

# Bastnäsite-(Nd), a new Nd-dominant member of the bastnäsite group from the Stetind pegmatite, Tysfjord, Nordland, Norway

RITSURO MIYAWAKI<sup>1,\*</sup>, KAZUMI YOKOYAMA<sup>1</sup> and TOMAS A. HUSDAL<sup>2</sup>

<sup>1</sup> Department of Geology and Paleontology, National Museum of Science and Nature, 4-1-1 Amakubo, Tsukuba 305-0005, Japan

\*Corresponding author, e-mail: miyawaki@kahaku.go.jp

<sup>2</sup> Veslefrikk 4, 8028 Bodø, Norway

**Abstract:** Bastnäsite-(Nd), ideally (Nd,La,Ce)(CO<sub>3</sub>)F, occurs in the Stetind pegmatite, Tysfjord, Nordland, Norway, in association with bastnäsite-(Ce), calcioancylite-(Nd) and/or kozoite-(Nd), stetindite, vyuntspakhkrite-(Y) and Y-bearing fluorite. It forms 20 μm wide zones in outer parts of tabular bastnäsite-(Ce) crystals. Bastnäsite-(Nd) is translucent and is pale purplish pink to colourless with a vitreous, greasy or pearly lustre. Bastnäsite-(Nd) has a Mohs hardness of 4–4½, is brittle, and shows an indistinct cleavage on {10 $\bar{1}$ 0} and an uneven fracture. The calculated density and mean refractive index are 5.23 g cm<sup>-3</sup> and 1.76, respectively. It is hexagonal, space group *P62c*, *a* = 7.0792(13), *c* = 9.721(2) Å, *V* = 421.92(18) Å<sup>3</sup> and *Z* = 6. The five strongest lines in the powder XRD pattern are [*d*(Å), *hkl*]: 4.86, 71, 002; 3.54, 70, 110; 2.86, 100, 112; 2.04, 31, 300 and 2.00, 48, 114. The electron-microprobe analyses lead to the empirical formula (on the basis of *M* = *C* = 1 *apfu*): Nd<sub>0.353</sub>La<sub>0.253</sub>Ce<sub>0.251</sub>Pr<sub>0.086</sub>Sm<sub>0.037</sub>Gd<sub>0.016</sub>Y<sub>0.004</sub>Dy<sub>0.001</sub>CO<sub>2.978</sub>F<sub>1.044</sub>. Bastnäsite-(Nd) is a member of the bastnäsite group, and is the Nd-dominant analogue of bastnäsite-(Ce), bastnäsite-(La) and bastnäsite-(Y). Bastnäsite-(Nd) formed as a late phase in cavities in Y-bearing fluorite, which in turn is a late formation of the pegmatite.

**Key-words:** bastnäsite, new mineral, neodymium carbonate fluoride, rare-earth elements, Stetind (Norway).

## 1. Introduction

The bastnäsite group consists of several members of hexagonal rare earth carbonate fluorides and hydroxides with ideal formula of *M*(CO<sub>3</sub>)*X*, where *M* = REE (rare earth elements) and minor Th, and *X* = F or (OH). Ce and F are the most dominant constituents, with bastnäsite-(Ce) being by far the most common member. Bastnäsite-(Ce) contains a variety of lanthanoids with enrichment in the light rare earth elements (LREE), and is one of the main resources of Ce and the other REE over the world. Two other F-rich members are known: bastnäsite-(La) (Vainshtein *et al.*, 1961) and bastnäsite-(Y) (Mineev *et al.*, 1970). The amount of Nd is usually considerable and sometimes comparable to Ce in bastnäsite-(Ce), as well as bastnäsite-(La) and bastnäsite-(Y). It has been known that Nd dominates over Ce in some specimens. Kolitsch *et al.* (1997), Kolitsch (1997) and Kolitsch *et al.* (2007) described bastnäsite-(Nd) as tiny off-white spherulitic aggregates from the Clara mine in Germany, but a proposal for a new mineral species was not submitted (U. Kolitsch, pers. comm., 2010).

One of the authors (T.H.) noticed that pinkish yellow crystals collected in the Stetind pegmatite, Tysfjord, Nordland, Norway, sometimes showed elevated Nd-content in his preliminary EDS analyses. An X-ray diffraction study on such a crystal revealed it to belong to the bastnäsite group,

and an electron microprobe analysis verified the Nd- and F-dominance. This Nd-analogue of bastnäsite-(Ce) and the name bastnäsite-(Nd) were approved by the Commission on New Minerals, Nomenclature and Classification, International Mineralogical Association (IMA-CNMNC) (2011–062). The mineral name bastnäsite-(Nd) follows the Levinson rule (Levinson, 1966) recommended by the IMA-CNMNC. Type material is deposited in the collections of the National Museum of Nature and Science, Japan, registration number NSM-MF15494.

