U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

THE DISTRIBUTION OF LANTHANIDES AND YTTRIUM IN THE MINERALS
OF THE MONAZITE FAMILY

by

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Abstract

Minerals of the monazite structural group include arsenates, phosphates, and silicates with the general formula $\text{ABO}_4$ where $A = \text{Bi}, \text{Ca}, \text{Ce}, \text{La}, \text{Nd}, \text{Th}, \text{U},$ and/or $\text{Y}$; and $B = \text{P}^{+5}, \text{As}^{+5}$, and/or $\text{Si}^{+5}$. Monazite-family minerals contain essential REE and $\text{PO}_4$, and may have minor amounts of other elements. Monazite-(Ce) is the predominant species, constituting 763 analyses (Tables 1 to 3). Another 18 analyses are for other species of monazite and gasparite-(Ce) (Table 4), cheralites (Table 5), and huttonites (Table 6). Two additional tables list average compositions of monazite-(Ce) from various rock types, and a final table indexes the analyses of monazite-(Ce) according to the localities.
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Abbreviations used in tables for methods of analysis

AAS atomic absorption spectrophotometry
CH chromatographic
EP electron microprobe
ICC inductively coupled plasma
INA instrumental neutron activation
OS optical spectrography
XF x-ray fluorescence

Fig. 1. Relationships in the monoclinic system CePO₄-Th(PO₄)₂-ThSiO₄, modified from Bowie and Horne (1953)

Fig. 2. Relations of atomic ratios, from the data of Table 7.
The monazite structural group of minerals consists of monoclinic arsenates, phosphates, and silicates of the general formula $ABO_4$, where $A = Bi, Ca, Ce, La, Nd, Th, U$, and/or $Y; B = As^{3+}, P^{5+}$, and/or $Si^{4+}$. The minerals in this group are:

- Brabantite, $CaTh(PO_4)_2$
- Cheralite, $(Ca, Ce, Th)(P, Si)O_4$
- Gasparite-(Ce), $(Ce, La, Nd)AsO_4$
- Huttonite, $ThSiO_4$
- Monazite-(Ce), $(Ce, La, Nd, Th)(P, Si)O_4$
- Monazite-(La), $(La, Ce, Nd)PO_4$
- Monazite-(Nd), $(Nd, La, Ce)PO_4$
- Rooseveltite, $BiAsO_4$

Rooseveltite has not been reported to contain rare earth elements (REE) and will not be considered further here.

Brabantite has been reported to contain 3.05% RE$_2$O$_3$, but individual lanthanides were not determined. Figure 1 (modified from Bowie and Horne, 1953) shows the relationships of monazite, cheralite, huttonite, and brabantite.

Within the monazite group, the monazite family consists of minerals essential REE as cations, and essential phosphate (arsenate in gasparite-(Ce)) as the anion. Non-essential Th, Ca, Mg, and Pb may substitute for the REE and Si may substitute for P; both substitutions can be up to 25 percent, as indicated in Bowie and Horne (1953), Figure 1.

The distribution of lanthanides and yttrium in monazite family minerals has been the subject of many papers. Monazite was recognized long ago to be a mineral that is a concentrator of the light lanthanides, in accordance with their occupancy of positions with coordination number ten (10). However, the considerable effect of the geologic environment of formation on the distribution of the lanthanides was not recognized until the work of Murata and co-workers (1953, 1957, 1958), confirmed in a review by Fleischer and Altschuler (1969).

Other reports describing monazite (and other REE minerals) in specific rock types include those by Holt (1965) (carbonatites), Marchenko (1967) (gneiss and migmatite), Heinrich and Wells (1980) (several associations), and Clark (1984) (several associations). In addition, papers by Ploshko (1961) and by Marchenko and Goncharova (1964) discuss formation of monazite by pneumatolytic and hydrothermal processes. Finally, we note that papers by Balashov and Pozharitskaya (1968) and by Wells (1977) dwell on the physical-chemical reasons for fractionation of REE found in rocks and minerals.

