Oxygen and Carbon Isotope Composition in Primary Carbonatites of the World: Data Summary and Linear Trends

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Abstract

The article contains the results of statistical processing of a large summary of δ¹⁸O-δ¹³C isotope values in the primary carbonatites of the world. From literary sources, 1593 paired values δ¹⁸O-δ¹³C from 173 carbonatite occurrences of the world were collected. This report exceeds all previously published reports on С-О isotopes in carbonatites by quantity of the used values and carbonatite occurrences. Statistical data analysis is performed on diagrams in the coordinates δ¹⁸O (‰, V-SMOW) - δ¹³C (‰, V-PDV). For each carbonatite occurrence, not only the arithmetic mean values are calculated, but also the regression line. Distinct linear trend of δ¹⁸O-δ¹³C values is found in half of the carbonatite occurrences. The starting, middle, and ending points of the trend line are determined. The slope of the trend line (angular coefficient) varies over a wide range. The trend is dominated by an average angular coefficient of 0.30 (positive correlation δ¹⁸O-δ¹³C). In the literature, it is associated with the Rayleigh high-temperature fractionation of carbonatite melts or with their sedimentary contamination. Half of the carbonatite occurrences do not show a linear trend of δ¹⁸O-δ¹³C values, probably due to the combined action of multidirectional trends. The initial ratio ⁸⁷Sr/⁸⁶Sr in the used carbonatite occurrences varies from 0.701 to 0.708. Statistics show no correlation of ⁸⁷Sr/⁸⁶Sr with the δ¹⁸O-δ¹³C system.

Keywords
Carbonatite Occurrences, Oxygen, Carbon and Strontium Isotopes, Linear Trends

1. Introduction

Oxygen and carbon isotope composition of carbonatites were summarized in a
number of previous works. The largest number of δ¹⁸O-δ¹³C values (about 440) was collected and used to construct histograms in [1]. In the work [2], 56 values from 8 carbonatite occurrences of Kola Alkaline Province were used, linear trends were identified. In the work [3], 70 analyzes from 20 carbonatite occurrences of Siberia and Mongolia were used; a diagram was proposed for determining the type of mantle using the ratio of O-C isotopes. In the work [4], the fields of point values are outlined in the δ¹⁸O-δ¹³C diagram for the Greenland, Europe, and North and South America regions without a division for individual carbonatite occurrences. The fields of primary igneous carbonatites on the δ¹⁸O-δ¹³C diagram are outlined in the works [1] [5] [6] [7]. These fields are used in the analysis of local isotope data in carbonatite studies.

This paper uses 1593 pairs of conjugate values of δ¹⁸O-δ¹³C out of 173 carbonatite occurrences of the world. In addition, a linear regression analysis of the values is performed for most occurrences. This paper exceeds all previously published reports on C-O isotopes in carbonatites by quantity of the used values and carbonatite occurrences. Data on the ratio ⁸⁷Sr/⁶⁶Sr in 92 carbonatite occurrences are taken additionally from the sources used. The limited size of the article does not allow to provide a complete database and a list of used references (about 100 titles).

Carbonatite occurrences are represented by bodies of various shapes and sizes (complexes, massifs, dikes, facies zones). Isotope analysis is applied to carbonatite rocks (sovite, alvikite, beforsite, etc.), monofractions of calcite, dolomite, ankerite, siderite. Authors of literature classify the analyzed material as primary carbonatites (PC). This is mainly done on the basis of petrographic studies, in which secondary endo- and exogenous minerals are not detected. Single anomalous values are excluded from the primary category by the author of the article. Numerous δ¹⁸O-δ¹³C values refer to secondary carbonatites in the used literature: carbonate tuffs and lavas, hydrothermal veins, hydrothermally altered and recrystallized carbonatites, weathered and oxidized carbonatites, secondary calcite. Data on secondary carbonatites is not used in this article.

All isotope diagrams have a horizontal x-axis δ¹⁸O (‰, V-SMOW) and a vertical y-axis δ¹³C (‰, V-PDV). The equal scale of both axes, a multiple of 1‰, allows to visually comparing the shape of the point sets (point fields) and the slope of the trend lines. The names of carbonatite occurrences and their identification number (ID) are coordinated with the database [8] and are given in English transcription.

2. Summary Data

The diagram in Figure 1 contains 1593 points of the δ¹⁸O-δ¹³C from 173 carbonatite occurrences, including various carbonatite facies in one occurrence. The number of points in the individual occurrences varies from 2 to 54. The points fill a very wide field. Analysis of the field is complex and incorrect due to the variable number and large scatter of points that characterize individual carbonatite occurrences. The contours PC-98% and PC-90% presented in the diagram are proved in Figure 2 and Figure 3.
Figure 1. Primary carbonatites (PC) of the world: a summary of $\delta^{18}O-\delta^{13}C$ paired values ($n = 1593$) and contours PC-98% (external) and PC-90% (internal).

Figure 2. Trend lines and middle points (black square) in occurrences with a linear trend ($n = 70$). Only middle points (black triangle) in other occurrences ($n = 103$). Polygonal contour PC-98% includes 98% of points.

