Is the partitioning of boron between tourmaline and muscovite dependent on the crystallization environment?

Závisí rozdělení bůru mezi turmalín a muskovit na prostředí krystalizace? (Czech summary)

(8 text figs)

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According to classical mineralogical wisdom, tourmaline contains the constant amount of 3.0 boron atoms per formula unit (p. f. u.) located in trigonal (BO₃) units of the structure, and muscovite is a boron-free mineral, so that a distribution coefficient Dₓ (concentration of B in tourmaline / concentration of B in muscovite) is infinity. Recent analytical and experimental results show, however, that both assumptions do not always hold. Reviews are presented on natural and synthetic Al-rich tourmalines (olenites) containing up to 2.27 B p. f. u. of excess boron located in the tetrahedral ring site replacing silicon, and on natural and synthetic micas in the system muscovite – boromuscovite (KAl₃[BSi₃O₉](OH)₂). Like for excess-boron olenite, boromuscovite synthesis is favored by high pressures and low temperatures. The muscovite with the highest B-content found thus far coexists with excess-boron olenite (resulting in a Dₓ-value of 5.62 in a unique pegmatite that may have formed at, or been subjected to, relatively high pressures and low temperatures. However, Al-rich, very Mg, Fe poor chemical environments alone may also favor tetrahedral boron in both minerals, because – if Mg²⁺, Fe²⁺ were present – these two elements would preferentially fractionate into tourmalines of the dravite-schörer series which thus far have always been found to contain only stoichiometric trigonal boron. At the same time, boron seems to fractionate preferably into these Mg, Fe-tourmalines rather than into muscovite, at least under normal crustal pressure conditions. More experimentation is warranted to determine variations of Dₓ as a function of PTX-conditions, with the possibility that this property be used to evaluate the conditions of formation of tourmaline – muscovite pairs.

Key words: tourmaline, olenite (with excess boron), muscovite, boromuscovite, high-pressure synthesis, element fractionation

Introduction

To many mineralogists and petrologists the question posed in the title of this paper may seem inadequate or superfluous. Tourmalines as studied over many decades, although known to exhibit extensive compositional variations, had been proven to contain stoichiometric amounts of boron (3.0 atoms per formula unit) located in the triangular (BO₃) groups of their structure, thus following the general crystal chemical formula X₃Y₆Z₂[Si₆O₁₈] (BO₃)₃( OH,F)₄. Muscovites, on the other hand, also often deviating rather strongly from their ideal formula K Al₃[AlSi₃O₁₀] (OH)₂ by incorporation of other elements, are traditionally not known as boron-bearing minerals. Thus, a distribution coefficient Dₓ (concentration of boron in tourmaline) / (concentration of boron in muscovite) should necessarily be infinity.

Results of research during the 1990ies imply that this attitude is hazardous, both from the angle of tourmaline and from that of muscovite. In 1991 a new mineral boromuscovite with the ideal formula K Al₃[BSi₃O₁₀] (OH)₂ was discovered in nature (Foord et al. 1991) and has since been synthesized in the laboratory (Schreyer – Jung 1997). As a novelty to the tourmaline series, Wodara (1996) and Wodara – Schreyer (1997, 1998) reported the synthesis of an olenite, the Al ead member of tourmaline (Sokolov et al. 1986), which carries excess boron replacing silicon. An excess-boron olenite of this type has since also been found in nature (Ertl et al. 1997).

The most important approach to the new problem of boron distribution between tourmaline and muscovite would, of course, be to obtain reliable boron analyses of the two minerals, at best in coexisting pairs occurring in the same rock. Unfortunately, such data are extremely rare in the older literature, and are only gradually becoming available more recently due to the growing awareness of scientists of this open question. The other approach, experimental studies on the individual stability relations of both excess-boron tourmalines and of boron-bearing muscovites, as well as directly on the boron distribution between different tourmaline and muscovite phases as a function of PTX-conditions are either not very far advanced, or were not even started. Therefore, the discussion to follow here can only be an introduction to the problem, summarizing the results available and trying to stimulate further research. Obviously, there are severe analytical difficulties involved, because the light element boron is hard to analyze on a macroscale, but this is necessary to ascertain element distribution between truly coexisting mineral phases.

Excess-boron in tourmaline

Despite recent questioning of the validity of evidence for boron excess in tourmaline (Bloodaxe et al. 1999) this is now a well established fact. Importantly, however, excess-boron is not a potential property of all chemical varieties of tourmaline, but seems to be confined to those carrying unusually high amounts of Al, or perhaps of other trivalent cations, linked with low Li in the Y position of the tourmaline structure.