## 2. Occurrence

Bastnäsite-(Nd) occurs in the Stetind pegmatite, Tysfjord, Nordland, Norway (68°10'15.20" N 16°33'10.65" E). The pegmatite belongs to a series of quartz-microcline NYF pegmatites found in the Tysfjord granite, a 1800 Ma old granitic orthogneiss, deformed during the Caledonian orogeny (Andresen & Tull, 1986). Lenticular bodies of Y-rich fluorite are a characteristic feature of these pegmatites, and the fluorite from the Stetind pegmatite is particularly rich in inclusions of various REE-minerals (Husdal, 2008). The new species stetindite (Schlüter *et al.*, 2009) and atelisite-(Y) (IMA 2010–065; Malcherek *et al.*, 2012) were also found in Y-rich fluorite from the Stetind pegmatite. Bastnäsite-(Ce) is very common in this

fluorite as well-formed, platy crystals in the numerous small cavities. In some of these crystals, bastnäsite-(Nd) forms thin (up to 20  $\mu\text{m}$  thick) zones in the outer parts. Crystals with zones of bastnäsite-(Nd) have been found in only a limited part of the fluorite, and are visually similar to those without Nd-dominant zones so they can only be identified with quantitative chemical data. They are, however, always closely associated with stettindite. Other associates in these cavities are Nd-dominant members of the ancylite group [pinkish round-shaped aggregates (<1 mm) of calcioancylite-(Nd) and/or kozoite-(Nd)] and vyuntspakhkite-(Y) as colourless to pale purplish oblong and flat crystals (ca.  $0.3 \times 0.1 \times 0.02 \text{ mm}^3$ ).

### 3. Physical and optical properties

Bastnäsite-(Nd) forms thin (up to 20  $\mu\text{m}$  thick) zones in outer parts of tabular hexagonal crystals (up to 0.2 mm in diameter) consisting of zoned bastnäsite-(Ce) and bastnäsite-(Nd) (Fig. 1). It is translucent and pale purplish pink to colourless. A white streak is inferred by comparison to bastnäsite-(Ce). The hardness is 4–4½ on the Mohs' scale, the tenacity is brittle. It has indistinct cleavage on {1010}, an uneven fracture and a vitreous, greasy or pearly lustre. The density could not be measured because of the zoning. The calculated density is  $5.23 \text{ g cm}^{-3}$  on the basis of the empirical formula. Optical properties were not determined because of the very small size of the Nd-dominant zones, however, the mean refractive index was calculated as  $n = 1.76$  on the basis of the Gladstone-Dale Relationship (Mandarino, 1981).

### 4. Chemical composition

The chemical composition of bastnäsite-(Nd) was determined by means of a JEOL JXA-8800M electron

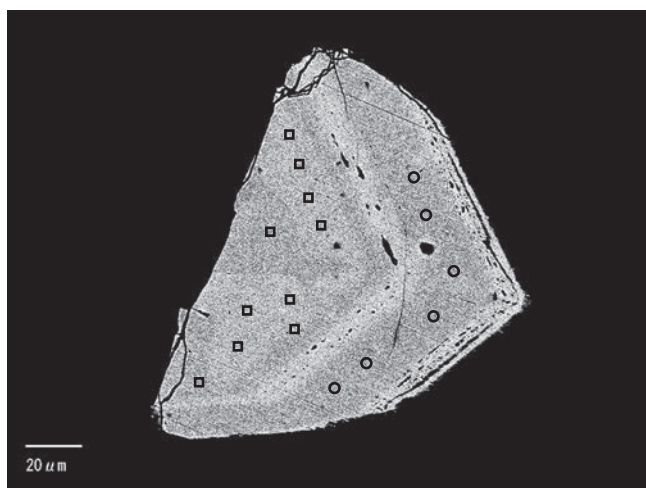


Fig. 1. SEM-BSE image of bastnäsite-(Nd) as a 20  $\mu\text{m}$  thick zone overgrowing bastnäsite-(Ce) from the Stettind pegmatite. The contrast of the image was strongly enhanced. The analysis spots are indicated with open circles and squares for bastnäsite-(Nd) and bastnäsite-(Ce), respectively.

microprobe analyzer. The analysis was carried out in the WDS mode under the conditions listed in Table 1 and as follows: 15 kV, 20 nA, and 5  $\mu\text{m}$  beam diameter. The amount of  $\text{CO}_2$  was estimated by stoichiometry using  $M$  (total cations) =  $C$ , because it could not be determined directly owing to the paucity of available material. The data of six spots in the Nd-dominant zone are given in Table 1 with those of ten spots in the Ce-dominant zone, for comparison.