Figure 3. The starting points in occurrences with a linear trend (fat point, $n = 70$) and in other occurrences (oblique cross, $n = 103$). The outer contour PC-98%. The internal contour PC-90% includes 90% of points and is divided into two halves of PC-45%.
Subsequent statistical analysis of isotope data uses summary indicators characterizing carbonatite occurrences. Trend (linear regression) analysis was performed in 140 occurrences that satisfy two conditions: 1) there are three or more points; 2) the arithmetic difference between the maximum and minimum δ18O values is more than 0.5‰. Trend lines under opposite conditions (less than three points and difference δ18O less than 0.5‰) cannot be reliable. The linear regression equation \( y = kx + b \) and the trend line are calculated in Microsoft Excel 97-2003. The complete database (it is too large to be here) contains a point diagram for each occurrence, a calculated angular coefficient \( k \), a constant \( b \), a coefficient of determination (approximation) \( R^2 \).

Examples of point diagrams in order of increasing coefficient \( R^2 \) are shown in Figure 4. According to the visual observation of the diagrams, the linear trend is absent or indistinct in the occurrences that have \( R^2 \) from 0.00 to 0.29. The number of such occurrences in the database is 70. The linear form of point fields begins to confidently be fixed from \( R^2 \geq 0.30 \) (occurrence 413. Chetlassky in Figure 4). The linear trend is found in 70 occurrences, where \( R^2 \) is from 0.30 to 0.99. The trend line is depicted as a vector directed upwards δ18O. Such a direction is taken in the literature on the geochemistry of carbonatites.

Appendix provides a summary Table with brief data on 173 carbonatite occurrences. The names of occurrences that are not in the database [8] are given without an ID number. Digital data include: 1) \( n, n^* \) is the number of paired values δ18O-δ13C in occurrences without a linear trend (\( n \)) and with a linear trend (\( n^* \)); 2) middle point arithmetic average δ18O-δ13C from among the values; 3) the starting point of the trend line or nonlinear field of δ18O-δ13C points; 4) minimum initial ratio 87Sr/86Sr. The position of carbonatite occurrences in the diagrams (Figure 2 and Figure 3) can be determined using the table values.

Trend line and middle point for 70 occurrences in which a linear trend is revealed are shown in the diagram (Figure 2). Only the middle point is shown for the remaining 103 occurrences. The polygonal contour PC-98% is delineated. It includes about 98% of all middle points. The diagram shows that trend lines vary significantly in length. The horizontal span of the lines (the arithmetic difference δ18Omax - δ18Omin) ranges from 0.5‰ to 11‰, in 90% of cases it does not exceed 7.5‰, on average it is 3.5‰.

The slope of the trend line varies widely, as seen in Figure 2. The slope is determined by the angular coefficient \( k \). Statistical analysis of the coefficient is shown in Figure 5. Three separate intervals of \( k \) are read on the point diagram: \(-0.73 \sim 0.09; 0.09 - 0.51; 0.51 - 1.51\). On the rose diagram, the intervals are shown as sectors, and the average for the three sectors is shown as vectors. Sector \( k \) with a range of 0.09 - 0.51 and a middle vector of 0.30 is sharply dominant. Sector \(-0.73 \sim 0.09 \) with a middle vector of \(-0.27 \) and sector 0.51 - 1.51 with a middle vector of 0.96 have a subordinate meaning.

The averaged shape of the field of points for three groups of occurrences with a linear trend and for one group without a trend is modeled in Figure 6. The
Figure 4. Examples of trend analysis of $\delta^{18}$O (x-axis, ‰) and $\delta^{13}$C (y-axis, ‰) values in carbonatite occurrences in order of increasing coefficient $R^2$.

arithmetic average differences $\delta^{18}$Omax - $\delta^{18}$Omin and $\delta^{13}$Cmax - $\delta^{13}$Cmin are calculated in each group. Rectangles with sides equal to these averages are shown in Figures 6(a)-(d). The modeled fields of points are inscribed in rectangles along the middle trend line. All fields in accordance with their averages are placed in Figure 6(e). Comparison of the fields shows that the lack of a clear linear form in the field 6d is due to the increased variation in the $\delta^{13}$C value. This may be due to the cumulative effect of trends 6a, 6b and 6c.
Figure 5. Point diagram (left) and rose diagram (right) of the angular coefficient $k$ in the regression equation $y = kx + b$ in occurrences with the linear trend $\delta^{18}O - \delta^{13}C$. The point diagram shows separate intervals $k$: $-0.73 - 0.09$ (average $-0.27$); $0.09 - 0.51$ (average $0.30$); $0.51 - 1.51$ (average $0.96$).

Figure 6. The averaged form of point fields: (a, b, c) occurrences with a linear trend with an angular coefficient of $0.96$, $0.30$ and $-0.27$; (d) occurrences without a linear trend with a middle point (straight cross) and a starting point (oblique cross); (e) comparison of the fields in the diagram.

Each carbonatite occurrence with a linear trend can be characterized by the starting point of the trend. The $\delta^{18}O$ of the starting point is equal to the minimum value in the statistical sample. The $\delta^{13}C$ value is calculated from the empirical regression equation. The values of $\delta^{18}O - \delta^{13}C$ starting points of the trends are given in the Table. Occurrences without a linear trend also imply the presence of a starting point. This follows from the previously made assumption that the nonlinear point field 6d in Figure 6 is the result of the cumulative influence of trends 6a, 6b and 6c. All trends are directed upwards $\delta^{18}O$, but in different directions along $\delta^{13}C$. Therefore, the starting point of field 6d must have $\delta^{18}O$ equal to the minimum of the statistical sample. The $\delta^{13}C$ value in some approximation can be taken equal to the average of the sample (Figure 6(d)). The $\delta^{18}O - \delta^{13}C$ of the starting point in the occurrences without the identified linear
trend is also given in the Table.