On the experimental side, an excess-boron olenite synthesized at 25 kbar, 600 °C, analyzed by electron microprobe and studied by various spectroscopic methods was
given the hypothetical structural formula (Wodara 1996; Schreyer et al. 2000) \((\text{Na}_{0.85-0.95}) (\text{Al}_{2-0.23}) (\text{Al}_{1.45-1.98}) [\text{Si}_{1.24} \text{B}_{2.27} \text{O}_{7.1}] (\text{BO}_{3})_3 \text{OH} \). The hypothetical nature of this formula does not relate to the tetrahedral coordination of the excess boron replacing Si, which was clearly demonstrated by spectroscopy, but primarily to the octahedrally coordinated Si, that could not be substantiated structurally thus far.

The only natural counterpart to this synthetic phase known thus far is the oleneite from the Stoffhütte pegmatite in the Koralpe, Styria, Austria, for which the combined results of wet chemical, electron microprobe and crystal structure analyses yielded the formula (Ertl et al. 1997) \((\text{Na}_{0.43} \text{Ca}_{0.24-0.33}) (\text{Al}_{1.23-1.33}) (\text{Li}_{1.33-0.28}) \text{Al}_6 [\text{Si}_{4.87} \text{B}_{1.22} \text{O}_{18.36}] (\text{OH})_3 \). Compared to the synthetic phase it contains a smaller amount of excess boron. The tetrahedral coordination of this excess boron was most recently substantiated by a new and independent crystal structure analysis (Hughes et al. 1999).

In contrast to these high-alumina tourmalines it was shown experimentally for the Mg end member phase dravite, ideally \(\text{Na}_2 \text{Mg}_2 \text{Al}_4 [\text{Si}_{6} \text{O}_{18}] (\text{BO}_{3})_3 \) \((\text{OH})_6 \) that – despite the presence of excess boron in the coexisting gas phase during the high-pressure syntheses – this synthetic tourmaline does not exhibit any excess boron beyond the theoretical value of 3.0 p. f. u. (Werding – Schreyer 1996).

In this same vein, it does not seem surprising that no tetrahedral boron could be found by the detailed investigations of Bloodaxe et al. (1999) on crystals of the schorl-dravite series. This obviously corroborates the earlier and much more extensive study by Povondra (1981) on 85 samples, primarily from Czechoslovakia, of that same series. Povondra (1981) had concluded that the boron atoms present in his tourmalines can only vary in the range 3.00±0.025.

Further impressive support from nature for the restriction of excess boron to alumina tourmalines varieties was most recently contributed by Kalt et al. (1999) through complete chemical analyses (except for hydrogen) of tourmalines occurring within the contact zone of the unusual Stoffhütte pegmatite that carries the excess-boron oleneite (see above). Within this contact zone against gneissose micaschists, tourmaline compositions cover the whole range of solid solutions from magnesian schorls to lithian olenites, which have excess-borone formulae similar to that given above. Most importantly, there is a positive linear relationship between the increasing amounts of excess boron per formula unit and the successive substitution of (Fe,Mg) in the octahedral Y site by Al.

The possibility of an introduction of excess boron into elbaitic tourmalines cannot be judged thus far. The careful analyses of 18 elbaites from Czechoslovakia by Povondra et al. (1985) only gave normal B values near 3.0 p. f. u. On the other hand, for the physical conditions of formation of the Stoffhütte pegmatite, a solid solution from the lithian oleneite of Ertl et al. (1997) discussed before to ideal elbaite, Na \((\text{Li}_{1.24} \text{Al}_{1.2}) \text{Al}_6 [\text{Si}_{6} \text{O}_{18}] (\text{BO}_{3})_3 \) \((\text{OH})_6 \) would seem to be viable. Most recently, Tagg et al. (1999) reported small amounts of tetrahedral boron in elbaites and elbaitic tourmalines from several pegmatites in the United States.

While there is thus no longer any doubt about the possible presence of excess boron in tourmalines of specific compositions, the next question arising is whether or not this replacement of silicon by boron in the tetrahedral site of the structure is restricted to certain PT-conditions of the experiment or of petrogenesis in nature. Unfortunately, the data available thus far from both sides are not satisfactory.