The empirical formula (based on the total cations  $M = C = 1 \text{ apfu}$ ) is:  $\text{Nd}_{0.353}\text{La}_{0.253}\text{Ce}_{0.251}\text{Pr}_{0.086}\text{Sm}_{0.037}\text{Gd}_{0.016}\text{Y}_{0.004}\text{Dy}_{0.001}\text{CO}_{2.978}\text{F}_{1.044}$ . The ideal formula of bastnäsite-(Nd) is  $\text{Nd}(\text{CO}_3)\text{F}$ .

### 5. Crystallography

Powder X-ray diffraction data were obtained using a 114.6 mm diameter Gandolfi camera with Ni-filtered  $\text{CuK}\alpha$  radiation. Fine fragments of bastnäsite-(Nd) were scratched from the Nd-dominant zone in the thin section used for the chemical analysis under a binocular microscope. The data were recorded on an imaging plate (IP) and processed with a Fuji BAS-2500 bio-image analyzer using a computer program written by Nakamuta (1999). The X-ray diffraction data could be indexed on the basis of a hexagonal bastnäsite-type unit-cell with the extinction rules for space group  $P\bar{6}2c$ . No diffraction peaks, which are typical for the  $P\bar{6}$  hexagonal  $\text{Nd}(\text{CO}_3)\text{OH}$ -type structure (Michiba *et al.*, 2011) having the larger unit-cell and lower symmetry, such as the 411 reflection at around  $d = 2.28 \text{ \AA}$ , were detected for the present F-dominant specimen. The unit-cell parameters were refined from the diffraction data and calibrated with an internal Si-standard reference material (NBS #640b), using the computer program of Toraya (1993);  $a = 7.0792(13)$ ,  $c = 9.721(2) \text{ \AA}$ ,  $V = 421.92(18) \text{ \AA}^3$  and  $Z = 6$ . The powder X-ray diffraction data of bastnäsite-(Nd) are given in Table 2 with those of bastnäsite-(Ce) in the same thin section, for comparison.

### 6. Discussion

Bastnäsite-(Nd) is a member of the bastnäsite group (Strunz and Nickel class 5.BD.35). It is the Nd-dominant analogue of bastnäsite-(Ce) (Ni *et al.*, 1993), bastnäsite-(La) (Vainshtein *et al.*, 1961) and bastnäsite-(Y) (Mineev *et al.*, 1970). Comparative data are listed in Table 3. The unit-cell volume of bastnäsite-(Nd) is comparable to those of bastnäsite-(Ce) and bastnäsite-(La), whereas it is larger than that of bastnäsite-(Y). Bastnäsite-(Nd) ( $P\bar{6}2c$ ) is chemically the F-analogue of hydroxylbastnäsite-(Nd) (Maksimovic & Pantó, 1985), whose true space group could be  $P\bar{6}$  as was found for the synthetic hexagonal  $\text{Nd}(\text{CO}_3)\text{OH}$  (Michiba *et al.*, 2011).

Fig. 2 shows the chondrite-normalised distribution patterns of lanthanoids in bastnäsite-(Nd) and related

Table 1. Chemical compositions of bastnäsite-(Nd) and bastnäsite-(Ce) from the Stetind pegmatite.