The diagram shows two groups of points (Figure 3): 1) the starting point of the trend line in the occurrences with a linear trend (n = 70); 2) the starting point of nonlinear fields in other occurrences (n = 103). The second group includes occurrences without a linear trend (n = 70), and also occurrences with only two points δ¹⁸O-δ¹³C (n = 24) and with a difference δ¹⁸Omax - δ¹⁸Omin < 0.5 (n = 9) that were excluded from the trend analysis. Visual analysis of the diagram allows to delineate the internal contour PC-90% in addition to the PC-98% contour justified in Figure 2. This contour includes a compact group of 90% starting points. The vertical line δ¹⁸O = 7.9‰ divides the contour PC-90% into two parts, each of which is 45% of the total number of starting points.

The contours of primary carbonatites PC-98%, PC-90% and PC-45% (left and right contours) are shown in the diagram (Figure 7). For comparison, the contours and points of primary igneous (mantle) carbonatites are given according to other authors. The closest is the left contour of PC-45% and the contour of Jones et al. [7]. The three middle vectors of the angular coefficient k are also shown in the diagram. The dominant trend k = 0.30 in the literature is usually associated with two factors that coincide in direction: 1) Rayleigh isotopic fractionation at high-temperature differentiation of carbonatite melts; 2) sedimentation (crustal) contamination of mantle melts. The second factor is illustrated by the directionality of the dominant trend on the contour of normal sedimentary rocks. The subordinate trend k = −0.27 is associated with the degassing of CO₂ from melts. Another subordinate trend k = 0.96 is not discussed in the literature. The beginning of the vectors is at the point (5‰ δ¹⁸O; −6.5‰ δ¹³C). The full sector of the angular coefficient (from −0.73 to 1.51) covers almost all occurrences from this point. Perhaps this point is close to the primary mantle source of carbonatites.

The used literature on O-C isotopy also contains data on the isotope composition of strontium. The minimum initial value of ⁸⁷Sr/⁸⁶Sr in 92 carbonatite occurrences is given in the Table. The field of minimum values in the coordinates ⁸⁷Sr/⁸⁶Sr-δ¹⁸O is presented in the diagram (Figure 8). There is no correlation between the values. The oblique line in the diagram is the line of mixing the mantle source (⁸⁷Sr/⁸⁶Sr = 0.702; δ¹⁸O = 5‰) and the sedimentary contaminant (⁸⁷Sr/⁸⁶Sr = 0.710; δ¹⁸O = 20‰) at equal concentrations of strontium in the sources. The stable enrichment of carbonatites with strontium in comparison with sedimentary carbonates is known. Under this condition, a band of points above the mixing line may reflect crustal contamination of magmas. However, a wide scatter of points below the mixing line leaves room for other hypotheses, including contamination of the source in the mantle. The PC-98%, PC-90% and PC-45% contours, previously substantiated in the coordinates δ¹⁸O-δ¹³C, are delineated in the diagram. The PC-45% contour is divided by the value ⁸⁷Sr/⁸⁶Sr = 0.704 into two fields. The field ⁸⁷Sr/⁸⁶Sr < 0.704 and δ¹⁸O < 7.75‰ can be considered as the primary mantle field in the O-C-Sr isotope system.
Figure 7. Fields and points of primary igneous carbonatites and middle trend vectors. NSC—normal sedimentary carbonates.

Figure 8. The isotope composition of strontium (minimum initial value) and oxygen (starting point) in carbonatite occurrences.

3. Conclusions

Data on the oxygen and carbon isotope composition of primary carbonatites for 173 carbonatite occurrences of the world were collected (1593 paired values of δ¹⁸O-δ¹³C). Primary carbonatites are rocks without petrographic signs of secondary hydrothermal and exogenous mineral changes. Primary carbonatites demonstrate a wide variation of the δ¹⁸O-δ¹³C values and linear trends, which indicates the isotopic heterogeneity of carbonatite substance.

Linear regression analysis of δ¹⁸O-δ¹³C values reveals linear trends in half of the carbonatite occurrences. The trend with an average angular coefficient of 0.30 (positive correlation δ¹⁸O-δ¹³C) sharply dominates. In the literature, this is explained by the Rayleigh high-temperature fractionation of carbonatite melts or by their sedimentary (crustal) contamination. The trend line span (arithmetic difference δ¹⁸Omax - δ¹⁸Omin) ranges from 0.5‰ to 11‰, on average it is 3.5‰. Increased trends (over 7.5‰) suggest the action not only of endogenous factors, but also the influence of secondary processes not recorded in petrographic ob-
The second trend with an average angular coefficient of $-0.27$ (negative correlation $\delta^{18}\text{O}-\delta^{13}\text{C}$) is rarer. This trend is usually associated with the CO$_2$ degassing from melts. A rare third trend is not discussed in the literature. It has an average angular coefficient of $0.96$ (positive correlation $\delta^{18}\text{O}-\delta^{13}\text{C}$). The linear trend of $\delta^{18}\text{O}-\delta^{13}\text{C}$ values is not detected in half of carbonatite occurrences due to increased variation of $\delta^{13}\text{C}$. This may be due to the combined action of different factors—contamination, high-temperature fractionation and degassing of melts.

The fields of primary carbonatites (PC) are delineated in the coordinates $\delta^{18}\text{O}-\delta^{13}\text{C}$ (‰), including $98\%$, $90\%$ and $45\%$ of the numbers of occurrences. The PC-$90\%$ contour can be considered acceptable for primary carbonatites. In-depth petrographic and other argumentation of the primary nature of carbonates is required for occurrences outside this contour. The PC-$45\%$ ($\delta^{18}\text{O} < 7.75\%$) contour with a high probability includes only primary carbonatites with a mantle source of a carbonate substance and with minimal effect of isotope fractionation or contamination of melts. A greater influence of these factors is expected for occurrences in the PC-$45\%$ ($\delta^{18}\text{O} > 7.75\%$) contour.