The syntheses of excess-boron olenites reported by Schreyer et al. (2000) were confined to high pressures of 10 kbar and more. A preliminary stability field (Fig. 1) based on the work of Wodara (1996) applies only to these high pressures but leaves open, whether excess-boron oleneite may, or may not, occur within the continental crust. Perhaps one might conclude by extrapolation that, if it occurs at all within the uppermost 35 km, it would be restricted to rather low temperatures. Another yet open problem discussed by Schreyer et al. (2000) refers to possible compositional variations of the synthetic olenites as a function of the PTX-conditions applied. Thus, the theoretical end-member composition of oleneite as defined by Sokolov et al. (1986), \(\text{Na}_{1.4} \text{Al}_2 \text{Al}_4 [\text{Si}_{6} \text{O}_{18}] (\text{BO}_{3})_3 \text{OH}_4 \), or \(\text{Na}_6 \text{Al}_7 \text{Al}_4 [\text{Si}_{6} \text{O}_{18}] (\text{BO}_{3})_3 \) \((\text{OH})_6 \) (Hawthorne – Henry 1999), may also appear as a stable synthetic phase, although with unknown stability limits. The natural oleneite described by Sokolov et al. (1986) from the type locality in the Kola Peninsula, Russia, seems to exhibit a normal boron content near 3.0 B p. f. u., although no direct boron analyses are available. Judging from its type of occurrence in a pegmatite cross-cutting metabasite, the pressure of its formation does not seem to have been very high. On the other hand, the excess-bo-

Fig. 1. Preliminary pressure-temperature stability field of excess-boron oleneite for high pressures based on seeded runs by Wodara (1996). Note that there may be compositional variations of excess-boron oleneite within the field of its growth (Schreyer et al. 2000).
ron olenite from the Stoffhütte pegmatite in Austria could have formed under rather high-pressure conditions. Its locality within the Koralpe is part of the Austroalpine Unit made up mainly of Hercynian crustal rocks that underwent subsequent Early Alpine subduction zone metamorphism. Following Hoinkes et al. (1999) pressures as high as 20 kbar may locally have been attained. Ertl-Brandstätter (1998) consider the occurrence to be a metapegmatite. However, the detailed field and time relations of the olenite-bearing pegmatite have not been worked out thus far, so that uncertainties remain. Nevertheless, at this stage of the investigations, the hypothesis that the excess-boron olenite of Stoffhütte formed at relatively high pressures and low temperatures is rather attractive.

**Boron in muscovite and boromuscovite**

Perhaps the earliest investigations on the presence of boron in muscovite are those of Harder (1959), who analyzed spectrographically 12 muscovite samples from various localities and obtained concentrations ranging from 11 to 1480 ppm B as equalling 0.003 to 0.46 wt. % B₂O₃. One sample that coexisted with tourmaline gave 0.016 wt. % B₂O₃. Relatively high values were from granite and pegmatite muscovites, the highest one from a muscovite of a tin deposit. Černý et al. (1995) analyzed muscovites and other micas from two tourmaline-bearing pegmatites of the Czech Republic, determining boron with an ion microprobe. They reported values between 0.048 and 0.239 wt. % B₂O₃ and one exceptionally high concentration of 1.10 wt. % from Rožná. This amounts to 0.127 B atoms p. f. u. in muscovite using the formula K₁₊₀.₅₂[Al₁₋₀.₅₂Si₁₋₀.₅₂O₁₀₋₀.₅₂](OH)₂. or to about 13 mol % of end member boromuscovite, K₁₋₀.₅₂Al₁₋₀.₅₂B₁₋₀.₅₂[Si₁₋₀.₅₂O₁₀₋₀.₅₂](OH)₂ (see Fig. 2). No record is available as to whether or not any of these muscovites occurred in direct grain contact with tourmaline or other boron-bearing minerals. At any rate, these muscovites represent primary and early products of pegmatite crystallization, probably more or less contemporaneous with tourmaline formation.

In contrast, the occurrences of boromuscovite known thus far (Foord et al. 1991; Novák et al. 1999) were clearly deposited from late hydrothermal fluids within pegmatites. They form fine-grained, snowlike coatings with thicknesses in the cm-range on primary minerals such as orthoclase and elbaite (l), either along ruptures or within miarolitic cavities. In the type locality, Little Three Mine of southern California (Foord et al. 1991), the composition of boromuscovite constitutes about 77 mol % of the ideal end member (Fig. 2), whereas at Rečice, Moravia, Czech Republic (Novák et al. 1999), boromuscovite occurs in two generations and varies compositionally between 61 and 97 mol % end member (Fig. 2; note however, that boron in the near-end-member mica was not analyzed but calculated by difference). All natural boromuscovites represent mixtures of the two polytypes 2M, and 1M in variable proportions. According to a Rietveld refinement of the Rečice material by Liang et al. (1995), boron in the tetrahedral sites is evenly distributed between the two polytypes.