This report is an update of Fleischer and Altschuler (1969) and includes a compilation of all available determinations of the lanthanides and yttrium in minerals of the monazite structural group, 786 in all. Monazite-(Ce) is the overwhelmingly dominant mineral, comprising no less than 763 of the analyzed samples. In Tables 1 to 6, atomic percentages of the REE plus contents of ThO$_2$ and U$_3$O$_8$ are listed in order of increasing sigma (the sum of the atomic percentages of La + Ce + Pr).
The averages tabulated in Tables 7 and 8 show the effect of the type of geological occurrence on the distribution of REE in monazite-(Ce), namely the increase in atomic percent of the light lanthanides and decrease of the yttrium content, from granitic pegmatites to granitic rocks to alkalic rocks and carbonatites. However, the range of composition is far less than in minerals of low REE content, and the variation of rare earth content in monazite is far less satisfactory as a guide to type of host rock than the variation in either apatite (Fleischer and Altschuler, 1969, 1986) or titanite (Fleischer, 1978).

The compositions of monazite-(Ce) in granitic rocks and in gneisses are not notably different. As discussed in detail by Rosenblum and Mosier (1983), the average composition of dark monazites (Table 7, column F) is distinct from those of (yellow) monazites of different genesis, and especially in their high content of europium. It should be noted that only one dark monazite (Table 4, no. 4) is not a monazite-(Ce).

Table 9 is an index in two parts. Table 9a lists localities and rock type for the analyses in Tables 1 through 6; Table 9b gives localities for Tables 1 through 3.
Table 1-1. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent.

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Table 1-3. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)  
((b) Tb + Y calc'd as Y)

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| Method | OS | XF | OS | OS | XF | OS | OS | OS | XF | XF |

<p>| Σ = La+Ce+Pr | 65.0 | 65.2 | 65.2 | 65.4 | 66.0 | 66.0 | 66.3 | 66.3 | 66.4 | 66.4 |
| La-Nd | 93.6 | 87.2 | 87.3 | 87.6 | 90.3 | 90.8 | 94.0 | 95.5 | 79.3 | 93.0 |
| Sm-Ho | 6.2 | 12.8 | 12.7 | 12.3 | 9.7 | 9.2 | 6.0 | 3.6 | 19.5 | 6.7 |
| Er-Lu | 0.2 | - | - | 0.1 | - | - | - | 0.9 | 1.2 | 0.3 |
| RE₂O₃, wt.% | - | - | - | 51.6 | - | - | - | 47.0 | - | 65.0 |
| La/Nd | 0.89 | 0.90 | 0.91 | 0.95 | 0.75 | 0.88 | 0.73 | 0.75 | 1.22 | 0.58 |
| ThO₂, wt.% | - | - | 12.1 | 9.89 | - | - | - | - | - | - |
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Method: XF, OS, CH, CH, INA, XF, XF, XF, OS, CH

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\( \Sigma = \text{La}+\text{Ce}+\text{Pr} \)

69.5 69.5 69.6 69.6 69.6 69.7 69.7 69.7 69.7 69.8

La-Nd 92.6 94.7 91.5 92.3 100.0 88.9 89.6 89.8 94.0 91.6

Sm-Ho 7.4 5.3 8.5 7.7 10.5 10.3 10.2 6.0 8.4

Er-Lu - - - - - 0.6 0.1 - - -

\( \text{RE}_2\text{O}_3, \text{wt.}\% \)

- - - - - - 61.8 - - -

La/Nd 0.95 0.98 1.00 0.73 0.60 1.27 1.13 0.87 0.72 0.82

\( \text{ThO}_2, \text{wt.}\% \)

- - - 10.1 11.4 2.0 14.3 11.2 3.3 9.5

\( \text{U}_3\text{O}_8, \text{wt.}\% \)

- - - - - - - - 0.1
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Method: XF OS OS OS OS OS CH OS EP XF

La/Nd | 91.7 | 92.3 | 94.3 | 95.8 | 100.0 | 87.4 | 89.2 | 92.9 | 94.8 | 91.0 |

Sm-Ho | 8.3 | 7.7 | 5.6 | 4.2 | - | 12.3 | 10.2 | 7.1 | 5.0 | 9.0 |

Er-Lu |     |     | 0.1 |     | - | 0.3 | 0.6 | - | 0.2 | - |

RE₂O₅, wt.% |     |     |     |     |     | 70.7 | - | 71.6 | - | - |

La/Nd | 1.00 | 0.77 | 1.17 | 0.84 | 0.65 | 1.28 | 1.08 | 0.85 | 0.64 | 1.00 |

ThO₂, wt.% |     |     |     |     |     | 5.3 | 12.2 | 7.37 | - | - |

U₃O₈, wt.% |     |     |     |     |     |     |     | 0.08 | - | - |
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Method

