Sulfur, carbon and oxygen isotopic compositions of Newania carbonatites of India: implications for the mantle source characteristics

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This study presents first report of the sulfur isotopic compositions of carbonatites from the Mesoproterozoic Newania complex of India along with their stable C and O isotope ratios. The δ34S_{V-CDT} (−1.4 to 2‰) and Δ33S (−0.001 to −0.13‰) values of these carbonatite samples (n = 7) overlap with the S isotope compositions of Earth’s mantle. Additionally, the δ13C_{PDB} and δ18O_{SMOW} values of these carbonatites also show overlapping compositions to that of Earth’s mantle. Based on these mantle–like stable isotopic compositions of carbonatites along with their higher crystallization temperature (~ 600 °C) compared to a hydrothermal fluid (<250 °C), we suggest that the sulfide minerals in these carbonatites were formed under a magmatic condition. The mantle like signatures in the δ34S, δ13C–δ18O, and 87Sr/86Sr values of these carbonatites rule out possible crustal contamination. Coexistence of the sulfide phase (pyrrhotite) with magnesite in these carbonatites suggests that the sulfide phase has formed early during the crystallization of carbonate magmas under reducing conditions. Overall restricted variability in the δ34S values of these samples further rules out any isotopic fractionation due to the change in the redox condition of the magma and reflect the isotopic composition of the parental melts of the Newania carbonatite complex. A compilation of δ34S of carbonatites from different complexes worldwide indicates limited variability for carbonatites older than 400 Ma, which broadly overlaps with Earth’s asthenospheric mantle composition. This contrasts with the larger variability in δ34S observed in carbonatites younger than 400 Ma. Such observation could suggest an overall lower oxidation state of carbonate magmas emplaced prior to 400 Ma.

Keywords: Carbonatites, Newania complex, Sulfur–carbon–oxygen isotopes, Mantle origin

INTRODUCTION

Carbonatites are unique magmatic rocks with more than 50% modal carbonates. The predominant carbon(ate)-rich nature of carbonatites implies that their petrogenesis is linked with the Earth’s carbon cycle. Carbonates in carbonatites could be of recycled in origin or derived from the incipient melting of primordial carbon-rich mantle. Recent studies on stable boron (δ11B) and calcium (δ44/40Ca) isotopic compositions of carbonatites worldwide have suggested that recycled origin of carbonates in carbonatites is more prevalent in the last 300 Ma (Hulett et al., 2016; Banerjee and Chakrabarti, 2019; Banerjee et al., 2021); the crustal recycling signature is less prevalent in carbonatites older than 300 Ma which mostly show pristine mantle–like compositions (Hulett et al., 2016; Banerjee et al., 2021).

Along with carbon, carbonatites are also enriched in sulfur (Mitchell and Krouse, 1975) and the sulfur species present in these magmas depend mainly on the mantle redox conditions. Therefore, sulfur isotopic compositions of carbonatites can provide additional insights into the evolution of these magmas and the mineralizing fluids (magmatic versus hydrothermal origin). The δ34S values of carbonatites (WR and sulfide minerals) from different complexes worldwide show significant variation (~ −15 to +15‰) (e.g., Mitchell and Krouse, 1975; Farrell et al., 2010; Gomide et al., 2013; Bolhar et al., 2020). Some of this variability has been explained by sulfur isotopic heterogeneity in the mantle source of carbonatites (Mitchell and Krouse, 1975; Bolhar et al., 2020). Additionally, the
variability in the $\delta^{34}S$ of carbonatites from different complexes worldwide are explained by temperature dependent fractionation between sulfide phases and parent magma, magmatic degassing, and oxidation state of parent carbonatite magma (e.g., Gomide et al., 2013; Bell et al., 2015).

Carbonatites of the Newania complex in Rajasthan, India are unique as they are primarily composed of dolomite and ankerite and are devoid of associated alkaline silicate rocks. This contrasts with the worldwide occurrence of carbonatites which are primarily calcicarbonatites and associated with alkaline, mafic and/or ultramafic silicate rocks (e.g., Jones et al., 2013 and references therein). Petrogenetic studies of this carbonatite complex have utilized mineral chemistry, stable carbon, oxygen, and radiogenic Nd and Sr isotope ratios to understand the source characteristics (Doroshkevich et al., 2010; Ray et al., 2010, 2013). Despite occurrences of sulfur-bearing minerals in the carbonatites of this complex, their sulfur isotopic compositions and its petrogenetic significance have not been investigated. In this study we report multiple sulfur isotope data of carbonatites from the Newania complex along with their stable carbon and oxygen isotope ratios to characterize the nature and source of the sulfur-bearing fluids and its petrogenetic implications. This study reports the first sulfur isotope data of carbonatites from the Indian subcontinent and investigate the source of sulfur in carbonatites from a unique carbonatite complex which is primarily composed of magnesio and ferrocarnobonatites.