Strontium in carbonatite occurrences has a wide variation of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from 0.701 to 0.708. This variation and the absence of correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and the $\delta^{18}\text{O}-\delta^{13}\text{C}$ allow both mantle and crustal contamination of carbonatite magmas.

The stated statistical data on the O, C and Sr isotope composition in primary carbonatites leave room for additional and alternative judgments.

**Conflicts of Interest**

The author declares no conflicts of interest regarding the publication of this paper.

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### Appendix

Carbonatite occurrences: δ¹⁸O-δ¹³C values of middle and starting points of trends; minimum initial ratio ⁸⁷Sr/⁸⁶Sr (n* – occurrences with a linear trend, n – other occurrences)

| ID | Occurrence note | Country | Literary source | n, n* | Middle point | Starting point | ⁸⁷Sr/⁸⁶Sr |
|----|----------------|---------|----------------|-------|--------------|---------------|-----------|
|    |                |         |                |       | δ¹⁸O | δ¹³C | δ¹⁸O | δ¹³C | ⁸⁷Sr/⁸⁶Sr |
| 1  | InOuzzal       | Algeria | Ouzegane et al., 1988 | 7     | 9.38 | −7.72 | 7.65 | −7.72 | -     |
| 5  | Bailundo      | Angola  | Pineau et al., 1973; Alberti et al., 1999 | 8*    | 9.60 | −5.34 | 6.70 | −6.50 | -     |
| 6  | Monte Verde    | Angola  | Pineau et al., 1973; Alberti et al., 1999 | 15*   | 9.01 | −4.53 | 5.30 | −6.21 | -     |
| 10 | Tchivira-Bonga | Angola  | Alberti et al., 1999 | 7*    | 12.28 | −3.74 | 9.42 | −4.51 | -     |
| 15 | Lupongola     | Angola  | Alberti et al., 1999 | 10*   | 9.23 | −7.37 | 7.52 | −7.88 | -     |
| 16 | Matongo       | Bourundi | Dolenek et al., 2015; Decree et al., 2015 | 13*   | 7.54 | −5.21 | 6.53 | −5.63 | -     |
| 19 | Lueshe        | Congo   | Самойлов, 1984 | 2     | 7.90 | −5.85 | 7.80 | −5.85 | -     |
| 21 | Wadi Tarr     | Egypt   | Shimron, 1975 | 3*    | 6.43 | −7.67 | 5.20 | −6.76 | -     |
| 29 | Rangwa        | Kenya   | Suva et al., 1975 | 5*    | 15.10 | −5.56 | 10.10 | −4.22 | 0.7042 |
| 33 | Homa Mountain | Kenya   | Dennis and Schrag, 2010 | 8*    | 8.51 | −3.36 | 7.70 | −3.52 | -     |
| 34 | Buru-siderite | Kenya   | Onguona, 1997 | 16    | 14.48 | −3.94 | 12.61 | −3.94 | -     |
| 39 | Kangankunde   | Malawi  | Dennis and Schrag, 2010; Nelson, 1987; Broom-Fendley et al., 2017 | 9     | 8.49 | −4.79 | 5.50 | −4.79 | 0.7016 |
| 47 | Chilwa Island | Malawi  | Simonetti and Bell, 1994 | 16    | 11.48 | −2.61 | 7.90 | −2.61 | 0.7032 |
| 48 | Tundulu       | Malawi  | Самойлов, 1984 | 2     | 12.35 | −3.25 | 10.40 | −3.25 | -     |
| 51 | Songwe Hill   | Malawi  | Broom-Fendley et al., 2016 | 4*    | 11.13 | −4.00 | 7.80 | −3.40 | -     |
| 64 | Tamazert      | Morocco | Bouabdellah et al., 2010; Marks et al., 2009 | 42    | 8.60 | −5.62 | 6.94 | −5.62 | 0.7033 |
| 73 | Xíluvo        | Mozambique | Melluso et al., 2004 | 3*    | 9.63 | −5.32 | 7.50 | −5.10 | 0.7032 |
| 75 | Swartbooisdrif| Namibia | Thompson et al., 2002 | 2     | 8.01 | −7.37 | 7.90 | −7.37 | -     |
| 78 | Okorusu       | Namibia | Le Roex and Lanyon, 1998 | 2     | 8.80 | −4.64 | 8.11 | −4.64 | 0.7043 |
| 79 | Ondurakorume  | Namibia | Le Roex and Lanyon, 1998 | 2     | 8.80 | −4.64 | 6.47 | −4.64 | 0.7035 |
| 82 | Lofdal        | Namibia | Vistorina Nandigolo, 2013 | 3*    | 8.08 | −5.13 | 6.43 | −5.57 | 0.7027 |
| 89 | Dicker Willem  | Namibia | Reid and Cooper, 1992 | 2     | 8.00 | −5.00 | 7.00 | −5.00 | -     |
| 103| Phalaborwa    | S. Africa | Suwa et al., 1975 | 4     | 9.05 | −3.85 | 8.00 | −3.85 | 0.7039 |
| 105| Spitskop-calcite | S. Africa | Harmer, 1999; Suwa et al., 1975 | 8*    | 14.14 | −2.86 | 11.70 | −2.80 | 0.7028 |
| 105| Spitskop-dolomite | S. Africa | Harmer, 1999; Suwa et al., 1975 | 7     | 16.72 | −1.99 | 15.97 | −1.99 | -     |
| 108| Noolgedacht   | S. Africa | Clarke, 1989 | 2     | 9.05 | −4.30 | 8.20 | −4.30 | -     |
| 109| Kruidfonten   | S. Africa | Clarke, 1989 | 5*    | 13.32 | −2.40 | 10.90 | −3.14 | -     |
| 113| Premier Mine  | S. Africa | Suwa et al., 1975 | 4*    | 11.93 | −6.50 | 11.40 | −6.84 | -     |
| 122| Zandkopsdrift | S. Africa | Onguona, 1997; Halama et al., 2007 | 10    | 14.95 | −5.77 | 13.20 | −5.77 | -     |
| 126| Oldoinyo Lengai | Tanzania | Bell and Keller, 1995; Halama et al., 2007 | 9     | 7.47 | −6.86 | 5.78 | −6.86 | 0.7044 |
Continued