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La-Nd

- | 91.3 | 91.9 | 92.1 | 97.0 | 90.7 | 91.3 | 93.0 | 89.3 | 91.3 | 100.0 |

Sm-Ho

- | 8.6 | 8.1 | 7.9 | 3.0 | 9.3 | 8.7 | 7.0 | 9.9 | 8.7 | - |

Er-Lu

- | 0.1 | - | - | - | - | - | - | 0.8 | - | - |

RE₂O₃, wt.%

|     | 36.3 | - | - | - | - | - | 56.29 | 47.2 | - |

La/Nd

|     | 1.21 | 0.96 | 0.91 | 0.78 | 1.30 | 1.36 | 0.92 | 1.03 | 0.77 | 0.48 |

ThO₂, wt.%

|     | 7.65 | 10.4 | 11.8 | - | - | - | - | 8.35 | 25.4 | 2.6 |

U₃O₈, wt.%

|     | - | 0.1 | - | - | - | - | - | 0.56 | - | - |
Table 1-15. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Table 1-16. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)
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Method
CH  CH  CH  -  EP  CH  OS  -  XF  -

Σ = La+Ce+Pr  72.3  72.3  72.3  72.3  72.3  72.4  72.4  72.5  72.6  72.6
La-Nd  89.8  91.1  91.6  92.6  93.1  90.4  95.4  95.2  90.7  93.9
Sm-Ho  8.8  7.3  7.5  7.4  6.9  8.2  4.6  4.8  8.4  6.1
Er-Lu  1.4  1.6  0.9  -    -    1.4  -    -    0.9  -    

RE₂O₃, wt.%  52.42  58.0  55.14  -    68.92  55.6  -    -    -    -    

La/Nd  1.13  1.31  1.44  0.92  1.00  0.94  0.93  1.05  1.24  0.91
ThO₂, wt.%  8.52  5.50  8.50  -    -    8.0  -    5.7  -    -    

U₃O₈, wt.%  -    -    -    -    -    -    -    -    0.1  -    

Table 1-17. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Table 1-18. Monazite from igneous and metamorphic rocks, atomic percent (cont'd)

(a) Eu + Gd calcd. as Gd; (b) Tb + Y calcd as Y

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Table 1-19. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)
(a) Eu + Gd calcd. as Gd; (b) Tb + Y calcd. as Y

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<th>Ho</th>
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Sm-Ho: 6.2 5.6 16.0 7.6 5.6 4.7 4.4 7.4 6.9 6.7
Er-Lu: 0.4 0.2 0.3 0.1 0.4 0.2
RE₂O₃, wt.%: 58.8 46.3 60.6 56.8 57.15 65.9 55.6
La/Nd: 0.95 1.20 2.21 1.26 0.90 1.13 1.22 1.52 1.06 1.13
ThO₂, wt.%: 19.5 7.1 6.44 8.0
U₃O₈, wt.%: 1.6 - - - - - - - -
Table 1-20. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Σ = La+Ce+Pr  74.6 | 74.6 | 74.6 | 74.7 | 74.8 | 74.9 | 74.9 | 75.7 | 75.0 | 75.0 |
La-Nd  91.9 | 94.3 | 100.0 | 95.1 | 92.9 | 94.8 | 95.3 | 95.5 | 91.2 | 93.4 |
Sm-Ho  7.7 | 5.7 | - | 4.9 | 6.6 | 5.2 | 4.7 | 4.5 | 8.8 | 6.6 |
Er-Lu  0.4 | - | - | - | 0.5 | - | - | - | - | - |
RE₂O₃, wt.% | - | - | - | - | 45.7 | - | - | - | 60.3 | - |
La/Nd  1.34 | 1.20 | 0.94 | 1.20 | 1.41 | 1.20 | 1.16 | 1.18 | 1.41 | 1.39 |
ThO₂, wt.% | - | - | 10.3 | - | - | - | 10.9 | 7.7 | 5.6 | - |
U₃O₈, wt.% | - | - | - | - | - | - | - | 0.4 | - |
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Table 1-26. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)
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Method
- CH | OS | XF | XF | OS | EP | OS | ID | CH | EP |