**GEOLOGICAL BACKGROUND**

The ~ 1473 Ma old Newania carbonatite complex is located in the state of Rajasthan in the north–western part of India (24°38’ N, 74°03’E) (Ray et al., 2013) and these carbonatites are primarily composed of ferrocarbonatites in the central part surrounded by magnesio carbonatite (Fig. 1a). The Newania carbonatites intrude into the 2.95 Ga old Untala Granite Gneiss, part of the Banded Gneissic Complex of Indian subcontinent (Fig. 1a), and host hydrothermal base metal deposits in the form of pyrochlore and chalcopyrite (Doroshkevich et al., 2010).

A mantle origin of the Newania carbonatite complex has been advocated by multiple studies based on their stable ($\delta^{13}C$, $\delta^{18}O$ and $\delta^{44}/^{40}Ca$ values) and radiogenic ($^{87}Sr/^{86}Sr$) isotopic compositions (Ray et al., 2010; Banerjee et al., 2021). However, the source of sulfur-bearing fluids in these carbonatites have never been investigated before. In the subsequent sections we discuss the mineralogy of these carbonatites, characterize the sulfide minerals, and their stable isotopic compositions. Carbonatite samples used in this study are primarily medium-to-coarse grained and were collected from a quarry (Fig. 1b).

**PETROGRAPHY**

Newania carbonatites are primarily composed of dolomite and ankerites with variable proportions of magnesite, phlogopite, amphibole, pyrochlore, and apatite in the groundmass (Doroshkevich et al., 2010; Ray et al., 2013). Sulfide minerals in the collected carbonatite samples are visible in hand specimen and these samples were analyzed further for their isotopic compositions. Back scattered electron (BSE) images were obtained for two carbonatites (Newania3 and Newania6) where sufficient samples were present for their petrography and isotopic studies (Fig. 2). The sulfide-bearing carbonatite samples from Newania show that carbonates are dominantly made up of Fe–rich magnesites with interstitial Mg–rich ankerites (Fig. 2). The accessory minerals include hematite, apatite, phlogopite, graphite and sulfide minerals which
are dominated by pyrrhotite (Fig. 2). Secondary alteration is visible along fractures (Fig. 2a).

**ANALYTICAL METHODS**

Powdered rock samples have been used in this study for their stable C–O \((n = 7)\) and multi–S isotope ratio \((n = 7)\) measurements. For the measurements of stable C–O isotopes, aliquots of powdered carbonatite samples were placed in small stainless steel thimbles and dropped into a reaction vessel containing pyrophosphoric acid at 100°C in a vacuum to produce CO2 gas. The released CO2 was purified by using pentane slush and collected by using liquid nitrogen cold traps. Isotope ratio measurements were carried out using a Thermo Fischer MAT 253 gas source–ion ratio mass spectrometer (IRMS) at Niigata University, Japan. Results are reported with respect to V-PDB (Vienna–Pee Dee Belemnite) and V-SMOW (Vienna–Standard Mean Ocean Water) for C and O isotopes, respectively. The external reproducibility of δ13C and δ18O values for the laboratory standard CO2 gas were 0.03 and 0.05‰, respectively.