| Place | Country | Origin | Study Authors | Age (Ma) | Depth (m) | Temperature (°C) | Heat Flow (mW/m²) | Heat Production (μW/m³) |
|-------|---------|--------|---------------|----------|-----------|------------------|-------------------|------------------------|
| Kerimasi | Tanzania | Zaitsev et al., 2013 | 3* | 9.43 | –3.73 | 7.43 | –4.20 |
| Panda Hill (Mbeya) | Tanzania | Suwa et al., 1975; Dennis and Schrag, 2010; Dolenek et al., 2015 | 13 | 7.48 | –4.70 | 5.90 | –4.70 | 0.7034 |
| Bukusu | Uganda | Cassola et al., 1984 | 2 | 10.40 | –2.90 | 8.50 | –2.90 |
| Tororo | Uganda | Nelson, 1987; Dennis, 2010 | 10* | 9.03 | –2.73 | 7.30 | –3.49 | 0.7025 |
| Sukulu | Uganda | Deines and Gold, 1973 | 8* | 9.65 | –2.66 | 7.30 | –3.18 | 0.7026 |
| Aley-calcite | Canada | Mader, 1986; Chakhmouradian et al., 2015 | 6 | 8.53 | –5.23 | 7.70 | –5.23 |
| Wicheeda-calcite | Canada | Trofanenko, 2014 | 2 | 6.94 | –6.29 | 6.91 | –6.29 |
| Wicheeda-dolomite | Canada | Trofanenko, 2014 | 4 | 9.72 | –5.59 | 9.36 | –5.59 |
| Eden Lake | Canada | Chakhmouradian et al., 2008 | 9 | 8.08 | –7.96 | 7.91 | –7.96 |
| Albany Forks | Canada | Suva et al., 1975 | 10* | 9.30 | –4.42 | 8.50 | –4.42 |
| St-Andre | Canada | Suva et al., 1975 | 15* | 10.78 | –2.55 | 8.70 | –3.32 |
| Oka | Canada | Dennis and Schrag, 2010; Chen and Simonetti, 2015; Haynes et al., 2003 | 26 | 6.96 | –5.43 | 6.44 | –5.43 | 0.7032 |
| Aillik Bay-dolomite | Canada | Tappe et al., 2006 | 3* | 11.13 | –2.77 | 10.80 | –2.82 | 0.7040 |
| Aillik Bay-dol-calc | Canada | Tappe et al., 2006 | 11 | 10.75 | –3.86 | 9.60 | –3.86 | 0.7039 |
| Paint Lake | Canada | Chakhmouradian et al., 2010 | 2 | 8.45 | –6.05 | 7.80 | –6.05 |
| Wekusko Lake | Canada | Chakhmouradian et al., 2009 | 7 | 23.54 | –5.83 | 20.04 | –5.83 | 0.7035 |
| Gardiner | Greenland | Nielsen and Buchardt, 1985 | 3* | 10.97 | –3.53 | 10.30 | –3.93 |
| Sarfartog | Greenland | Tappe et al., 2011 | 2 | 12.02 | –3.21 | 11.63 | –3.21 | 0.7036 |
| Grnmedal-Ika | Greenland | Pearson 1997; Coulson et al., 2003; Halama et al., 2005 | 18 | 7.70 | –4.40 | 6.65 | –4.40 | 0.7029 |
| Qaarssuk-olivine sövite | Greenland | Knudsen and Buchardt, 1991 | 7* | 7.47 | –3.31 | 7.06 | –3.47 |
| Qaarssuk-sövite | Greenland | Knudsen and Buchardt, 1991 | 4 | 7.28 | –3.82 | 6.90 | –3.82 |
| Qaarssuk-dolomite sövite | Greenland | Knudsen and Buchardt, 1991 | 5* | 8.40 | –3.29 | 7.32 | –3.51 |
| Igaliko | Greenland | Coulson et al., 2003 | 9 | 13.02 | –3.81 | 8.60 | –3.81 | 0.7027 |
| Bearpaw Mount. | USA | Dennis and Schrag, 2010 | 8* | 8.70 | –7.74 | 8.30 | –8.19 |
| Bear Lodge | USA | Moore, 2014 | 10 | 10.12 | –9.20 | 8.70 | –9.20 | 0.7046 |
| Wet Mountains | USA | Armbrustmacher, 1979 | 4 | 8.88 | –4.40 | 7.10 | –4.40 |
| Iron Hill | USA | Jones et al., 2013; Hugh et al., 1966 | 3* | 8.33 | –5.13 | 7.30 | –5.66 | 0.7046 |
| Magnet Cove | USA | Haynes et al., 2003; Nelson et al., 1988 | 8* | 7.30 | –5.50 | 5.40 | –5.66 | 0.7035 |
| Cerro Sapo | Bolivia | Schultz et al., 2004 | 4* | 9.84 | –8.39 | 7.16 | –7.71 | 0.7034 |
| Chiaracke | Bolivia | Schultz et al., 2004 | 3 | 12.10 | –5.60 | 11.90 | –5.60 | 0.7035 |
| Angico dos Dias | Brazil | Antonini et al., 2003 | 16 | 14.78 | –6.48 | 11.92 | –6.48 | 0.7033 |
| Catalao II | Brazil | Vincenza Guarino et al., 2016 | 10 | 8.79 | –6.00 | 8.45 | –6.00 | 0.7050 |
| Catalao I | Brazil | P. F. de Oliveira Cordeiro et al., 2011 | 5* | 10.86 | –5.74 | 9.20 | –5.27 | 0.7051 |
| Salitre | Brazil | Brod, 1999 | 12* | 7.55 | –6.90 | 6.90 | –7.23 |
| Araxa | Brazil | Santos and Clayton, 1995 | 4* | 9.78 | –6.98 | 8.70 | –6.88 |