La + Ce + Pr = 76.0
La-Nd = 3.3
94.4
94.7
95.0
97.2
100.00
94.8
95.3
95.6

Sm-Ho = 6.7
5.6
5.4
5.3
4.8
2.8
-5.1
4.6
4.4

Er-Lu = -
-0.2
-0.1
0.1

RE₂O₃, wt.% = 52.13
46.8
63.75

La/Nd = 1.54
1.27
1.14
1.35
1.18
1.05
1.08
1.28
1.10
1.25

ThO₂, wt.% = 6.46
15.3
8.12
4.00
11.6

U₃O₈, wt.% = 0.09
-0.30


Table 1-27. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Method: EP, XF, CH, XF, XF, XF, XF, XF, OS

\[ z = La + Ce + Pr \]

\[ \Sigma = La + Ce + Pr \]

La-Nd: 76.2 76.2 76.2 76.2 76.3 76.4 76.4 76.5 76.5 76.5 76.5

Sm-Ho: 10.4 5.1 4.8 4.7 6.5 4.7 5.1 5.0 4.7

Er-Lu: - - - - 1.6 0.5 - - - -

RE₂O₃, wt.%: 60.2 - - - 62.4 - - - -

La/Nd: 1.77 1.30 1.25 1.35 1.67 1.20 1.40 1.45 1.40 1.09

ThO₂, wt.%: 4.5 - - - 8.75 - - - -

U₂O₈, wt.%: 2.5 - - - - - - - -
Table 1-28. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Method  | CH  | XF    | XF | EP  | XF  | XF  | -  | OS  | OS  | XF  |               |
Σ = La+Ce+Pr | 76.6 | 76.6 | 76.6 | 76.7 | 76.7 | 76.8 | 76.8 | 76.8 | 76.8 | 76.8 |               |
La-Nd    | 93.4 | 94.2 | 96.2 | 94.7 | 95.3 | 92.8 | 95.2 | 95.8 | 96.1 | 96.4 |               |
Sm-Ho    | 6.6  | 5.8  | 3.8  | 5.1  | 4.5  | 5.6  | 4.7  | 4.2  | 3.9  | 3.4  |               |
Er-Lu    | -    | -    | -    | 0.2  | 0.2  | 1.6  | 0.1  | -    | -    | 0.2  |               |
RE₂O₃, wt.% | -    | -    | 55.1 | 49.05 | 68.3 | -    | -    | -    | -    | -    |               |
La/Nd    | 1.14 | 1.45 | 1.18 | 1.21 | 1.04 | 1.31 | 1.26 | 1.33 | 1.36 | 1.19 |               |
ThO₂, wt.% | 8.48 | -    | -    | -    | -    | -    | -    | -    | 6.7  | -    |               |
U₃O₈, wt.% | 0.04 | -    | -    | -    | -    | -    | -    | -    | -    | -    |               |
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**Method**

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| Σ = La+Ce+Pr | 76.8 | 76.8 | 76.9 | 76.9 | 76.9 | 76.9 | 76.9 | 76.9 | 76.9 | 76.9 |
| La-Nd | 97.1 | 100.0 | 90.8 | 91.6 | 94.1 | 94.2 | 94.4 | 95.2 | 95.2 | 95.3 |
| Sm-Ho | 2.9 | - | 8.8 | 7.7 | 5.6 | 5.4 | 5.6 | 4.8 | 4.8 | 4.6 |
| Er-Lu | - | - | 0.4 | 0.7 | 0.3 | 0.4 | - | - | 0.1 |
| RE₂O₃, wt.% | 61.0 | - | - | - | 53.99 | 50.13 | - | - | - | - |
| La/Nd | 1.08 | 1.09 | 2.01 | 1.59 | 1.25 | 1.40 | 1.50 | 1.55 | 1.30 | 1.26 |
| ThO₂, wt.% | 7.23 | 9.7 | - | - | - | 5.77 | - | - | - | - |
| U₃O₈, wt.% | - | - | - | - | - | - | - | - | - | - |

