*. 2nd. Edit. Springer, Berlin.
- WYLLIE, P. J. (1967): *Ultramafic and related rocks*. John Wiley and Sons Inc., New York etc.
- YODER, H. S., & TILLEY, C. E. (1962): *Origin of basalt magmas*. *J. Petrology*, 3, 346—521, Oxford.