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|   | Location         | Country |   |   |   |   |
|---|----------------|---------|---|---|---|---|
| 299 | Tapira | Brazil | Brod, 1999 | 45° | 9.32 | −6.54 | 5.40 | −7.84 | 0.7052 |
| 303 | Jacupiranga | Brazil | Comin-Chiaramonti et al., 2007; Haynes et al., 2003; Nelson, 1987 | 25° | 7.28 | −6.37 | 5.40 | −7.21 | 0.7050 |
| 305 | Barra do Itapirapua | Brazil | Andrade et al., 1999; Santos and Clayton, 1995; Andrade et al., 1999; Comin-Chiaramonti et al., 2001 | 9° | 8.34 | −5.91 | 6.70 | −6.46 | - |
| 306 | Mato Preto | Brazil | Comin-Chiaramonti et al., 2007; Haynes et al., 2003; Nelson, 1987 | 20° | 12.35 | −1.38 | 8.00 | −6.96 | 0.7047 |
| 310 | Chiriguelo | Paraguay | Gomide et al., 2016; Comin-Chiaramonti et al., 2007; Haynes et al., 2003; Nelson, 1987 | 20° | 14.97 | −6.36 | 5.40 | −7.78 | 0.7072 |
| 318 | Wajilitage | China | W. Song et al., 2017 | 9° | 7.62 | −4.62 | 6.40 | −3.91 | 0.7037 |
| 323 | Bayan Obo-dike | China | Yang X et al., 2000; Le Bas 2000; Andrade et al., 1999; Comin-Chiaramonti et al., 2001 | 12° | 14.24 | −6.03 | 11.90 | −6.75 | - |
| 325 | South Qinling | China | C. Xu et al., 2014 | 17° | 11.45 | −4.78 | 8.62 | −6.16 | 0.7036 |
| 332 | Dashigou | China | H.-M. Ye et al., 2013 | 7 | 8.70 | −3.88 | 8.24 | −3.88 | 0.7056 |
| 332 | Yuantou | China | C. Xu et al., 2010 | 2 | 9.16 | −6.68 | 9.13 | −6.68 | - |
| 337 | Miaoya | China | Çimen et al., 2018 | 10 | 11.14 | −5.23 | 9.41 | −5.23 | 0.7036 |
| 338 | Shaxiongdong | China | C. Xu et al., 2008 | 5° | 7.58 | −5.94 | 6.92 | −6.05 | - |
| 340 | Maoniuping | China | Z. Hou et al., 2009 | 7° | 8.03 | −5.97 | 7.00 | −6.91 | 0.7061 |
| 340 | Muluozhai | China | Z. Hou et al., 2009 | 5 | 8.70 | −6.72 | 7.22 | −6.72 | 0.7066 |
| 340 | Lihuang | China | Z. Hou et al., 2009 | 2 | 11.00 | −4.85 | 10.10 | −4.85 | 0.7063 |
| 346 | Sarnu-Dandali | India | Ray and Ramesh, 1999; Ray et al., 2000 | 7° | 8.91 | −5.10 | 8.20 | −5.52 | - |
| 349 | Mundwara | India | Ray and Ramesh, 1999; Ray et al., 2000 | 8° | 7.54 | −5.44 | 6.00 | −6.55 | - |
| 350 | Newania | India | Viladkar and Ramesh, 2014 | 7° | 10.51 | −4.24 | 7.60 | −5.49 | 0.7021 |
| 355 | Siriwasan | India | Viladkar and Gittins, 2016 | 14 | 12.50 | −6.17 | 8.50 | −6.17 | 0.7054 |
| 356 | Amba Dongar | India | Gwalani et al., 2010; Viladkar and Ramesh, 2014; Simonetti et al., 1995 | 48 | 10.88 | −4.16 | 7.20 | −4.16 | 0.7055 |
| 356 | Amba Dongar-dike | India | Viladkar and Ramesh, 2014; Gwalani et al., 2010 | 21° | 11.75 | −4.11 | 7.60 | −4.71 | - |
| 357 | Swangkre | India | Ray et al., 1999 | 7 | 9.51 | −3.60 | 9.30 | −3.60 | - |
| 358 | Sung Valley | India | Ray et al., 1999; Srivastava et al., 2005; Viladkar and Ramesh, 2014 | 35 | 7.66 | −3.06 | 7.10 | −3.06 | 0.7047 |
| 360 | Samchampi | India | Ray et al., 1999 | 11 | 7.25 | −3.60 | 7.00 | −3.60 | - |
| 365 | Hogenakkal | India | Pandit, 2002 | 4 | 8.23 | −6.13 | 8.10 | −6.13 | 0.7016 |
| 366 | Samalpatti | India | Ackerman et al., 2017 | 6 | 10.78 | −3.50 | 10.10 | −3.50 | 0.7058 |
| 367 | Sevattur | India | Pandit, 2003; Kumar et al., 1998; Ackerman et al., 2017 | 12 | 8.93 | −5.25 | 7.51 | −5.25 | 0.7052 |
| 369 | Mulakkadu | India | Pandit, 2002 | 5 | 7.44 | −3.78 | 7.30 | −3.78 | 0.7066 |
| 378 | Matcha | Kirgystan | Vrublevskii, 2017 | 9° | 20.73 | −3.58 | 18.00 | −5.49 | 0.7070 |
| 379 | Hongcheon | S. Korea | Kim et al., 2005; Kwon and Yeang, 2003 | 7° | 9.53 | −6.36 | 7.96 | −7.71 | - |
| 379 | Yonghwa | S. Korea | Jieun Seo et al., 2016 | 7 | 9.23 | −7.00 | 7.70 | −7.00 | - |
| 380 | Mushugai Khuduk | Mongolia | Владыкин и др., 2004 | 4 | 15.73 | −1.53 | 15.20 | −1.53 | 0.7054 |