**Table 1-29.** Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd) (a) Eu + Gd calc. as Gd; (b) Tb + Y calc. as Y
Table 1-30. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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35
|   | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Y/(Y+La) | Method | RE₂O₃ wt.% | La/Nd | ThO₂ wt.% | U₃O₈ wt.% |
| La | 24.4 | 23.9 | 28.3 | 29.0 | 26.6 | 25.0 | 24.1 | 26.9 | 16.3 | 23.0 |
| Ce | 47.8 | 48.1 | 43.5 | 43.1 | 45.8 | 475. | 48.4 | 46.3 | 55.3 | 48.7 |
| Pr | 5.1  | 5.3  | 5.5  | 5.2  | 5.0  | 5.0  | 5.1  | 4.4  | 6.0  | 5.9  |
| Nd | 18.1 | 18.4 | 18.9 | 19.6 | 18.3 | 15.5 | 14.4 | 17.3 | 17.5 | 18.2 |
| Sm | 2.7  | 3.3  | 3.8  | 1.8  | 2.8  | 5.0  | 5.4  | 2.9  | 3.0  | 1.5  |
| Eu | -    | -    | -    | 0.3  | -    | -    | -    | -    | -    | a    |
| Gd | 1.9  | 1.0  | -    | 0.9  | 1.5  | 2.0  | 2.6  | 2.2  | 1.9^a| 1.9  |
| Tb | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    |
| Dy | -    | -    | -    | 0.1  | -    | -    | -    | -    | -    | 0.3  |
| Ho | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    |
| Er | -    | -    | -    | -    | -    | -    | -    | -    | 0.4  |
| Tm | -    | -    | -    | -    | -    | -    | -    | -    | -    |
| Yb | -    | -    | -    | -    | -    | -    | -    | -    | 0.1  |
| Lu | -    | -    | -    | -    | -    | -    | -    | -    | -    |
| Y/(Y+La)x100 | - | (0.9) | - | - | - | (1.4) | (1.7) | - | (2.0) | (3.2) |
| Method | XF | OS | XF | XF | XF | EP | EP | XF | CH | - |
| Σ = La+Ce+Pr | 77.3 | 77.3 | 77.3 | 77.3 | 77.4 | 77.5 | 77.6 | 77.6 | - | - |
| La-Nd | 95.4 | 95.7 | 96.2 | 96.9 | 95.7 | 93.0 | 92.0 | 94.9 | 95.1 | 95.8 |
| Sm-Ho | 4.6  | 4.3  | 3.8  | 3.1  | 4.3  | 7.0  | 8.0  | 5.1  | 4.9  | 3.7  |
| Er-Lu | -    | -    | -    | -    | -    | -    | -    | 0.5  |
| RE₂O₃ wt.% | -    | -    | -    | -    | -    | -    | -    | 63.4 | 59.7 | 50.0 | - | 54.71 |
| La/Nd | 1.35 | 1.30 | 1.50 | 1.48 | 1.45 | 1.61 | 1.67 | 1.55 | 0.93 | 1.26 |
| ThO₂ wt.% | -    | 9.3  | -    | -    | -    | 4.1  | 5.6  | -    | -    | 7.64 |
| U₃O₈ wt.% | -    | -    | -    | -    | -    | 0.1  | 0.2  | -    | -    | 0.29 |
Table 1-32. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd.)

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Table 1-33. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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- XF 52.9 - - - - - - - - -
- OS 1.53 1.34 1.34 1.45 1.64 1.45 1.54 1.50 1.38 1.35
- XF 18.7 7.57 - - 0.18 - - - 1.04 -
- OS - - - - - - - - - -
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Table 1-34. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)
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La-Nd | 98.1 | 95.3 | 95.8 | 97.0 | 93.0 | 93.5 | 93.7 | 95.3 | 95.8 | 95.1
Sm-Ho | 1.9 | 4.5 | 3.6 | 3.0 | 7.0 | 6.3 | 6.1 | 4.0 | 4.2 | 4.4
Er-Lu | - | 0.2 | 0.6 | - | - | 0.2 | 0.7 | - | 0.5
RE$_2$O$_3$, wt.% | - | - | - | 64.6 | 61.3 | - | - | 60.84 | 61.8
La/Nd | 0.72 | 1.43 | 1.14 | 1.25 | 1.55 | 1.51 | 1.56 | 1.64 | 1.50 | 1.56
ThO$_2$, wt.% | - | - | - | 5.60 | 6.5 | - | - | 4.26 | -
U$_3$O$_8$, wt.% | - | 0.25 | - | 0.2 | - | - | - | - | -
Table 1-35. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

(a) Eu + Gd calcd. as Gd; (b) Tb + Y calcd. as Y

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Table 1-36. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Method:
- XF
- CH

\( \varepsilon = \frac{La+Ce}{Pr} \)
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- 78.8
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- 78.8
- 78.8
- 78.9
- 78.9
- 78.9
- 78.9