Pure end-member boromuscovite was first synthesized as a single-phase product at high pressures (15–30 kbar) by Jung (1996). Only some selected results of this work were published thus far in abstracts by Schreyer – Jung (1997) and Schreyer (1999). Using the seeding technique, Jung (1996) had determined the approximate stability field of boromuscovite (Fig. 3), with the surprising result that it is actually a high-pressure mineral, requiring minimum pressures of about 5 kbar at 500 °C and 10 kbar at 750 °C. At lower pressures, that is under conditions where the normal muscovite end member is stable (compare Fig. 3), boromuscovite breaks down to K feldspar + an Al-borate (probably Al₂B₂O₇) + a boron-bearing fluid. At pressures >10 kbar and high temperatures, boromuscovite – in the presence of water – melts, or dissolves, congruently, at temperature values consistently about 100 °C lower than the upper stability limit of muscovite (Fig. 3). This type of stability field would explain readily why boromuscovite does not form under the low-pressure, medium-temperature conditions of pegmatite.

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Fig. 2. Binary system muscovite – boromuscovite showing compositions of boron-bearing natural micas (solid rectangles) as well as some of the synthetic boromuscovites (open rectangles) prepared by Jung (1996). For details on localities and references see text.

![Figure 2](image-url)
other chemical variables as well, it is clear that their cell volumes plot consistently below the linear extrapolation curves between the pure muscovite and pure boromuscovite data. The same holds for the synthetic boromuscovite solid solution of Jung (1996) containing 70 mol % of the end member. It seems, therefore, that aluminous boromuscovites exhibit an extremely non-ideal behaviour with strongly negative excess mixing volumes, which would explain the apparently preferable formation of these members of the solid solution series, both in nature and experiment, over a wide PT-range (see Fig. 4).

Importantly, the boron-richest natural muscovite known thus far was recently discovered in the Stoffhütte pegmatite of the Koralpe, which is the host rock of the excess-boron oleneite discussed in the previous section. The analyses reported by Bernhardt et al. (1999) were obtained on books of up to 20 by 1.5 cm size and yielded 2.86 wt. % of B₂O₃ equalling 32 mol % of boromuscovite end member. 2M₄ is the only polytype present. Its cell volume is also given in Fig. 5 and seems to indicate that there is no excess mixing volume in this range of the muscovite–boromuscovite solid solution series.

Discussion

In order to approach the problem of boron distribution between tourmaline and muscovite it may be convenient
to define a distribution coefficient as $D_B = (B_2O_3 \text{ in tourmaline in wt. %}) / (B_2O_3 \text{ in muscovite in wt. %}).$

Applying this to the few cases in the more recent literature where boron analyses of muscovite were reported (Fig. 2), and where these muscovites are known to coexist with tourmaline, or if not directly — occur in pegmatites that carry abundant tourmaline, the following picture arises.

For the two Moravian pegmatites Rožná and Dobrá Voda studied by Černý et al. (1995) tourmaline (schorl to elbaite) occurs among the primary minerals and appears to be often associated (although perhaps not in grain contact) with the muscovites that were analyzed. If we assume the tourmalines to exhibit stoichiometric boron contents and take for them an average $B_2O_3$-content of 10.0 wt. %, the $D_B$-values range from 208 to 9.1, the latter applying to the exceptionally high-boron muscovite of Rožná with 13 mol % boron-muscovite end member (Fig. 2).

For the unusual olinite-muscovite pegmatite of Stoffhütte in the Alps, the $D_B$-value of 5.6 is still lower, although now the $B_2O_3$-content of the tourmaline phase has risen to 16.06 wt. % (Ertrl et al. 1997).

