Carbonatites: Complex and Controversial
Evolution of Carbonatite Melts
Role in Diamond Formation
Formation of REE Deposits
Distinctive Mineralogy
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Carbonatites
Guest Editors: Gregory M. Yaxley, Michael Anenburg, and Suzette Timmerman

Carbonatites: Contrasting, Complex, and Controversial
Vadim S. Kamenetsky, Anna G. Doroshkevich, Holly A. L. Elliott, and Anatoly N. Zaitsev

Evolution of Carbonatite Magmas in the Upper Mantle and Crust
Gregory M. Yaxley, Bruce A. Kjarsgaard, and A. Lynton Jaques

Carbonatitic Melts and Their Role in Diamond Formation in the Deep Earth
Suzette Timmerman, Anna Spivak, and Adrian P. Jones

Formation of Rare Earth Deposits in Carbonatites
Michael Anenburg, Sam Broom-Fendley, and Wei Chen

The Distinctive Mineralogy of Carbonatites
Andrew G. Christy, Igor V. Pekov, and Sergey V. Krivovichev

Carbonatites and Global Tectonics
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The Mineralogical Society of Great Britain and Ireland is an international society for all those working in the mineral sciences. The society aims to advance the knowledge of the science of mineralogy and its applications to other subjects, including crystallography, geochemistry, petrology, and environmental science and economic geology. The society further contributes through scientific meetings and the publication of scientific journals, books, and monographs. The society publishes Mineralogical Magazine and Clay Minerals. Students receive their first year of membership free of charge. All members receive Elements.

Website: www.minsocam.org
Contact: business@minsocam.org

Society News Editor: Andrea Koziol (akoziol1@udayton.edu)

The Clay Minerals Society (CMS) began in 1952 as the Clay Minerals Committee of the US National Academy of Sciences – National Research Council. In 1962, the CMS was incorporated with the purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. The CMS holds annual meetings, workshops, and field trips, and publishes Clays and Clay Minerals and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to CMS Workshop Lectures, and Elements.

Website: www.clay.org
Contact: cms@clays.org
Society News Editor: Bhabananda Biswas (bhabananda.biswas@geoche.org)

The Geochemical Society (OS) is a non-profit organization founded in 1955 for scientists involved in the practice, study, and teaching of geochemistry. Members are members of the society that supports the many facets of mineralogy.

Website: www.geochemosoc.org
Contact: geochemosoc@geochemosoc.org
Society News Editor: Kevin Johnson (kjohnson@geochemosoc.org)

The European Association of Geochemistry was founded in 1996 and is a non-profit organization dedicated to promoting geochemistry internationally. The society is a dynamic association that organizes the Goldschmidt Conference® in Europe, publishes Geochemical Perspectives and Geochemical Perspectives Online, and organizes scientific excellence through awards, supports early career scientists, sponsors workshops and conferences in Europe, organizes distinguished lecture and outreach programs, publishes job opportunities, newsletters and blogs, and partners with other learned societies to strengthen geochemical international networks.

Website: www.eag.eu.com
Contact: office@eag.eu.com
Society News Editor: Alice Williams (awilliams@eag.eu.com)

The International Association of GeoChemistry (IAGG) has been a preeminent international geochemical organization since 1967. Its principal objectives are to foster cooperation in the development of applied geochemistry by sponsoring specialist scientific symposia and the activities organized by its working groups and by supporting the peer-reviewed journal, Applied Geochemistry. The administrative activities of IAGG are handled by its board, comprising an executive and ten ordinary members. Day-to-day administration is performed through the IAGG’s business office.

Website: www.iage-society.org
Contact: businessoffice@iage-society.org
Society News Editor: Chris Gardner (BusinessOffice@IAGG-Society.org)

The Société Française de Minéralogie et de Cristallographie (French Mineralogy and Crystallography Society) was founded in 1878. The purpose of the society is to promote mineralogy and crystallography. Membership benefits include the Journal of the French Society of Mineralogy, and reduced registration fees for SFMC meetings.

Website: www.sfmc-fr.org
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The Association of Applied Geoscientists is a US-based professional organization founded in 1970 that publishes the peer-reviewed journal of applied geochemistry. It aims to advance the science of geochemistry and the environment, further the common interests of exploration chemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, and support scientific meetings and development. Membership of the AAG includes the AAG journal, Geochemistry: Exploration, Environment, Analysis, the AAG newsletter, EXPLOR; and Elements.

