Contr. Mineral. and Petrol. 45, 231—236 (1974)

Al and Ti Contents of Hornblende, Indicators of Pressure and Temperature of Regional Metamorphism

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Received March 25, 1974

Abstract. Chemical analyses of hornblendes from different regional metamorphic terrains and from rocks of different metamorphic grade have been compared. Hornblendes of low-pressure type are distinguished from hornblendes of high-pressure type by their Al^{VI} and Si contents. The Ti content of hornblende is shown to increase with metamorphic temperature from the greenschist-amphibolite transition facies to the hornblende-granulite facies.

Introduction

Hornblendes in this paper are called calciferous amphiboles containing more than 1.50 Ca, less than 1.00 Na, and less than 7.50 Si (on the basis of 23 O). Hornblendes are formed in a wide range of pressure, temperature, and chemical environment in metamorphic and magmatic rocks, and the variing composition of the hornblende solid solution reflects the conditions of formation. This paper is concerned with hornblendes that occur in regional metamorphic rocks of different facies and facies series.

Detailed investigations in some metamorphic areas have shown that hornblende chemistry may be related to metamorphic grade though is much more dependant on rock composition (Shido and Miyashiro, 1959; Engel and Engel, 1962; Binns, 1965; Bard, 1970). Furthermore, there are significant differences in hornblende chemistry between different regional metamorphic terrains, that means different metamorphic facies series (Shido and Miyashiro, 1959; Fabriès, 1968).

Leake (1965, 1971) recognized that hornblendes in magmatic and contact metamorphic rocks generally have lower Al^{VI} and Si contents than hornblendes in regional metamorphic rocks. He suggested that the Al^{VI} content is pressure dependant, and showed that the maximum possible Al^{VI} in calciferous and subcalciferous amphiboles increases regularly as Al^{IV} increases.

Kostyuk and Sobolev (1969), on the basis of a statistical analysis, distinguished a variety of paragenetic types of calciferous amphiboles in metamorphic rocks. They concluded that increasing pressure causes a slight increase in Al^{VI}, whereas increasing temperature causes a slight increase in Al^{IV} and alkalies. The postulated Al^{IV} increase with temperature is in contradiction to detailed investigations of Shido and Miyashiro (1959), Engel and Engel (1962), Binns (1965) and Bard (1970). These authors recognized slight increases of alkalies and Ti, and sometimes significant decreases of Al^{VI} and Fe^{3+} with increasing metamorphic grade. This may be interpreted as a change from tschermakitic composition in the low-grade amphibolite facies versus pargasitic composition in the hornblende-granulite facies. On the other hand, in the greenschist facies actinolite is formed which rapidly must change composition versus tschermakite in the amphibolite facies. The rather complex dependance of the Al content upon temperature, pressure, and chemical environment makes it difficult to use as an indicator of metamorphic grade.

Increasing Ti contents are currently admitted to be favoured by rising temperature. Shido and Miyashiro (1959), Binns (1965), and Bard (1970) recognized that the pleochroic scheme of hornblende varies as metamorphic grade varies. The colour parallel n_γ changes from blue green, green, brown green to brown with increasing metamorphic grade. This change of colour is suggested to be caused by increasing Ti relative to Fe (Binns, 1965; Raase, 1972a).

Al and Si Contents of Hornblende from Different Metamorphic Facies Series

Th Al^{VI} and Si content of hornblendes from some regional metamorphic terrains which are petrographically well-known is plotted in Fig. 1. The diagonal solid line in Fig. 1 is taken from Leake (1965) and indicates the maximum possible Al^{VI}. It can be seen that hornblendes from low-pressure regional metamorphic facies series from the central Abukuma plateau, Japan (Shido and Miyashiro, 1959), the Sierra de Aracena, SW Spain (Fabriès, 1968; Bard, 1970), the Broken Hill district, New South Wales (Binns, 1965), and the Adirondack mountains, New York (Engel and Engel, 1962), are relatively low in Al^{VI} and Si, and plot well below the line of maximum possible Al^{VI}. In these regional metamorphic series andalusite or sillimanite and cordierite occur, whereas kyanite is absent. Probably the highest pressure was reached in the Adirondack mountains. According to Engel and Engel (1962) the pressure should be in the range of 3–6 kbar, according to Turner (1968) a pressure of 3–4 kilobars is probable. Pressures less than ca. 5 kbar seem not to be sufficient to form hornblendes with maximum Al^{VI} content. Al^{VI} and Si of these hornblendes are below the broken line presumably drawn parallel to the line of maximum Al^{VI}.