For the two localities of boron-muscovite known thus far, it is rather questionable that an equilibrium distribution of boron has been attained between the late hydrothermal mica phases and any tourmalines of earlier generations on which these micas had precipitated. On the other hand, according to Novák (1999, Fig. 2) the stages of elbaite and boromuscovite precipitation may be relatively closely spaced in time. At any rate, if equilibrium existed, the lowest $D_B$-values (1.80–1.12) would result, again assuming 10 wt. % $B_2O_3$ for tourmaline. Judging from the facts that tourmaline stability fields extend to very low temperatures (see Fig. 1 here and Werding – Schreyer (1996) for other tourmalines) and that tourmaline may occur as an authigenic mineral, there should theoretically be no difficulty for the coexistence of boromuscovite and tourmaline (see also Novák 1999).

Thus, there may be a remarkable decrease of the boron distribution coefficient $D_B$ between tourmaline and muscovite phases from the classically assumed value of infinity, which may indeed be true for many geologic environments, to nearly unity. Once understood and calibrated, this property carries the potential to be used for evaluating the conditions of formation or equilibration of tourmaline-muscovite mineral pairs and their enclosing rocks.

The most important question to be solved is, of course, which parameters can influence the distribution coefficient $D_B$. Temperature and especially pressure are obvious candidates, if the conditions of formation of the Stoffhütte, Koralpe, pegmatite really involved relatively high pressures. In addition, there may be bulk compositional effects, above all the amount of boron in the rock-forming system, for pegmatites the boron activity of the fluid phases during their cooling history. In a very qualitative empirical and partly hypothetical way, the sketch of Fig. 6 may help to initiate discussion.

The abscissa of Fig. 6 separates Mg, Fe-rich mafic silicate minerals on the left side from Al-rich salic silicate minerals on the right side. For boron-free systems or rocks along the top line it is well known that the two mineral groups can coexist. If boron is added along the ordinate axis downwards, most of the mafic minerals are being converted, as a function of growing boron activity, into Mg, Fe-tourmalines. The experiments of Frondel and Colette (1957), who reacted various kinds of silicate mineral grains and magnetite with borate solutions, may serve as an example for this kind of boron metasomatism. At moderate boron activities these tourmalines coexist with the boron-free mafic minerals. It should be remembered here, that biotites may also incorporate boron: Stubic – Roy (1962) as well as Hazen – Wones (1972) were able to synthesize philogepite phases, in which all tetrahedral Al is replaced by boron. However, no biotites with high B-values were ever described from nature, and the boron concentrations found in biotite by Harder (1959) are in the low ppm range. Therefore, possible solid solubility is ignored in Fig. 6. Among the salic minerals, it is clear that all the Al in albite may be substituted by boron to form the feldspar reedmargnerite (for further information see Werding – Schreyer 1996; Schreyer – Werding 1997). On the other hand, petrographic work on the pegmatite from Stoffhütte, Austria,
by Kalt et al. (1999) indicates that the sodic plagioclase of this rock is being partly replaced by myrmekitic intergrowths of quartz with the excess-boron olenite cited earlier in this paper. Thus, plagioclase is apparently not stable in the presence of excess boron, and the two minerals, olenite and plagioclase, may coexist at intermediate boron activities. Between muscovite and boromuscovite a series of solid solution exists as discussed in the last section. Pure Al-silicates like kyanite or andalusite carry no, or only trace amounts of, boron (Harder 1959), but with increasing boron activity growing amounts of the boron-bearing mineral domortierite (Weding – Schreyer 1996) will coexist. From the analytical work of Kalt et al. (1999) on samples from the Stoffhütte pegmatite it is now clear that a complete solid solution exists between magnesian schorl and excess-boron olenite (see Fig. 6). The other salic boron minerals shown at the lower right corner of Fig. 6 (reedomgernerite, dumortierite) are probably compatible with the Mg, Fe-tourmalines. Finally, it is evident from many rock types that these Mg, Fe-tourmalines may also coexist with the boron-free salic minerals, so that the diagonal “tie line” is justified. On the other hand, no coexistence seems to be possible between the boron-free mafic minerals in the upper left corner with the salic boron minerals in the lower right.