For S isotope ratio measurements, sulfide was extracted from the powdered rock samples and multiple separate rock chips containing sulfide minerals using a method described in Mishima et al. (2017). Approximately 1–4 g of powdered samples were treated in glass containers. The containers were purged with nitrogen gas followed by
addition of 20 ml each of 5 M HCl and CrCl2 solution. The samples were allowed to react with HCl and CrCl2 mixture for 48 h. In this process, liberated S from the sample was converted to H2S which upon reaction with alkaline Zn trap solution (a 3:5 mixture of 0.2 M zinc acetate and 2 M NaOH) was precipitated as ZnS. The precipitated ZnS was cleaned by using 18.2 M Ω–cm water and further converted to Ag2S by reacting with 10 ml of 0.1 M AgNO3 and 1 ml of 10 M HNO3. The precipitated Ag2S was extracted by decanting the chemical mixture upon centrifugation and further cleaned by using 18.2 M Ω–cm water and dried in an oven at 60 °C. Approximately 0.6–0.9 mg of Ag2S powder was mixed with ~ 15 mg CoF2 and wrapped in a pyro foil (590 °C). This mixture was flash heated using a Curie–point pyrolizer to liberate SF6 gas from the sample and the gas was passed through a vacuum line and gas chromatographs following the procedure described in Ueno et al. (2015). The purified SF6 was introduced into the mass spectrometer for sulfur isotopic measurements using a Thermo Fischer MAT 253 mass–spectrometer at Niigata University. The obtained values for S isotope ratios were normalized using the standard Vienna Canyon Diablo Troilite (V–CDT). Repeated measurements of SI IAEA standards produced an external reproducibility better than 0.6‰ for δ34S and 0.01‰ for Δ33S (1 SD, n = 20). Sulfur concentrations in these samples were estimated based on the obtained Ag2S amount and the initial weight of the powdered carbonatite samples.

RESULTS

Stable carbon and oxygen isotope ratios of seven carbonatites, multi–S isotope compositions of six carbonatite samples with their S concentrations along with their 87Sr/86Sr (Banerjee et al., 2021), are reported in Table 1 and shown in Figures 3–5. The δ13C (−4.2 to −5.2‰) and δ18O values (+5.5 to +7.3‰) of seven carbonatite samples display limited variability. The δ34S and Δ33S values of these samples range from −1.4 to 2.0‰ and 0.001 to −0.13‰, respectively. Sulfur concentration in these samples range from 44 to 1511 µg/g.

DISCUSSION

Variation in the δ34S value of carbonatites from a particular complex is primarily controlled by crustal contamination, heterogeneity in the mantle source, variation in the redox condition of the magma, and magmatic degassing. While the δ34S values of constituent mineral phases of carbonatites represent the isotopic fractionation between sulfur–bearing mineral phases and the melt or fluid, the whole rock δ34S represents the total isotope value
Understanding the variation in $\delta^{13}$C and $\delta^{18}$O

The $\delta^{13}$C and $\delta^{18}$O values of magmatic rocks provide a first order understanding of the source of carbon in the rocks and subsequent secondary modifications that may have occurred during their emplacement (Fig. 3). Most of the carbonatites in the Indian subcontinent show elevated $\delta^{13}$C and $\delta^{18}$O values which are higher than typical mantle values primarily due to the fractional crystallization process, recycled carbon in the source and/or low-$T$ and hydrothermal modification during emplacements (e.g., Ray and Ramesh, 2006; Ackerman et al., 2017). In contrast, carbonatites from the Newania complex, used in this study, show limited variability in $\delta^{13}$C and $\delta^{18}$O which overlap with the field defined for primary mantle carbonatite (Fig. 3). The $\delta^{13}$C and $\delta^{18}$O values of the Newania carbonatite samples of this study suggest that: (1) these carbonatites are primarily magmatic in origin without any significant contribution of recycled crustal components to their mantle source, (2) carbonatites of this complex are not affected by any crustal contamination, and (3) samples used in this study are not affected by any low-$T$ or hydrothermal alteration upon emplacement. Therefore, these carbonatite samples also provide an ideal opportunity to understand the source of sulfur in these melts and their isotopic evolution.

Sulfur isotopic compositions of the Newania carbonatites

Crustal Contamination. The $\delta^{34}$S values of Earth’s mantle has been estimated to be close to zero. Such estimation includes the $\delta^{34}$S values of asthenospheric mantle (0 ± 2‰) and primitive upper mantle (+0.5‰) (Rollinson, 1993; Ripley, 1999; Peters et al., 2010; Marini et al., 2011). A relatively recent study of mid-oceanic ridge basalts (MORB) and ocean island basalts (OIB) devoid of any recycled crustal components, reveals that Earth’s asthenospheric mantle has $\delta^{34}$S values of −1.28 ± 0.33‰ (Labidi et al., 2012). On the contrary, the lithospheric mantle shows a broader range of −3 to +3‰ as revealed from measurements of sulfide minerals from orogenic lherzolites (Chaussidon and Lorand, 1990). The higher $\delta^{34}$S values of some of these sulfides from lithospheric mantle are thought be the result of contamination with continental crust; the latter showing a significantly higher $\delta^{34}$S value of +7‰ (e.g., Farrell et al., 2010; Marini et al., 2011 and references therein).