| No. | Location          | Country | Reference Details                                                                 |
|-----|-------------------|---------|-----------------------------------------------------------------------------------|
| 383 | Ulugei           | Mongolta| Kuleshov, 1986                                                                     |
| 393 | Zhlobin          | Belarus | Veretennikov and dr., 2007                                                          |
| 398 | Khibiny          | Russia  | Zaitzev, 1996; Покровский, 2000                                                     |
| 399 | Ozernaya Varaka  | Russia  | Самойлов, 1984                                                                     |
| 400 | Africkanda       | Russia  | Самойлов, 1984                                                                     |
| 401 | Lesnaya Varaka   | Russia  | Кухаренко и Донцова, 1962                                                            |
| 405 | Telyachi Island  | Russia  | Beard et al., 1996                                                                 |
| 406 | Turiy Mys        | Russia  | Dunworth and Bell, 2001; Demeny et al., 2004                                       |
| 407 | Kovdor           | Russia  | Плюснин и др., 1980; Владыкин и др., 2004                                          |
| 408 | Sallanlatvi      | Russia  | Demeny et al., 2004                                                                 |
| 409 | Vuoriyarvi       | Russia  | Demeny et al., 2004; Владыкин и др., 2004                                          |
| 410 | Tikaheozero      | Russia  | Щипцов, 1988                                                                      |
| 413 | Chetlassky       | Russia  | Удоратина и др., 2014; Шумилова и др., 2012                                       |
| 417 | Guli             | Russia  | Владимырик и др., 2000                                                              |
| 418 | Odikhincha       | Russia  | Плюснин и др., 1980                                                                 |
| 420 | Kugda            | Russia  | Покровский, 2000                                                                   |
| 426 | Magan            | Russia  | Кравченко и Багдасаров, 1987                                                       |
| 428 | Essei            | Russia  | Кравченко и Багдасаров, 1987; Владыкин и др., 2004                                  |
| 436 | Up. Petropavlovka| Russia  | Proskurnin et al., 2010                                                             |
| 437 | Edelveis         | Russia  | Vrublevskii, 2015                                                                  |
| 438 | Tagna            | Russia  | Владыкин и др., 2004                                                                |
| 439 | Nizhnesayansky   | Russia  | Doroshkevich et al., 2016; Владыкин и др., 2004                                    |
| 440 | Verkhesayansky   | Russia  | Владыкин и др., 2004                                                                |
| 441 | Kharly           | Russia  | Vrublevskii, 2003                                                                  |
| 443 | Zhidoy           | Russia  | Morikyio et al., 2000                                                               |
| 445 | Karasug-calcite  | Russia  | Nikiforov et al., 2006                                                             |
| 446 | Karasug-siderite | Russia  | Nikiforov et al., 2006                                                             |
| 447 | Karasug-Teli     | Russia  | Nikiforov et al., 2006                                                             |
Continued

