

## ON THE OCCURRENCE AND DISTRIBUTION OF BORON IN PEGMATITE

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**Abstract.** Spectrochemical analyses show that a large number of pegmatite deposits are relatively rich in boron, which is highly concentrated — up to several tenths of a percent — in minerals containing beryllium or rare earth elements (including thorium) or both, as major constituents. Certain rare muscovites are also enriched in boron. The results are discussed.

Only a few mineral species containing boron as a major constituent are known to occur in pegmatite. Of these tourmaline varieties are by far the most common. In rare cases danburite, hellandite (OFTE-DAL, 1964), or homilite may occur in fair quantities; other species are hardly worth mentioning. Relatively few pegmatite deposits carry tourmaline or other boron minerals. In Norway, for instance, the occurrence of such pegmatites is largely restricted to certain districts.

Spectrochemical analyses have revealed that many other pegmatites contain boron in significant quantities, and that the boron is then largely concentrated in certain types of minerals.

The spectrograms were taken with a Hilger "Large" quartz spectrograph with a rotating stepped sector in front of the slit, the arcing conditions and other details of the procedure being carefully standardized. Highly purified carbon electrodes (Ringsdorff RW-I) were used; test spectrograms of the empty carbons did not show any trace of the sensitive B-lines (2497.7 and 2496.8). For a preliminary survey a series of spectrograms of the pure mineral powders were taken. A number of these showed relatively very strong B-lines, too strong for convenient intensity readings, and the corresponding specimens were

selected for quantitative B determinations. Two sets of standard mixtures were prepared. Both contain tourmaline in quantities to give  $B_2O_3$ -contents of 1%, 0.1%, 0.01%, but the base substance is amazonite in the one set and apatite in the other. Working curves were constructed from repeated exposures of both sets, and both curves are well represented by sloping straight lines. But the apatite mixtures give more consistent results than the amazonite mixtures, partly because the amazonite appears to weaken the B-lines considerably (probably due to the large quantities of alkalis present), partly because the phosphorus lines from the apatite make very convenient internal intensity standards. Nevertheless some of the results obtained by means of the amazonite mixtures appear to be quite reliable and are utilized below. Naturally the mineral samples were diluted with amazonite or apatite respectively before arcing, mostly in the ratio 1:4. The quantitative determinations may be taken as accurate to  $\pm 20\%$ , but such an accuracy can be claimed only for part of the data utilized in the table. Many samples were examined in the pure state only (without admixture of amazonite or apatite) especially those which contain less  $B_2O_3$  than 0.1%, as they would give too weak B-lines if diluted. By comparing exposures of pure and diluted samples in a number of cases an approximate working curve for pure samples was constructed, and by means of this the spectrograms of the pure samples were evaluated. The figures obtained in this way are naturally less accurate than the others. But they doubtless give a correct general picture. In addition, for reasons given below, the table does not in general record individual values.

*Boron concentrations in Norwegian pegmatite minerals.*

Concentrations not recorded (0) are lower than about 0.01%.

	$B_2O_3, \%$
Yttrofluorite. Hundhomen, Tysfjord .....	0
Chrysoberyl. Nateland, Iveland .....	0
Ilmenite. Iveland .....	0
Davidite. Iveland .....	0
Betafite. Kragerø .....	0.03
Microlite. Spro, Nesodden .....	0.05
Landås, Iveland .....	0.3
Columbite. 15 samples from 11 localities .....	0