Carbonatites from the Newania complex display $\delta^{34}$S values ranging from −1.4 to 2‰ (Table 1 and Figs. 4 and 5) and all the samples overlap with $\delta^{34}$S of Earth’s asthenospheric mantle (0 ± 2‰) (Ripley, 1999; Peters et al., 2010; Marini et al., 2011). A probable crustal contamination signature for these samples can be ruled out based on several arguments: (1) due to extremely low viscosity and temperature, carbonate magmas ascend rapidly through the country rocks (Jones et al., 2013) which results in the limited time of interaction with the crust, (2) sulfur concentration in carbonate magmas, in general, is much higher than average continental crust (~ 100 ppm) (Hutchison et al., 2019) which makes the S isotopic compositions of carbonate magmas almost immune to the effect of any contamination with country rocks during emplacement, (3) the $\delta^{13}$C-$\delta^{18}$O values of all the samples show mantle like compositions (Fig. 3), and (4) $\delta^{34}$S values of these samples show extremely non-radiogenic depleted mantle like compositions (Fig. 5). Based on the collective evidence, we suggest that the sulfur isotopic compositions of the Newania carbonatites reflect the parental magma compositions.

Magmatic versus hydrothermal origin of sulfur. Early formed sulfide minerals would likely retain their parental melt compositions and carry their mantle source signature while the sulfur isotopic composition of late formed sulfide minerals could be perturbed by the interaction with the country rocks (Mitchell and Krouse, 1975). Petrographic observations of textural equilibrium of carbonates and accessory minerals in association with the presence of graphite as inclusion within carbonates and mineral geothermometers (graphite-magnesite) of Newania carbonatites suggest a crystallization temperature of more than 600 °C (Doroshkevich et al., 2010). Temperatures of emplacements of typical carbonatite
magmas are ~ 300-700 °C which are much higher than temperatures of late-stage hydrothermal fluids (<250 °C) (Mitchell and Krouse, 1975; Fosu et al., 2020). Therefore, the estimates of crystallization temperatures of Newania carbonatites indicate that most sulfides would form under magmatic conditions.

As mentioned earlier, sulfur isotopic compositions of Newania carbonatite samples (δ34S = −1.4 to 2.0‰, Δ33S = 0.001 to −0.13‰) overlap with Earth’s mantle composition (Fig. 3) suggesting a mantle origin of sulfur in these magmas. The additional evidence of magmatic origin of sulfur is also corroborated from their overlapping values with Earth’s mantle compositions in the plot δ13C versus δ34S (Fig. 4a) and δ13C versus δ34S (Fig. 4b).

**Sulfur speciation and redox state of magma.** Formation of sulfur–bearing species in carbonatites and their isotopic compositions provide constraints on the redox conditions of the magma and their time of formation during the crystallization sequence (Mitchell and Krouse, 1975; Farrell et al., 2010; Gomide et al., 2013; Hutchison et al., 2019). For example, Mitchell and Krouse (1975) proposed that carbonatites with crystallization temperature between 500–700 °C tend to have pyrrhotite as their dominant sulfide mineral phase indicating a reduced (lower oxidation state) magmatic condition. However, the δ34S value of this sulfide phase could change with time depending on the change in the redox condition of the magma during their evolution (Marini et al., 2011; Hutchison et al., 2019).

Back scattered electron images of two carbonatite samples of the Newania complex show that pyrrhotite is the dominant sulfide–bearing phase in these carbonatites (Fig. 2). Moreover, co-existence of pyrrhotite with magnesite (Fig. 2), the carbonate mineral which forms earliest during the crystallization sequence of a carbonatite magma, suggests that the sulfur phase in these carbonatites was formed during the earliest phase of the crystallization of the magma. Additionally, the limited variation in the δ34S values of majority of the analyzed samples seem to rule out any sulfur isotopic fractionation due to the change in oxidation state of the magma.