| Location                  | Country           | Authors, Year(s) | A      | B      | C      | D      |
|---------------------------|-------------------|-----------------|--------|--------|--------|--------|
| Karasug-Ulatay            | Russia            | Nikiforov et al., 2006 | 3*     | 11.70  | −4.30  | 10.40  | −4.02 |
| Yuzhnoe                   | Russia            | Никифоров и др., 2000; Рипп и др., 2000 | 4*     | 7.55   | −5.60  | 6.20   | −5.97 |
| Khaluta                   | Russia            | Никифоров и др., 2000; Рипп и др., 2000 | 8      | 12.03  | −6.50  | 9.30   | −6.50 | 0.7057 |
| Oshurkovo                 | Russia            | Никифоров и др., 2000; Рипп и др., 2000 | 10     | 10.74  | −6.40  | 7.00   | −6.40 | 0.7053 |
| West. Baical-calcite      | Russia            | Савельева et al., 2016 | 4      | 12.70  | −3.98  | 12.50  | −3.98 | 0.7048 |
| West. Baical-dolomite     | Russia            | Савельева et al., 2016 | 6*     | 12.37  | −3.28  | 11.90  | −3.48 | 0.7057 |
| Yuzhnoe                   | Russia            | Doroshkevich et al., 2007; Ласточкин, 2009 | 10     | 10.16  | −1.59  | 9.10   | −1.59 |
| Pogranichnoe              | Russia            | Doroshkevich et al., 2006 | 3      | 8.67   | −0.20  | 8.41   | −0.20 | 0.7038 |
| Murun                     | Russia            | Владыкин и др., 2004; Покровский, 2000 | 20     | 8.42   | −7.36  | 6.0    | −7.36 | 0.7062 |
| Seligdar                  | Russia            | Doroshkevich et al., 2018 | 5      | 16.48  | −5.36  | 15.90  | −5.36 | 0.7064 |
| Khani                     | Russia            | Владыкин и др., 2004 | 2      | 8.55   | −8.20  | 8.50   | −8.20 | 0.7045 |
| Ingili                    | Russia            | Владыкин и др., 2004 | 2      | 8.05   | −6.55  | 8.00   | −6.55 |
| Arbarastakh               | Russia            | Владыкин и др., 2004 | 3      | 8.27   | −5.07  | 7.60   | −5.07 |
| Koksharovsky              | Russia            | Октябрьский и др., 2010 | 9      | 11.00  | −5.17  | 9.00   | −5.17 |
| Eppawala                  | Sri Lanka         | Мантилаке et al., 2008; Питавала et al., 2003 | 27*    | 14.27  | −2.69  | 7.70   | −3.73 | 0.7049 |
| Karacayır                 | Turkey            | Суичи, 2012; Лихов и др., 2007 | 11*    | 10.06  | −1.71  | 6.50   | −2.59 |
| South Nam Xe              | Vietnam           | T. Nguyễn Thị et al., 2014 | 17     | 9.80   | −3.30  | 9.10   | −3.30 | 0.7082 |
| Mt Weld                   | Australia         | Salier et al., 2004 | 5      | 10.51  | −5.44  | 9.24   | −5.44 | 0.7033 |
| Yungul                    | Australia         | Gwalani et al., 2010 | 37*    | 13.84  | −5.69  | 10.40  | −6.20 |
| Cummins Range             | Australia         | Downes et al., 2014 | 6*     | 8.28   | −4.10  | 7.50   | −4.17 |
| Mud Tank                  | Australia         | Wilson, 1979      | 4      | 7.50   | −4.13  | 7.50   | −4.13 | 0.7032 |
| Haast River-calcite       | New Zealand       | Cooper and Paterson, 2008 | 6*     | 8.97   | −6.22  | 6.70   | −6.69 |
| Haast River-dolomite      | New Zealand       | Cooper and Paterson, 2008 | 4*     | 13.48  | −5.18  | 11.50  | −5.77 |
| Sokli                     | Finland           | Демене et al., 2004 | 7*     | 7.86   | −3.76  | 7.10   | −4.13 |
| Laivajoki                 | Finland           | Нюканен et al., 1997 | 7*     | 6.81   | −4.44  | 5.91   | −3.93 |
| Kortejärvi                | Finland           | Нюканен et al., 1997 | 7*     | 7.49   | −4.03  | 6.58   | −3.87 |
| Siilinjarvi               | Finland           | Нюканен et al., 1997 | 6      | 9.22   | −4.07  | 7.40   | −4.07 |
| Laacher See               | Germany           | Hugh et al., 1966; Jones et al., 2013 | 13     | 7.39   | −6.60  | 6.30   | −6.60 |
| Rockeskyll                | Germany           | Riley et al., 1999 | 3*     | 12.40  | −5.07  | 11.10  | −4.94 | 0.7041 |
| Kaiserstuhl               | Germany           | Hubberten, 1988; Dolenek et al., 2015; Dennis and Schrag, 2010 | 54     | 9.69   | −5.95  | 5.70   | −5.95 | 0.7036 |
| Pelagonian Zone           | Greece            | Schenker et al., 2018 | 6      | 10.75  | −5.49  | 10.40  | −5.49 | 0.7042 |
| Location          | Country     | Source                                           | N  | Zn (ppm) | Cu (ppm) | Ni (ppm) | Fe (ppm) | Mn (ppm) |
|-------------------|-------------|--------------------------------------------------|----|----------|----------|----------|----------|----------|
| Mt. Vulture       | Italy       | Stoppa et al., 2016; Rosatelli et al., 2010      | 4* | 10.90    | -4.78    | 10.30    | -4.93    |          |
| Fen               | Norway      | Broom-Fendley et al., 2016; Andersen, 1987       | 8  | 6.90     | -4.79    | 5.70     | -4.79    | 0.7021   |
| Alnö              | Sweden      | Roopnarain, 2013; Hugh et al., 1966; Jones et al, 2013 | 29 | 7.71     | -5.53    | 6.40     | -5.53    | 0.7029   |
| Chernigovsky      | Ukraine     | Луговая и др., 1978                              | 11 | 8.49     | -5.77    | 5.30     | -5.77    | 0.7013   |
| Loch Borralan     | UK Scotland | Young et al., 1994                              | 2  | 10.36    | -5.02    | 10.32    | -5.02    |          |
| Fuerteventura     | Spain       | Hoernle et al., 2002; Шумилова и др., 2012       | 12 | 7.32     | -5.72    | 6.60     | -5.72    |          |
| Sao Vicente       | Cape Verdes | Hoernle et al., 2002                            | 2  | 7.85     | -4.80    | 7.30     | -4.80    | 0.7031   |
| Fogo              | Cape Verdes | Hoernle et al., 2002                            | 4* | 6.58     | -6.70    | 5.30     | -7.09    | 0.7031   |