While the sketch of Fig. 6 yields a first survey of compatibility and solubility relations between the minerals involved, it is unable – because of its multicomponent, multiphase nature – to depict element fractionations between the coexisting minerals and solid solutions. Thus, for the topic of this paper, a closer approach is necessary. The chemical system comprising all the tourmalines of the base line of Fig. 6 together with the muscovite-boromuscovite solid solutions (Fig. 2) includes at least eight components (Na₂O, K₂O, MgO, FeO, Al₂O₃, B₂O₃, SiO₂, H₂O), so that the construction of simplified concentration triangles for depicting phase relations becomes very difficult. Therefore, in Fig. 7 two relevant partial systems of solid solution are selected and compared to each other. In the lower portion, the system muscovite-boromuscovite (Fig. 2) with some of the known micas is shown again, whereas the upper portion represents a simplified series of solid solution between ideal olenite and the theoretical end member resulting solely from substitution of tetrahedral Si by B⁺H as discussed by Schreyer et al. (2000), including (in projection) the excess-boron olenite synthesized by these authors as well as the natural excess-boron olenite described from the Stoffhütte pegmatite (Ertl et al. 1997). The only “tie line” drawn is that of the olenite – muscovite pair of the Stoffhütte pegmatite with its D₈⁺ value shown in between. The remaining D₈⁺ values given ranging from infinity to ideal olenite – muscovite to 2.51 for the theoretical end member excess-boron olenite with boromuscovite are calculated, but may not apply under any condition. Here is where experiments are needed.

In Fig. 8 a similar plot is presented for the two partial systems muscovite – boromuscovite and the Mg, Fe-tourmalines with the end member dravite as an example. According to present knowledge (see above) there is no excess boron in these tourmalines. Depending on the boron contents of the micas, the D₈⁺ values would vary from infinity to 1.15, but – except for the Rozna muscovite – such mica-tourmaline coexistences were not discovered as yet. The Koralpe muscovite is not plotted here, because no grain contacts exist for this mica with a Mg, Fe-tourmaline. However, such observations may become available in the future from boron analyses of coexisting muscovites and tourmalines in the contact zone of this pegmatite.

Fig. 6. Simplified sketch showing compatibility (thin lines) and solid solubility relations (heavy lines) between various groups of boron-free and boron-bearing silicate minerals. For detailed discussion see text. Note incompatibility of mafic minerals in the upper left with the boron-rich phases in the lower right. This is not a phase diagram!
In summary, it is quite clear that boron partitioning between tourmaline and muscovite may vary widely, but the reasons are only poorly understood at present. The following influences should be considered:

1. High pressures may favor boron introduction into the muscovite phase and into the silicon position of tourmaline, which would be in accordance with the crystal chemical prediction of preferential boron fractionation into tetrahedral sites with increasing pressures. The unique Stoffhütte pegmatite from Koralpe, Austria, may be an example.

2. A potential temperature influence is expected to be in the direction that lower temperatures would favor boron introduction into both minerals, as shown by the boromuscovite stability field (Fig. 3).

3. The bulk chemistry of the rock excluding boron may also be important (compare Fig. 5), so that highly aluminous, Mg, Fe-poor systems favor the introduction of boron into muscovite as well as of excess boron into tourmaline (olenite) as also suggested by the Stoffhütte pegmatite. On the other hand, in Mg, Fe-bearing systems, boron may preferentially fractionate into the dominantly Mg, Fe-rich tourmalines. Or — looking at the picture from the side of element distribution of the basic components — Mg and Fe in such systems may be preferentially partitioned into the tourmaline phase to form essentially members of the
Závěs rozdělení bůru mezi turmalín a muskovit na prostrédí krystalizace?

Je známo, že rozdělení bůru mezi turmalín a muskovit může kolísat v širokém rozmezí, ale důvody pro tuto skutečnost nejsou zatím příliš jasné. Můžeme uvážovat následující vlivy:

(i) Vysoký tlak upřednostňuje vstup bůru do muskovitu a do tetradérické pozice krému v turmalínů, což by mohlo být v souvislosti s krystalochimickými předpoklady přednostní frakcionace bůru do tetradérické pozice se vzájemněm třem. Unikátní Stoffbund typ muskovit v Alpách (Koralpe) v Rakousku může být typickým příkladem.

(ii) Lze očekávat, že pokles teploty upřednostní vstup bůru do obou minerálů, jak je ukázáno na poli stability muskovitu (Obr. 3).

(iii) Čelekované složení horniny, někdeji na bůru, může to být také důležité (srovnajte Obr. 6). Vysyce hlinité struktury obsahující Fe a Mg je bůr frakcionován do převážajících Fe-Mg-turmalínů. Nebo z přehledu distribuce základních komponent, Fe a Mg mohou být v takových systémech přednostně frakcionovány do turmalínů a produkovat tyrannické feny skorovitým druhy hlinité (olenitové) komponenty. Tížový mechanismus frakcionace by mohl vysvětlit skutečnost, proč je olenit v přírodě tak významný.


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