Hornblendes from the Grampian Highlands, Scotland (Wiseman, 1934; Tilley, 1938; Shido and Miyashiro, 1959), the St. Gotthard region, Swiss Alps (Steiger, 1961), the Hohe Tauern, Austria (Paulitsch, 1948; Raith, 1971; Raase, 1972b), the Orange area, Massachusetts (Robinson and Jaffe, 1969), the Black Hills, South Dakota (Raychaudhuri, 1964), and the Sanbagawa belt, Japan (Banno, 1964), are formed at pressures probably above 5 kilobars. In pelitic rocks of these regions kyanite occurs. These hornblendes plot with great majority between the broken line and the line of maximum Al^{VI} in Fig. 1.

Fig. 1 permits a rather good distinction between hornblendes of low-pressure type and of high-pressure type of regional metamorphism. Hornblendes plotting above the broken line in Fig. 1 should be formed at pressures above approx. 5 kbar, and hornblendes below this line probably are formed at lower pressure. Some hornblendes plotting below the broken line may be formed at high pressure in rocks of exceptional composition.

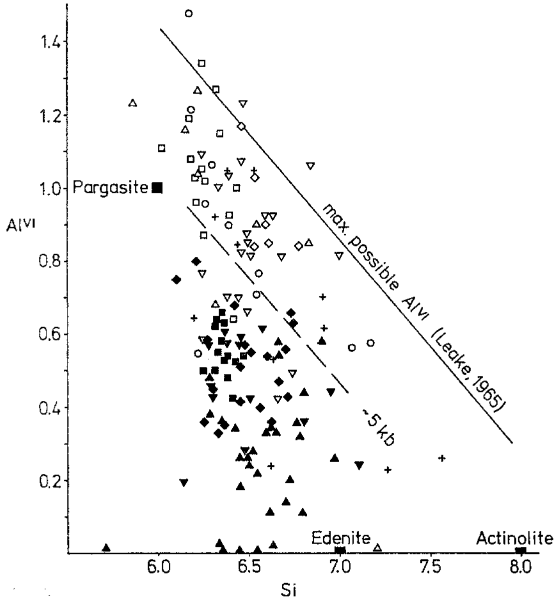

Fig. 1. Relation between Al^{VI} and Si of hornblendes (basis 23 O) from low-pressure regional metamorphic terrains (black symbols) and from high-pressure metamorphic terrains (open symbols and crosses). Symbols: ▼ central Abukuma plateau, Japan (Shido and Miyashiro, 1959); ▲ Sierra de Aracena, SW Spain (Fabriès, 1968; Bard, 1970); ◆ Broken Hill district, New South Wales (Binns, 1965); ■ Adirondack mountains, New York (Engel and Engel, 1962); ○ Grampian Highlands, Scotland (Wiseman, 1934; Tilley, 1938; Shido and Miyashiro, 1959; Matthews and Cheeney, 1968); □ St. Gotthard region, Swiss Alps (Steiger, 1961); △ Hohe Tauern, Austria (Paulitsch, 1948; Raith, 1971; Raase, 1972b); ▽ Orange area, Massachusetts (Robinson and Jaffe, 1969); ◇ Black Hills, South Dakota (Raychaudhuri, 1964); + Sanbagawa belt; Japan (Banno, 1964)

Ti Contents of Hornblende in Relation to Metamorphic Grade

Kostyuk and Sobolev (1969) did distinguish different paragenetic types of hornblende corresponding to different metamorphic facies and rock composition, but the overlapping of hornblende compositions in diagrams Al—Fe + Mn/Fe + Mg, Na + K—Al − (Na + K), and Al^{IV}–Al^{VI} used by them, generally is so large that it is impossible to relate a hornblende of a definite composition to a definite paragenetic type. A comparison of the composition of hornblendes from rocks of different metamorphic grade has shown that the clearest variation which can be related to metamorphic grade, is displayed by the Ti content.