Constituent	Bastnäsite-(Nd)		Bastnäsite-(Ce)		Probe standard	Analytical Line
	wt%	Range	wt%	Range		
Y <sub>2</sub> O <sub>3</sub>	0.19(15)	0.02–0.46	0.49(30)	0.10–1.03	YP <sub>5</sub> O <sub>14</sub>	Y <i>Lα</i>
La <sub>2</sub> O <sub>3</sub>	18.64(126)	16.57–20.37	10.31(59)	9.61–11.62	LaP <sub>5</sub> O <sub>14</sub>	La <i>Lα</i>
Ce <sub>2</sub> O <sub>3</sub>	18.64(104)	16.63–20.03	29.88(120)	28.42–32.22	CeP <sub>5</sub> O <sub>14</sub>	Ce <i>Lα</i>
Pr <sub>2</sub> O <sub>3</sub>	6.41(34)	5.89–6.94	4.65(27)	4.11–5.06	PrP <sub>5</sub> O <sub>14</sub>	Pr <i>Lβ</i>
Nd <sub>2</sub> O <sub>3</sub>	26.86(54)	26.09–27.45	21.75(49)	21.17–22.82	NdP <sub>5</sub> O <sub>14</sub>	Nd <i>Lα</i> <sup>b</sup>
Sm <sub>2</sub> O <sub>3</sub>	2.95(25)	2.50–3.23	5.26(65)	3.90–5.91	SmP <sub>5</sub> O <sub>14</sub>	Sm <i>Lα</i> <sup>b</sup>
Gd <sub>2</sub> O <sub>3</sub>	1.30(11)	1.05–1.38	3.21(74)	1.61–3.92	GdP <sub>5</sub> O <sub>14</sub>	Gd <i>Lβ</i>
Dy <sub>2</sub> O <sub>3</sub>	0.07(11)	0.00–0.30	0.39(20)	0.13–0.72	DyP <sub>5</sub> O <sub>14</sub>	Dy <i>Lα</i> <sup>c</sup>
F	8.98(8)	8.85–9.07	9.06(15)	8.80–9.32	CaF <sub>2</sub>	F <i>Kα</i>
CO <sub>2</sub> <sup>a</sup>	19.92		20.12			
O = F	–3.78		–3.82			
Total	100.18		101.3			
	No. cation ( <i>M</i> = <i>C</i> = 1 <i>apfu</i> )		No. cation ( <i>M</i> = <i>C</i> = 1 <i>apfu</i> )			
Y	0.004		0.009			
La	0.253		0.138			
Ce	0.251		0.398			
Pr	0.086		0.062			
Nd	0.353		0.283			
Sm	0.037		0.066			
Gd	0.016		0.039			
Dy	0.001		0.005			
F	1.004		1.044			
C	1		1			

Standard deviations are given in parentheses.

<sup>a</sup>Calculated (see text).

<sup>b</sup>Calibrated for overlapping interference by Ce *Lβ* lines.

<sup>c</sup>Calibrated for overlapping interference by Eu *Lβ* lines.

Table 2. Powder X-ray diffraction data for bastnäsite-(Nd) and bastnäsite-(Ce).

<i>h</i>	<i>l</i>	<i>k</i>	Bastnäsite-(Nd)			Bastnäsite-(Ce)		
			<i>I</i> <sub>meas.</sub>	<i>d</i> <sub>meas.</sub>	<i>d</i> <sub>calc.</sub>	<i>I</i> <sub>meas.</sub>	<i>d</i> <sub>meas.</sub>	<i>d</i> <sub>calc.</sub>
0	2	0	71	4.86	4.86	62	4.87	4.86
1	0	1	70	3.54	3.54	64	3.54	3.54
1	2	1	100	2.86	2.86	100	2.86	2.86
2	2	0	2	2.59	2.59			2.59
0	4	0	22	2.43	2.43	16	2.43	2.43
1	4	0	3	2.26	2.26			2.26
2	3	0	3	2.23	2.23			2.23
3	0	0	31	2.04	2.04	35	2.04	2.04
1	4	1	48	2.00	2.00	38	2.01	2.00
3	2	0	29	1.883	1.884	32	1.882	1.884
1	5	0	2	1.854	1.853			1.854
2	0	2	8	1.768	1.770	11	1.766	1.769
2	2	2	16	1.662	1.663	29	1.661	1.663
0	6	0	4	1.621	1.620			1.621
3	4	0	11	1.563	1.564	12	1.563	1.564
1	6	1	13	1.474	1.473	11	1.472	1.473
2	4	2	8	1.430	1.431	9	1.430	1.431
4	0	1	4	1.337	1.338	13	1.339	1.338
4	2	1	12	1.289	1.290	13	1.289	1.290
3	6	0	5	1.269	1.270	14	1.270	1.270
0	8	0	2	1.215	1.215			1.215
2	6	2	4	1.195	1.195			1.195
3	0	3	3	1.180	1.180	8	1.179	1.180
4	4	1	7	1.172	1.172	11	1.172	1.172
1	8	1	5	1.150	1.149			1.150
3	2	3	7	1.148	1.147	10	1.147	1.146

Table 3. Comparative data for bastnäsite-(Nd), bastnäsite-(Ce), bastnäsite-(La) and bastnäsite-(Y).