Website: www.appliedgeochem.org
Contact: office@appliedgeochem.org
Society News Editor: Caranaza (ejmcaranza@gmail.com)

The Deutsche Mineralogische Gesellschaft (DMG; German Mineralogical Society) was founded in 1908 “to promote miner­alogy and all the sciences related to it, in plumes in teaching and research as well as the personal relationships among all members.” The society has traditionally been listed in the list of honorary fellows, which include M.v. Laue, G. v. Tschermak, P.Engel, C.W. Correns, and H. Strunz. Today, the subdisciplines in the DMG range from more traditional communities, such as materials science, solid state chemistry/physics, and the environmental sciences. The DMG regularly tries to support young researchers, e.g., to attend conferences and short courses. Membership benefits include the European Journal of Mineralogy, Elements, and G&M.

Website: www.dmng-home.org
Contact: post@dmng-home.org
Society News Editor: Klaus-Dieter Grevel (klaus-dieter.grevel@rub.de)

The Società Italiana di Mineralogia e Petrologia (Italian Society of Mineralogy and Petrology), established in 1940, is an international society that organizes distinguished lecture and poster sessions each year. Its goals include receiving European Journal of Mineralogy, Pluton, and Elements, and a reduced registration rate for special events.

Website: www.socminpet.it
Contact: segreteria@socminpet.it
Society News Editor: Costanza Bonadiman (bdcs@mcg.it)

The International Association of Geoanalysts (IAA) is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Activities include the management of proficiency-testing programs for bulk-rock and solid-state methods; the production and certification of reference materials; and the publication of the association’s journal, Geo-standards and Geoanalytical Research.

Website: www.geoanalyst.org
Contact: jmc@bgc.as
Society News Editor: Alicia Cruz-Uribe (alicia.cruzuribe@jams.org)

The Polskie Towarzystwo Mineralogiczne (Polish Society of Poland) was founded in 1969, and it works together professionals and amateurs interested in the field of mineralogy, crystallography, petrology, geochemistry, and economic geology. The society promotes links between the mineralogical sciences, education, and technology through its annual conferences, field trips, invited lectures, and publishing. Membership benefits include subscriptions to Mineralogia and Elements.

Website: www.mineralogia.pl
Contact: ptmin@ptmin.pl

The International Association on the Genesis of Ore Deposits (IAGD) was established in 1963 to promote international cooperation and to increase knowledge in the field of the genesis of ore deposits: it is affiliated to the International Union of Geological Sciences (IUGS). The society organizes quadrennial symposiums and congresses, in cooperation with the International Geological Congress and SGA Biennial Meetings. The society awards prizes and commissions promote ore deposit research and sponsor an international speaker to give seminars and lectures. The society publishes the IAGD Journal, Elements, and other publications, and a subscription to Elements.

Website: www.iagod.org
Contact: http://iagod.node/87
Society News Editor: Simon Jowitt (simon.jowitt@uq.edu.au)

The Swiss Geological Society (SGG) was established in 1882 and comprises specialist groups in the fields of mineralogy, petrology, sedimentology, seismology, and paleontology. The society is part of the Swiss Academy of Sciences and promotes the advancement and dissemination of geological sciences in Switzerland. The society organizes the annual Swiss International Science Congress (SISK) and publishes the Swiss Journal of Geosciences (SJG), which is now fully “open access.” Members receive the Journal of Geosciences, publishing in the SJG and participating at the SISK.

Website: https://www.geolch.org
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Society News Editor: Julien Allaz (julien.allaz@edu.ethz.ch)

The Meteoritical Society (METAS) was an international organization founded in 1933 for scientists, collectors, and educators to advance the study of meteorites and planets, which are extraterrestrial materials and their parent asteroids, comets, and planets. Members receive our journal, Meteoritics & Planetary Science, and reduced rates for annual meetings. The Modern Meteorite Congress (MMC) is held every three years.

Website: www.meteoritical.org
Contact: meteorsociety@icloud.com
Society News Editor: Cari Corrigan (corrigan@jcu.edu)

The Japan Association of Geochemical Sciences (JAMS) was established in 1938 in Japan, founded in 1955, and the Japanese Association of Mineralogists, Petrologists, and Economic Geologists, established in 1928. The JAMS covers the fields of mineral sciences, geochemistry, and petrology. Membership benefits include receiving the Journal of the Japanese Association of Geochemical, Petrological, and Economic Geologists and supporting the professional advancement of young researchers, e.g., to attend conferences and short courses. Membership benefits include subscriptions to Geochemical Perspectives and Elements.