**Implications on the δ34S of mantle source of Newania carbonatites and future work.** A comparison of the δ34S values of carbonatite samples from the Newania complex with that of the existing δ34S values of carbonatites from different complexes worldwide (e.g., Farrell et al., 2010; Gomide et al., 2013; Bolhar et al., 2020) is shown in Figure 6. The δ34S values of the Newania carbonatites overlap with that of the athenospheric mantle as well as compositions of carbonatite complexes older than
Carbonatites older than 400 Ma display limited variability in the $\delta^{34}S$ values compared to the younger carbonatites; the latter showing a large range in the $\delta^{34}S$ values with most young carbonatites displaying lower $\delta^{34}S$ than the asthenospheric mantle source (Fig. 6). The overall restricted variability in the $\delta^{34}S$ values for carbonatites older than 400 Ma could indicate that $f_{O_2}$ and $f_{S_2}$ of these carbonatite magmas were much lower (i.e., more reduced). However, this hypothesis needs to be corroborated by future studies involving sulfur isotopic measurements of a large number of globally distributed WR-carbonatite samples and their individual sulfide minerals.

**CONCLUSION**

The $\delta^{34}S$ and $\Delta^{33}S$ values of Newania carbonatites show overlapping compositions to that of Earth’s asthenospheric mantle. Based on the mantle-like sulfur isotope compositions as well as $\delta^{13}C$ and $\delta^{18}O$ ratios, it could be suggested that the source of sulfur in the Newania carbonatites were primarily mantle derived. Coexistence of magnesite and pyrrhotite further advocates that the sulfide phases were formed earlier during the time of crystallization of the magma; while overall constricted $\delta^{34}S$ values in these samples rules out any isotopic fractionation due to the change in the redox condition of the magma during its evolution.

The $\delta^{34}S$ values of Newania carbonatites overlap with the sulfur isotopic composition of carbonatites from different complexes worldwide of age >400 Ma. This observation possibly suggests an overall lower oxidation state of carbonatite magmas emplaced prior to 400 Ma.

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**SUPPLEMENTARY MATERIAL**

Color version of Figure 1 is available online from https://doi.org/10.2465/jmps.201130e.

**REFERENCES**

Ackerman, L., Magna, T., Rapprich, V., Upadhyay, D., et al. (2017) Contrasting petrogenesis of spatially related carbonatites from Samalpatti and Sevattur, Tamil Nadu, India. Lithos, 284, 257–275.

Banerjee, A. and Chakrabarti, R. (2019) A geochemical and Nd, Sr and stable Ca isotopic study of carbonatites and associated silicate rocks from the ~65 Ma old Ambadongar carbonatite complex and the Phenai Mata igneous complex, Gujarat, India: Implications for crustal contamination, carbonate recycling, hydrothermal alteration and source-mantle mineralogy. Lithos, 326, 572–585.

Banerjee, A., Chakrabarti, R. and Simonetti, A. (2021) Temporal evolution of $\delta^{44}/\delta^{40}Ca$ and $^{138}Sr/^{87}Sr$ of carbonatites: implications for crustal recycling through time. Geochimica et Cosmochimica Acta, 307, 168–191.

Bell, K., Zaïtsev, A.N., Spratt, J., Fröjdö, S. and Rukhlov, A.S. (2015) Elemental, lead and sulfur isotopic compositions of galena from Kola carbonatites, Russia: implications for melt and mantle evolution. Mineralogical Magazine, 79, 219–241.

Bolhar, R., Whitehouse, M.J., Milani, L., Magalhães, N., et al. (2020) Atmospheric S and lithospheric Pb in sulphides from the 2.06 Ga Phalaborwa phoscorite-carbonatite Complex, South Africa. Earth and Planetary Science Letters, 530, 115939.

Chaussidon, M. and Lorand, J.P. (1990) Sulphur isotope composition of orogenic spinel lherzolite massifs from Ariège (North-Eastern Pyrenees, France): An ion microprobe study. Geochimica et Cosmochimica Acta, 54, 2835–2846.

Doroshkevich, A.G.E., Ripp, G. and Viladkar, S. (2010) Newania carbonatites, Western India: example of mantle derived magnesium carbonatites. Mineralogy and Petrology, 98, 283–295.

Farrell, S., Bell, K. and Clark, I. (2010) Sulphur isotopes in carbonatites and associated silicate rocks from the Superior Province, Canada. Mineralogy and Petrology, 98, 209–226.