Euxenite. 44 samples from 22 localities. Range: 0.02–0.8.	
	Average 0.2
Polymignite. Stavern .....	0.05
Fergusonite. 6 samples from 3 localities. Range: 0.02–0.2.	
	Average 0.1
Samarskite. 20 samples from 7 localities. Range: 0–0.3.	
	Average 0.1
Yttrotantalite. 5 samples from 4 localities. Range: 0–0.1.	
	Average 0.03
Uraninite. 3 samples from 2 localities.....	0
Xenotime. 3 samples from 3 localities .....	0
Monazite. 6 samples from 4 localities. Range: 0–0.1. Average	0.03
Phenacite. Kragerø .....	0.1
Topaz. 17 samples from several localities.....	0
Garnet. Langesundsfjord and Tørdal .....	0
Allanite. 5 samples from 4 localities. Range: 0–0.1. Average	0.04
Zircon. 7 samples from several localities .....	0
Alvite. Kragerø.....	0.3
Thorite. 30 samples from 13 localities. Range: 0–0.5. Average	0.2
Wöhlerite. Langesundsfjord .....	0
Guarinite. Langesundsfjord .....	0.2
Johnstrupite. Langesundsfjord .....	0.3
Mosandrite. Langesundsfjord. 3 samples .....	0.3
Sphene (Yttrotitanite). Kragerø and Snarum .....	0.03
Thortveitite. Iveland. 3 samples. Range: 0–0.1. Average..	0.03
Thalenite. 3 samples from 3 localities .....	0.05
Astrophyllite. Gjerdingen, Nordmarka .....	0
Eucolite. Langesundsfjord .....	0?
Catapleite. Langesundsfjord. 2 samples .....	0
Beryl. Tørdal. 3 samples .....	0
Aegirine. Langesundsfjord. 3 samples .....	0
Barkevikite. Langesundsfjord. 2 samples .....	0
Meliphanite. 6 samples from 3 localities .....	0.5
Leucophanite. 5 samples from 3 localities .....	0
Biotite. 3 samples.....	0
Muscovite, ordinary .....	0
Muscovite, pink. 7 samples from 4 localities. Range: 0–0.1.	
	Average 0.03

Lepidolite and Li-muscovite. Tørdal, 4 samples .....	0
Feldspars .....	0
Nepheline (Elæolite). Langesundsfjord .....	0?
Gadolinite. 81 samples from 22 localities. Range: 0.05—2.5.	
	Average 0.2

Some comments on the table:

*Columbite.* The localities are in the Moss district (4), at Spro in Nesodden, in the Kragerø district, in Gjerstad, in Søndeled, in Iveland (2), at Hundholmen in the Tysfjord. One sample from Tangen near Kragerø gave visible B-lines; this sample was relatively rich in rare earth elements.

*Euxenite.* A few blomstrandine and polycrase specimens are included. The localities are at Spro in Nesodden, in Sannidal, in the Arendal district (3), in Iveland—Evje (14), in Hidra (Hitterø) and nearby districts (3). Repeated B-determinations on materials from the same locality, or even from the same specimen, sometimes disagree to such an extent that the variations surpass any reasonable limits of error. Thus the distribution of B may apparently be very uneven. It was thought that the B-concentration might be higher near the surface of a crystal than in the core, and a few large crystals were examined to test this possibility. However, the results were indifferent: in one case there was a slight enrichment near the surface, but in other cases no real difference was observed. At any rate it is obvious that a single B-determination can not be taken as representative of the locality in question. Therefore only the range of observed concentrations and the arithmetic mean are given in the table.

*Fergusonite.* The localities are in the Moss district, in the Arendal district, and at Høgetveit in Evje. 3 samples from Høgetveit agree well in giving  $B_2O_3$ -contents between 0.1% and 0.2%, but a fourth sample gave a much lower concentration. Also here local variations are conspicuous.

*Samarskite* and *Yttrotantalite.* The localities are in the Moss district (6), near Arendal, at Bjortjern in Mykland, in Iveland (3). Samarskite appears to be on the average richer in B than yttrotantalite, but the examined material, especially of yttrotantalite, may not be sufficient to justify such a conclusion.

*Monazite.* Only 2 samples showed notable B-contents: Tolåsen near Moss and Narestø near Arendal.

*Allanite.* The localities are in the Kragerø and Arendal districts, in Evje and at Hundholmen. Only the samples from Kragerø and Evje showed notable B-contents.