La-Nd
- 95.4
- 92.3
- 93.7
- 95.4
- 96.4
- 96.6
- 93.2
- 93.4
- 94.4
- 95.0

Sm-Ho
- 4.4
- 7.3
- 6.1
- 4.1
- 3.6
- 3.3
- 6.8
- 6.2
- 5.4
- 5.0

Er-Lu
- 0.2
- 0.4
- 0.2
- 0.5
- 0.1
- 0.4
- 0.2

RE₂O₃, wt. %
- 61.69
- 59.7
- 61.21

La/Nd
- 1.22
- 2.06
- 1.64
- 1.57
- 1.43
- 1.52
- 1.99
- 1.33
- 1.56
- 1.72

ThO₂, wt. %
- 4.62
- 5.32

U₃O₈, wt. %
- -
Table 1-37. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)
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Table 1-38. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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**Method**

| OS | XF | EP | EP | XF | XF | XF | XF | XF |

**Σ = La+Ce+Pr**

| La-Nd | 100.00 | 94.6 | 97.4 | 97.4 | 91.8 | 92.5 | 94.5 | 94.8 | 96.3 | 97.5 |
| Sm-Ho | 5.4   | 2.6 | 2.6 | 6.2 | 5.9 | 5.5 | 5.1 | 3.7 | 2.5 |     |
| Er-Lu | -     | -   | -   | 2.0 | 1.6 | -   | 0.1 | -   |     |     |
| RE₂O₃, wt.% | - | - | 57.65 | 59.06 | 48.8 | 49.4 | 48.3 | - | - | - |
| La/Nd | 1.32 | 1.57 | 1.43 | 1.43 | 2.12 | 1.98 | 1.98 | 1.58 | 1.65 | 1.74 |
| ThO₂, wt.% | 8.2 | -   | 8.04 | 8.07 | -   | -   | -   | -   | -   | -   |
| U₃O₈, wt.% | - | - | 0.64 | 0.91 | - | - | - | - | - | - |
Table 1-39. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)
(a) Eu + Gd calcd. as Gd; (b) Tb + Y calcd. as Y; (c) Tb + Dy + Y calcd. as Y

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### Table 1-40. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

(a) Eu + Gd calcd. as Gd

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<td>- (4.4) (4.0)</td>
<td>(0.9) (4.2)</td>
<td>(3.3)</td>
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RE₂O₃, wt.% - - - 67.2 - - - - -

La-Nd 94.6 94.7 95.1 95.8 94.6 94.2 94.6 94.7
Sm-Ho 5.3 5.1 4.8 4.2 5.3 5.4 5.7 5.3 5.2
Er-Lu 0.1 0.2 0.1 - 0.1 - 0.2 0.1 0.1

Method XF XF XF CH CH CH X X X X

Σ = La+Ce+Pr 79.8 79.8 79.8 79.8 79.9 79.9 80.0 80.0 80.0

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Method
- EP
- XF
- EP
- OS
- XF
- XF
- EP
- EP
- XF

\[ \varepsilon = \text{La+Ce+Pr} \]
- 80.7| 80.7| 80.8| 80.8| 80.8| 89.9| 80.9| 80.9| 80.9| 80.9

\[ \text{La-Nd} \]
- 97.2| 97.2| 97.8| 97.8| 100.0| 95.9| 97.1| 97.5| 98.1| 98.5

\[ \text{Sm-Ho} \]
- 2.8| 2.8| 2.2| 2.2| - | 4.7| 2.9| 2.5| 1.9| 1.5

\[ \text{Er-Lu} \]
- -| -| -| -| -| 0.4| -| -| -| -

\[ \text{RE}_2\text{O}_3, \text{wt.\%} \]
- 54.87| 60.8| -| -| -| -| 62.46| 62.33| 69.4

\[ \text{La/Nd} \]
- 1.52| 1.49| 1.15| 1.51| 1.27| 1.63| 1.75| 1.50| 1.32| 1.49

\[ \text{ThO}_2, \text{wt.\%} \]
- 10.89| 8.44| -| 2.45| 7.5| -| -| 8.71| 1.79| -

\[ \text{U}_3\text{O}_8, \text{wt.\%} \]
- -| -| -| -| -| -| -| 0.48| -| -
Table 1-45. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

(a) Eu + Gd calcd. as Gd; (b) Tb + Y calcd. as Y

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Table 1-46. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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Table 1-47. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