	Bastnäsite-(Nd) <sup>a</sup>	Bastnäsite-(Ce) <sup>a</sup>	Bastnäsite-(Ce) <sup>b</sup>	Bastnäsite-(La) <sup>c,d</sup>	Bastnäsite-(Y) <sup>e</sup>
Formula	(Nd,La,Ce)CO <sub>3</sub> F	(Ce,Nd,La)CO <sub>3</sub> F	(Ce,La,Nd)CO <sub>3</sub> F	(La,Ce,Nd)CO <sub>3</sub> F	(Y,Dy,Er)CO <sub>3</sub> F
Space group	<i>P</i> 62c	<i>P</i> 62c	<i>P</i> 62c	<i>P</i> 62c	<i>P</i> 62c
<i>a</i> (Å)	7.0792(13)	7.0774(17)	7.118(1)	7.117(3)	6.57(2)
<i>c</i> (Å)	9.721(2)	9.724(5)	9.7621(1)	9.669(17)	9.48(2)
<i>V</i> (Å <sup>3</sup> )	421.92(18)	421.8(3)	428.27	424.1	354
<i>Z</i>	6	6	6	6	6
<i>D<sub>x</sub></i> (g cm <sup>-3</sup> )	5.23	5.24	5.10	5.12	4.72
Colour	Pale purplish pink	Pale purplish pink	Yellow	Dark brown	Dark red

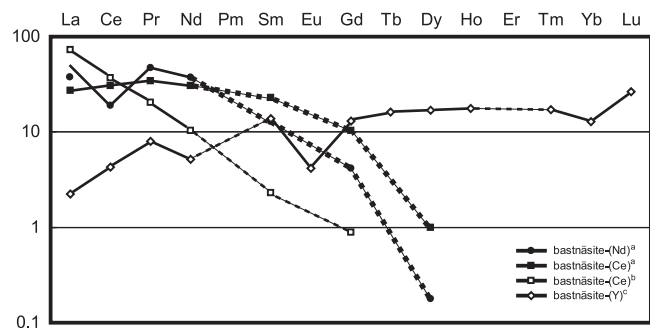
<sup>a</sup>Present study.<sup>b</sup>Ni *et al.* (1993).<sup>c</sup>Vainshtein *et al.* (1961).<sup>d</sup>Kupriyanova (1968).<sup>e</sup>Mineev *et al.* (1970).

Fig. 2. Chondrite-normalized lanthanide distribution patterns of bastnäsite-(Nd) and bastnäsite-(Ce) from the Stetind pegmatite. (a) Stetind pegmatite (present study); (b) Gallinas Mountains (Ni *et al.*, 1993); (c) Verkhne-Espe alkaline massif (Mineev *et al.*, 1970).

minerals. Bastnäsite-(Nd), as well as bastnäsite-(Ce), is rich in LREE with larger ionic radii, in contrast to bastnäsite-(Y), which has a flat pattern. The characteristic feature is a Ce negative anomaly in the pattern of bastnäsite-(Nd) which results in the relative abundance of Nd over Ce. On the contrary, bastnäsite-(Ce) from the Gallinas Mountains, New Mexico (Ni *et al.*, 1993) showed a linear decrease in the pattern. Nd is the second dominant REE following the predominant Ce, namely Ce > Nd > La, in bastnäsite-(Ce) from the Stetind pegmatite, while La follows Ce (Ce > La > Nd), in bastnäsite-(Ce) from the Gallinas Mountains. The enrichment of middle REE such as Sm, Gd and Dy in bastnäsite-(Ce) relative to bastnäsite-(Nd) in the Stetind pegmatite reflects on the density and electron scattering. Although Nd is heavier than Ce, bastnäsite-(Nd) from the Stetind pegmatite showed slightly lower density than the associated bastnäsite-(Ce) (Table 3). On the back-scattered electron image with strongly enhanced contrast (Fig. 1), the Nd- and Ce-dominant areas can be discriminated, usually, as darker and brighter, respectively.

Bastnäsite-(Nd) formed as a late phase in cavities in Y-bearing fluorite, which in turn is a late formation in the pegmatite. As the mineral is associated with stetindite (Ce<sup>4+</sup>SiO<sub>4</sub>), it is reasonable to assign the Nd-dominance

among REE in bastnäsite-(Nd) to the partial oxidation of Ce<sup>3+</sup> to Ce<sup>4+</sup> in the mineralising fluids, and the fixation of Ce in an own mineral phase, stetindite.

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