*Thorite.* A few orangite specimens are included. The localities are in the Langesundsford (2), in the Bamble—Kragerø district (2), in Søndeled, in Gjerstad, in the Arendal district (3), in Evje, in Hidra (Hitterø) and nearby districts (3). Nearly all thorite samples show  $B_2O_3$ -contents of 0.1% or more.

*Thortveitite.* Only one of the samples (Torvelona) showed a notable B-content.

*Meliphanite.* The localities are 2 in the Langesundsford (in the "Melinophanzone" of BRØGGER) and 1 at Nalum near Stavern. The B-content appears to be remarkably constant; all quantitative determinations agree in giving values close to 0.5%  $B_2O_3$ .

*Leucophanite.* The localities are 2 in the Langesundsford and 1 in Lågendalen.

*Muscovite.* The pink varieties come from cleavelandite pegmatites in Tørdal, in Iveland and at Ågskaret in the Holandsfjord. The Tørdal and Holandsfjord samples are particularly rich in B. The latter locality is a granite pegmatite with abundant tourmaline, and its pink mica appears to contain more than 0.1%  $B_2O_3$ . The pink micas in question seem to be very late products.

*Nepheline.* Weak B-lines are visible in the spectrogram, but the crystals (elæolite) are rich in inclusions and the B-content might belong to these.

*Gadolinite.* The localities are in Tørdal, in Gjerstad, in the Arendal district, in Iveland—Evje (14), in Hidra (Hitterø) and nearby districts (4), at Hundholmen. As with the euxenites the B-concentrations sometimes appear to vary strongly within a single deposit or a single specimen. Every one of the 81 samples examined showed a significant B-content, in the majority of cases between 0.05% and 0.5%  $B_2O_3$ . The gadolinite from Gjerstad (Gryting) is exceptional containing about 2.5%  $B_2O_3$ , but it demonstrates that considerable quantities of boron (possibly still higher percentages) may be found concentrated in gadolinite.

*Helvine.* Samples from Lågendalen and Holandsfjord give distinct B-lines, especially one from the latter tourmaline-rich deposit. The B-contents may be of the order of 0.1%.

*Discussion.* From the data given above it appears that boron is a very common minor constituent of pegmatite deposits, and that boron may be highly enriched — up to 0.1% or more — in certain kinds of pegmatite minerals. These are, apart from tourmaline etc., species which contain beryllium (e.g. meliphanite) or rare earth elements including thorium (e.g. euxenite, thorite) or both (gadolinite) as major constituents. Pegmatite bodies which carry one or more of such species can nearly always be shown to contain boron in significant quantities. On the other hand it must be borne in mind that common pegmatite minerals whose boron contents are below the limit of detection, might possibly contribute notably to the total boron content of a deposit because of their great abundance. But this is not very likely since minerals like feldspars, quartz and common micas are known to be extremely poor in boron.

The great majority of the pegmatite localities which have yielded material for the present investigation are not known to carry tourmaline. It appears that many ordinary granite pegmatite bodies might have carried tourmaline in the absence of rare earth minerals. A very large number of Norwegian granite pegmatite bodies must be relatively rich in boron. The majority of these are situated in Precambrian gneiss areas. Their boron contents may be in support of the interpretation of their ancient country rocks as meta-sediments of marine origin. In the Langesundsfjord area marine sediments occur in the near vicinity of the pegmatite veins. The "Melinophanzone", which includes all known occurrences of meliphanite and homilite in the Langesundsfjord and also the nordenskiöldine locality (BRØGGER, 1890, 157), is about 200 m wide and runs roughly parallel to the larvikite boundary a few hundred metres distant from the present outcrops of Silurian sediments (BRØGGER, l.c., Taf. XXIX). It looks as if the pegmatite veins in this zone were due to media which have been in contact with particularly B-rich Silurian horizons. Note that in leucophanite, which is in every respect closely similar to meliphanite and which does not occur in the Melinophanzone, no boron was detected. Apparently pegmatites outside the Melinophanzone have formed from material which has not passed through B-rich sediments. Some of these pegmatites, notably Låven, are even closer to the larvikite boundary than the Melinophanzone, but the immediately adjacent sedimentary rock is sandstone, which is not expected to be notably enriched in boron.