Fosu, B.R., Ghosh, P. and Viladkar, S.G. (2020) Clumped isotope...
geochemistry of carbonatites in the north-western Deccan igneous province: Aspects of evolution, post-depositional alteration and mineralisation. Geochimica et Cosmochimica Acta, 274, 118-135.

Gomide, C.S., Brod, J.A., Junqueira-Brod, T.C., Buhn, B.M., et al. (2013) Sulfur isotopes from Brazilian alkaline carbonatite complexes. Chemical Geology, 341, 38-49.

Hulett, S.R., Simonetti, A., Rasbury, E.T. and Hemming, N.G. (2016) Recycling of subducted crustal components into carbonatite melts revealed by boron isotopes. Nature Geoscience, 9, 904-908.

Hutchison, W., Babiel, R.J., Finch, A.A., Marks, M.A., et al. (2019) Sulphur isotopes of alkaline magmas unlock long-term records of crustal recycling on Earth. Nature communications, 10, 1-12.

Jones, A.P., Genge, M. and Carmody, L. (2013) Carbonate melts and carbonatites. In Carbon in Earth (Hazen, R.M., Jones, A.P. and Baross, J.A. Eds.). Reviews in Mineralogy and Geochemistry, 75, Mineralogical Society of America, Chantilly, VA., 289-322.

Labidi, J., Cartigny, P., Birck, J.L., Assayag, N. and Bourrand, J.J. (2012) Determination of multiple sulfur isotopes in glasses: a reappraisal of the MORB δ34S. Chemical Geology, 334, 189-198.

Marini, L., Moretti, R., Accornero, M. (2011) Sulfur isotopes in magmatic-hydrothermal systems, melts, and magmas. In Sulfur in Magmas and Melts: Its Importance for Natural and Technical Processes (Behrens, H. and Webster, J.D. Eds.). Reviews in Mineralogy and Geochemistry 73, Mineralogical Society of America, Chantilly, VA., 423-492.

Mishima, K., Yamazaki, R., Satish-Kumar, M., Ueno, Y., et al. (2017) Multiple sulfur isotope geochemistry of Dharwar Supergroup, Southern India: Late Archean record of changing atmospheric chemistry. Earth and Planetary Science Letters, 464, 69-83.

Mitchell, R.H. and Krouse, H.R. (1975) Sulphur isotope geochemistry of carbonatites. Geochimica et Cosmochimica Acta, 39, 1505-1513.

Peters, M., Strauss, H., Farquhar, J., Ockert, C., et al. (2010) Sulfur cycling at the Mid-Atlantic Ridge: A multiple sulfur isotope approach. Chemical Geology, 269, 180-196.

Ray, J.S. and Ramesh, R. (2006) Stable carbon and oxygen isotopic compositions of Indian carbonatites. International Geology Review, 48, 17-45.

Ray, J.S., Shukla, A.D. and Dewangan, L.K. (2010) Carbon and oxygen isotopic compositions of Newania Dolomite Carbonatites, Rajasthan, India: implications for source of carbonatites. Mineralogy and Petrology, 98, 269-282.

Ray, J.S., Pande, K., Bhutani, R., Shukla, A.D., et al. (2013) Age and geochemistry of the Newania dolomite carbonatites, India: implications for the source of primary carbonatite magma. Contributions to Mineralogy and Petrology, 166, 1613-1632.

Ripley, E.M. (1999) Systematics of S and O isotopes in mafic igneous rocks and related Cu-Ni-PGE mineralization. In Dynamic Processes in Magmatic Ore Deposits and their Application to Mineral Exploration (Keays, R.R., Lesher, C.M., Lightfoot, P.C. and Farrow, C.E.G. Eds.). Geological Association of Canada Short Course, 13. Geological Association of Canada, St John’s, Newfoundland, Canada, 133-158.

Rullinson, H. (1993) Using Geochemical Data: Evaluation, Presentation, Interpretation. pp. 352, Addison Wesley Longman, Essex, UK.

Salters, V.J. and Stracke, A. (2004) Composition of the depleted mantle. Geochemistry, Geophysics, Geosystems, 5.

Ueno, Y., Aoyama, S., Endo, Y., Matsu'ura, F. and Foriel, J. (2015) Rapid quadruple sulfur isotope analysis at the sub-micromole level by a flash heating with CoF3. Chemical Geology, 419, 29-35.