Website: jams.la.coocan.jp
Contact: KY10422@nifty.ne.jp
Society News Editor: Tomoski Morishita (morishita.mp@kansai-kyoiku.ac.jp)

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Website: www.iagod.org
Contact: http://iagod.node/87
Society News Editor: Simon Jowitt (simon.jowitt@uq.edu.au)

Affiliated Societies
The European Mineralogical Association, the European Mineralogical Union, and the International Association for the Study of Clays are affiliated societies of Elements. The affiliated status is reserved for those organizations that serve as an “umbrella” for other groups in the fields of mineralogy, geochemistry, and petrology but that do not themselves have a membership base.
THE POWER OF MYSTERIOUS WORDS

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One of the joys of growing up in a little-remarked-upon corner of the upper Midwest USA is that it came with its own secret words and rituals—cricks and bubblers, hotdishes and euchre. The Wisconsin patois served as a daily reminder that humans have a passion for using mysterious languages to express the numinous: cants and glossolalia that describe new things or express new ideas or emotions, and that draw lines, intentionally or otherwise, between the community of “insiders” and everyone else.

Scientists do much the same thing, particularly when wrestling with new, challenging, or hotly debated problems. Quantum mechanics is arguably among the most important and widespread systems of scientific thought, and underlies cell phones and much else in modern life, yet how many of us could provide appropriate definitions of its secret words—‘eigenstate’, ‘nonlocality’, ‘Hilbert space’, and so forth?

But as a maturing scientific discipline winds down its first-order debates and begins to take firm shape, the specialists may tame their jargon, making an abstruse intellectual home ready to receive outside guests. Igneous petrologists are a familiar community that has (mostly) forced its major mysteries into a unified paradigm and tidied up its talk. Time was, competence in the field demanded that you were free in your speech and writing. Today, you can cover most any igneous rock you encounter using a standardized system of doozies and odd nomenclature that occupy the boxes on a ternary diagram. Of course, there are still a few ‘mangerites’ and ‘sanukitoids’ and ‘shonkinites’. Today, you can cover most any igneous rock you encounter using a standardized system of doozies and odd nomenclature that occupy the boxes on a ternary diagram. Of course, there are still a few ‘mangerites’ and ‘sanukitoids’ and ‘shonkinites’. Today, you can cover most any igneous rock you encounter using a standardized system of doozies and odd nomenclature that occupy the boxes on a ternary diagram.

When you dig into the substance of this issue of Elements you will discover that carbonatites remain untamed mysteries, still approached through exotic words that reflect strange, half-understood objects and ideas. There are ‘bastnäsites’, ‘beforsites’, and ‘carbocernaites’. ‘Phoscorites’, ‘søvites’ (and more) await you, all hiding in the less understood corners of the room, but, overall, this is a field whose original secret language has been redacted, systematized, and demystified.

Oldoinyo Lengai (Tanzania) is the only active volcano on Earth that erupts natrocarbonatite lava.

“Rejoice!” I say. Certainty and simplicity are overrated. The author of this issue’s Perspectives piece, Francesco Stoppa, makes an on-point reference to the 19th century conflict between pluto- and neptunists. Like that debate from the founding era of the geosciences, the study of carbonatites forces us to confront parts of the rock record that are peculiar, unfamiliar, composed of substances outside our daily experience, and that have formed in environments that don’t fit neatly into accepted categories. Are carbonatites fundamentally igneous or metamorphic rocks? Perhaps “Yes” to both sides. Do they derive from the lithosphere, or are they rooted in processes from the deep mantle? You be the judge. Our authors may struggle with, and sometimes disagree about, these and other first-order questions. But that mysteriousness and uncertainty comes with something special—an opportunity to encounter a subject that is wide open to transformational discovery and reinterpretation.

John Eiler
Principal Editor
EXECUTIVE COMMITTEE

Elements is published through the collaboration of 18 participating scientific societies. The Elements editorial team is responsible for the content and the day-to-day management of the magazine. The Elements Executive Committee is responsible for the management of the magazine through financial oversight, approval of editorial appointments, and facilitating a close working relationship between the editorial team and the participating societies.

The Elements Executive Committee consists of members appointed by their respective participating society. Current members of the committee are as follows (in alphabetical order by society): Ryan Noble (AAG), Katerina Dontsova (CMS), Klaus Mezger (DMG), Daniel Frost (EAG), Sasha Turchyn (GS), Alicia Cruz-Uribe (IAG), Orfan Shouakar-Stash (IAGC), Simon Jowitt (IAGOD), Ritsuro Miyawaki (JAMS), Catherine Corrigan (Met Soc), Heather Jamieson (MAC), Barb Dutrow (MSA), Mark Hodson (MSGB), Marek Michalik (PTMIN), Blanca Bauluz (SEM), Sylvie Demouchy (SFMC), Costanza Bonadiman (SIMP), and Jörg Hermann (SGS).

The Chair of the Executive Committee is responsible for initiating, promoting, and summarizing discussions among members of the committee via e-mail or other means; for communicating with the Executive Editor when needed; and for coordinating an annual meeting with the Executive Editor and Principal Editors.