Not very much can be said about the mechanism of incorporation of boron in the minerals in question. The substitution of  $B^{3+}$  for  $Be^{2+}$  is to be expected from a crystal chemical point of view; it would even represent a pronounced "capture" process since the B-ion is even smaller than the Be-ion. It is natural to explain the B-content of meliphanite in this way, and also that of phenacite which occurs in a very B-rich environment. In gadolinite this substitution is probably also important, but here we also have to consider the nearly invariable association of boron with rare earth elements, which will be discussed below. Only a few specimens of beryl, the most common Be-mineral, have been examined. No boron was found in these, although the gadolinite from the same locality was fairly rich in boron. It is probably not justified to conclude that beryl is unable to incorporate boron. Beryl often occurs so abundantly in a deposit that a reasonable total content of boron would represent very low concentrations only. A pegmatite carrying both beryl and tourmaline might allow the question to be settled, but the writer does not know of any such pegmatite. The opposite substitution, Be for B (which would represent an "admission"), appears to be less common although homilite and hellandite have been shown to contain beryllium. Tourmaline specimens from several localities did not show any trace of Be, not even in cases (Kragerø and Holandsfjord) where Be is known to be present in the environment.

The striking enrichment of boron in almost every specimen of rare earth pegmatite minerals is not easily explained. A closer review of the material shows that this enrichment is largely restricted to metamict (or otherwise altered) specimens. Crystalline minerals like yttrifluorite, xenotime, monazite, thortveitite, uraninite only exceptionally contain notable quantities of boron. (In xenotime and monazite one might consider the substitution of B for P, but this does not seem likely because of the large difference in charge.) Gadolinite is sometimes perfectly crystalline, in the present case particularly the material from Tørdal. Actually this material is considerably poorer in boron than the majority of the other examined (metamict) gadolinite specimens. Also the uneven distribution of boron in many metamict specimens, referred to above, indicates a connection between the alteration process and the boron enrichment. Non-metamict specimens of the fairly common pegmatite minerals euxenite-blomstrandine, fergu-

sonite, samarskite-yttrotantalite, thorite, etc. do not seem to exist, and it is not possible to tell whether or not such specimens might contain boron. But at any rate high contents of boron appear to be typical of all metamict pegmatite minerals. If enrichment in boron is connected with the breakdown of the crystals, crystal chemical considerations are of course irrelevant. In addition these minerals contain no atoms for which boron is likely to substitute. The boron must apparently be diffusely distributed in the metamict medium. It is not clear why boron should be attracted from the environs by this medium. The small ionic size and rather high charge might possibly be significant. The radioactivity of these minerals (which is supposed to be essential to the process of metamictization) brings about "auto-oxidation": an O-ion is liberated for each transition U—Pb or Th—Pb. These O-ions might possibly combine with B-ions from the environs. But the efficiency of this process is obviously negligible in the present cases.

Micas from pegmatite deposits do not in general contain boron in excess of a few ppm. Exceptions are some very special muscovites which may occur in cleavelandite-quartz pegmatite. Probably they have formed at a stage when boron was relatively abundant in the environment. At any rate they demonstrate that dioctahedral micas may in certain circumstances contain boron in concentrations of 0.1% or more. As to the sites of the B-ions a definite statement is hardly possible. Micas containing boron as a major constituent have been synthesized (STUBICAN and ROY, 1962). The formulas assigned to these show B in stead of Al in the tetrahedral positions. Also the B-content of the chlorite mineral manandonite has been interpreted in this way (STRUNZ, 1957). In the present case, however, it is tempting to propose that B may occupy some of the empty octahedral positions in dioctahedral mica. These empty octahedra appear to be able to accept ions of highly varying sizes (ROSENGVIST and JØRGENSEN, 1963). This proposal is also supported by the fact pointed out by HARDER (1959) that in the majority of cases dioctahedral micas contain substantially higher amounts of boron than trioctahedral micas.

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