(a) Eu + Gd calcd. as Gd

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| 92.9 | 97.6 | 94.6 | 96.5 | 97.6 | 99.1 | 95.3 | 98.5 | 98.3 | 100.0 |
| 6.9  | 2.4  | 1.8  | 3.3  | 2.4  | 0.9  | 4.5  | 1.5  | 1.7  | -    |
| 0.2  | -    | 3.6  | 0.2  | -    | 0.2  | -    | -    | -    | -    |
| RE_2O_3 | - | 70.11 | 62.5 | 52.3 | 59.55 | - | 54.7 | - | - |
| La/Nd | 2.12 | 1.44 | 2.58 | 2.08 | 1.82 | 1.70 | 1.83 | 1.79 | 1.76 | 2.04 |
| ThO_2, wt.% | - | - | - | - | - | 7.47 | - | - | 6.7 |
| U_3O_8, wt.% | - | - | - | - | - | - | - | - | - |
Table 1-50. Monazite-(Ce) from igneous and metamorphic rocks, atomic percent (cont'd)

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**Method**  
EP | EP | OS | OS | XF

**$\varepsilon =$**  
La+Ce+Pr | 88.3 | 88.4 | 88.5 | 88.5 | 88.6 | 88.6 | 88.6 | 88.8 | 88.9 | 89.0

La-Nd | 99.0 | 99.4 | 98.1 | 99.6 | 98.2 | 98. | 98.5 | 99.0 | 99.2 | 97.2

Sm-Ho | 1.0 | 0.6 | 1.8 | 0.4 | 1.8 | 1.7 | 1.5 | 1.0 | 0.7 | 2.4

Er-Lu | - | - | 0.1 | - | - | 0.1 | - | - | 0.1 | 0.4

RE$_2$O$_3$ | - | 62.92 | 65.20 | - | - | 9.2 | 59.24 | - | 66.1 | -

La/Nd | 3.67 | 3.24 | 4.19 | 3.17 | 4.05 | 4.2 | 3.74 | 4.00 | 3.57 | 3.55

ThO$_2$, wt.% | - | 3.23 | - | - | 1.8 | - | 11.6 | - | 0.08 | -

U$_3$O$_8$, wt.% | - | - | - | - | - | - | - | - | 0.4 | -
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Method

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La-Nd   | 95.6 | 94.9 | 96.2 | 95.9 | 96.0 | 95.0 | 96.0 | 96.9 | 94.7 | 96.4 |
Sm-Ho   | 4.4  | 5.1  | 3.8  | 4.1  | 4.0  | 5.0  | 4.0  | 3.1  | 5.3  | 3.6  |
Er-Lu   |     |     |     |     |     |     |     |     |     |     |
RE2O3   |     |     |     |     |     |     | 62.6 | 61.45 |     |     |
La/Nd   | 1.00 | 1.19 | 1.01 | 1.15 | 1.07 | 1.21 | 1.11 | 1.03 | 1.35 | 1.03 |
ThO2, wt.% | 9.8  | 8.2  | 4.44 | 8.6  | 4.91 | 12.4 | 11.6 | -    | 9.7  |
U3O8, wt.% |     |     |     | 0.23 |     | 0.26 |     |     |     |     |
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Method
- EP
- EP
- EP
- XF
- EP
- XF

- $\Sigma = \text{La+Ce+Pr}$
- 80.8 80.9 81.4 82.3 85.7 86.4

- La-Nd
- 93.0 96.9 97.2 96.9 99.4 98.5

- Sm-Ho
- 7.0 3.1 2.8 3.0 0.6 1.4

- Er-Lu
- - - - 0.1 - 0.1

- $\text{RE}_2\text{O}_3$
- - - - 58.24 68.90 61.86

- La/Nd
- 1.65 1.39 1.27 1.81 1.78 2.49

- $\text{ThO}_2$, wt.%
- 11.7 6.3 5.75 8.1 1.28 6.6

- $\text{U}_3\text{O}_8$, wt.%
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Method

| RE₂O₃ | 70.70 | 67.45 | 55.70 | 72.72 | -   | -   | -   | 66.32 | -   | 67.55 |
| La/Nd | 0.33  | 0.40  | 0.73  | 0.49  | 0.60 | 0.69 | 0.63 | 0.77  | 0.63 | 0.69  |
| ThO₂, wt.% | 0.75  | 0.32  | 0.001 | 0.35  | -   | -   | -   | 0.54  | -   | 1.0   |
| U₃O₈, wt.% | -     | -     | -     | -     | -   | -   | -   | -     | -   | -     |
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\[ \xi = \text{La} + \text{Ce} + \text{Pr} \]