In Fig. 2 the Ti content of hornblendes from rocks of different metamorphic facies is represented. The following metamorphic facies have been distinguished:

1. Greenschist-amphibolite transition facies (according to Turner, 1968), characterized by epidote-amphibolites which may contain albite or albite besides oligoclase.

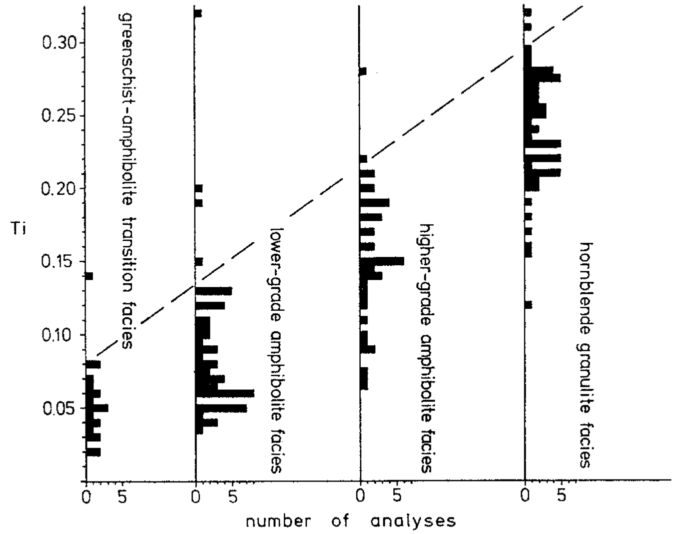

Fig. 2. Histogram of Ti contents of hornblende (on basis of 23 O) in rocks of four metamorphic facies. As to the specification of the metamorphic facies see text. The distances between the metamorphic facies on the abscissa are arranged so that the maximum Ti contents give a straight line, drawn as broken line in the diagram. Reference of analyses used: Banno (1964), Bard (1970), Binns (1965), Compton (1958), Davidson (1971), Engel and Engel (1962), Eskola (1952), Holdaway (1965), Hutton (1940), Leelanandam (1970), Mason (1962), Matthews and Cheeney (1968), van der Plas and Hügi (1961), Raase (1972b), Raith (1971), Ray (1970), Raychaudhuri (1964), Robinson and Jaffe (1969), Seitsaari (1953), Shido and Miyashiro (1959), Steiger (1961), Tilley (1938), Wiseman (1934)

2. Low-grade amphibolite facies, with amphibolites containing oligoclase-andesine and pelitic rocks containing staurolite and kyanite where the pressure was high, and andalusite where the pressure was low.

3. High-grade amphibolite facies, pelitic rocks containing sillimanite.

4. Hornblende-granulite facies.

Although there is some overlapping in Ti contents regarding neighbouring metamorphic facies, there is a clear trend of increasing Ti with metamorphic grade. The broken line in Fig. 2 presumably indicates the maximum possible Ti in hornblende of respective metamorphic facies. Values plotting above this line may come from hornblendes which have not been completely separated from inclusions of sphene, rutile or ilmenite, or may be errors in analysis. The variation of compositions below the broken line may be attributed to a deficiency of bulk rock composition in Ti, to the coexistence of different Ti-containing minerals with hornblende, and to the rough limitation of the metamorphic facies. Hornblendes from different metamorphic facies series have been included in Fig. 2, because the pressure does not seem to influence the Ti-values significantly. The maximum possible Ti of hornblendes should be essentially a function of metamorphic temperature.

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