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Table 7-1. Average composition of monazite-(Ce), Tables 1-3, atomic percent

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Key to Table 7
A-E = from Table 1:
A=av. of 117 analyses from granitic pegmatites;
B=av. of 187 from granites, granodiorites, and quartz monzonites;
C=av. of 44 from gneisses;
D=av. of 13 from alkalic rocks and alkalic pegmatites;
E=av. of 25 from carbonatite;
F=av. of 46 dark monazites from Table 3;
G=av. of 151 from placers (Table 2)

Note: The averages for R.E. compositions do not include data from analyses in which La, Ce, Pr, or Nd were not determined. However, determinations of Y/(Y+Ln) and for ThO₂ or U₃O₈ from such analyses were used in calculating the averages above.

The averages for U₃O₈ are considered to be uncertain. For example, for A, the average of 1.18% becomes 0.40% if the highest determination (15.64% is omitted; the average for G of 1.16% becomes 0.33% if the two highest determinations (5.43, 6.1%) are omitted.
Table 8-1. Previously published average compositions of monazites, atomic percent

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ThO₂, wt.%

U₃O₈, wt.%
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Table 9a. Locality and Rock Type Index - Monazite-(Ce)
### Table 9a. Locality and Rock Type Index - Monazite-(Ce) (contd.)

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| 296      | Vainshtein et al. | 1955   | Badeiba, Transvaal, Brazil      | pegmatite          |
| 297      | Vainshtein et al. | 1956b  | Temryak, Azov region, U.S.S.R.  | pegmatite          |
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| 299      | Vainshtein et al. | 1955   | Korea                           | pegmatite          |
| 300      | Murata et al.     | 1953   | Shelby dist., N. Carolina       | quartz monzonite   |
|          |                   |        |                                 | pegmatite          |
| 301      | Pavlenko et al.   | 1966   | Milizei massif, E. Tuva, Brazil  | biotite            |
| 302      | Lyakhovich and Barinskii | 1961 | Edygaei massif, W. Tuva, Brazil | quartz vein        |
| 303      | Vainshtein et al. | 1956b  | Temryuk, Azov region, U.S.S.R.  | pegmatite          |
| 304      | Mannucci et al.   | 1986   | Alps, Italy                     | fissure            |
| 305      | Mannucci et al.   | 1986   | Alps, Italy                     | pegmatite          |
| 306      | Gavrilo and Turanskaya | 1958 | Kirograd, Ukraine               | granite            |
| 307      | Orsa et al.       | 1967   | Middle Dniepr region, Ukraine   | pegmatite          |
|          |                   |        |                                 | granite            |
| 308      | Lazarenko et al.  | 1980   | Ekaterinava, Ukraine            |                 |
| 309a,b,c | Ploshko and Knyazaeva | 1965 | Urushten complex, Caucasus      |                 |

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|          | Murata et al.     | 1957   | Chesterfield, Va.               | granite            |
| 312-313  | Vainshtein et al. | 1956b  | Gorevka, Ukraine                | granite            |
| 314      | Aleksiev and Tsetkovskaya | 1962 | Rila Mts., Bulgaria             | granite            |
| 315      | Zayats and Kuts   | 1964   | Gnilopyat river basin, Ukraine  | Archean biotite    |
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| 316      | Nadashovskii et al. | 1969 | Far Eastern, U.S.S.R.           | alkali granite     |
| 317-318  | Vainshtein et al. | 1956b  | Gorovka, Ukraine                | granite            |
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| 320      | Vainshtein et al. | 1955   | Ostrope, Austria                | pegmatite          |
| 321      | Wylie             | 1950   | Olary, S. Australia             | gold mine          |</p>
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| Table 6. |          | Kosterin and Zuev | 1962 | not given                | veinlet in granophyre   |
|          |          |                  |      |                           | huttonite-monazite      |
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| 4        |          | Pavlenko et al.  | 1965 | S.E. Siberia              |                         |
| 5        |          | Kucha            | 1980 | Bogatyn area, Lower Silesia, Poland | huttonite-monazite     |
| 6        |          | Kucha            | 1980 | Bogatyn area, Lower Silesia, Poland | huttonite-monazite     |
| 7        |          | Kucha            | 1980 | Bogatyn area, Lower Silesia, Poland | huttonite-monazite     |
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Fig. 1. Relationships in the monoclinic system CePO$_4$-CaTh(PO$_4$)$_2$-ThSiO$_4$ modified from Bowie and Horne (1953).
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