The editorial team greatly appreciates all the work that Dan has done on our behalf over the past 6 years. Thank you! And we look forward to working with Cari in the future.

Daniel (Dan) Frost has been part of the Executive Committee since 2013 as the European Association of Geochemistry (EAG) representative. He has served as the Executive Committee Chair since 2015 and will be stepping down from the Chair position at the end of 2021.

Catherine (Cari) Corrigan was elected to be the next Chair and will begin her term of service in January 2022. Cari has represented the Meteoritical Society (Met Soc) since 2013 and is the editor for the CosmoELEMENTS column.

FROM THE EDITORS

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International response to COVID-19 has resulted in scientific meetings being canceled or postponed. Check meeting web pages for ongoing updates.

2022


January 23–28 MRS Spring Meeting, Honolulu HI, USA. Web page: www.mrs.org/meetings-events/spring-meetings-exhibits/2022-mrs-spring-meeting

February 20–23 46th International Conference on the Chemistry of Natural Zeolites, Ischia, Italy. Web page: web.earthsciences.dal.ca/Halifax2022/


May 15–20 ABSICON 2022, Atlanta, GA, USA. Web page: www.absicon2022.org

May 22–27 Gordon Research Conference: Geochemistry of Mineral Deposits, Castelldefels, Spain. Web page: www.g2022meeting.org/gordon-conference


July 19–21 International Archean Symposium, Perth, WA, Australia. Web page: 6ias.org/

July 24–29 12th International Symposium on the Geochemistry of the Earth’s Surface (GES-12), Zurich, Switzerland. Web page: geol12.com


July 30–August 4 2nd IAGC International Conference (AIG-14 and WRI-17), Sendai, Japan. Web page: www.wr17.com

July 31–August 4 Microscopy & Microanalysis 2022, Portland, OR, USA. Web page: forthcoming


August 15–19 12th International Kimberlite Conference, Yellowknife, NT, Canada. Web page: www.12zkc.ca

August 21–25 Fall ACS National Meeting & Exposition, Chicago, IL, USA. Web page: www.acs.org/

August 23–26 Internation Symposium on Environmental Geochemistry (ISEG 2022), Moscow, Russia. Web page: iseg2022.org

October 9–12 Geological Society of America National Meeting, Denver, CO, USA. Web page: forthcoming


September 11–15 GeoMinKöln 2022, Cologne, Germany. Web page: www.geominkoeln2022.de

September 12–15 Earth Mantle Workshop (EMAW), Toulouse, France. Web page: emaw2021.sciencesconf.org

September 19–23 Chapman Conference: Distributed Volcanism and Distributed Volcanic Hazards, Flagstaff, AZ USA. Web page: www.agu.org/Chapmans-Distributed-Volcanism

October 9–12 Geological Society of America National Meeting, Denver, CO, USA. Web page: forthcoming

The meetings convened by the societies participating in Elements are highlighted in yellow. This meetings calendar was compiled by Andrea Kozioł. To get meeting information listed, please contact her at akoziol@udayton.edu
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As this issue of *Elements* clearly demonstrates, carbonatites are unique and fascinating igneous rocks, with incredibly diverse mineralogy, that also represent vital resources of critical metals, such as the rare earth elements and niobium. Although carbonatites are now known worldwide, much of the early work to identify them was done in Africa, particularly around Oldoinyo Lengai (Tanzania) led by the late John Barry Dawson (1932–2013). Barry was a professor at the University of Edinburgh (UK) when one of us (KG) was there during the 1990s doing a PhD on alkaline igneous rocks and carbonatites; his interest and enthusiasm for the subject was infectious. Barry’s initial work on Oldoinyo Lengai, and his recognition of it as a carbonatite volcano, was done when he was a geologist for the Geological Survey of Tanganyika, around the time of Tanzanian independence. This was a time when colonial attitudes still strongly governed the way geological work was done in Africa, and the early papers on carbonatites abound with names of former colonies such as Rhodesia, Nyasaland, and South-West Africa.

The Geological Survey of Tanganyika was part of the Directorate of Colonial Geological Surveys, an organisation established in 1947 and based in London (Dixey 1957). This organisation provided geologists, geophysicists, geochemists, and mineral resource experts to geological survey organisations across Africa. Most of the geoscientists were graduates from British universities; reports from the time draw a tacit distinction between the skilled expatriate geologists and the local staff (who were rarely, if ever, mentioned). Part of the directorate’s work was to understand mineral resources in what were once British colonies, and Dixey’s 1957 review stated that it “paid particular attention to carbonatite complexes and has done much to stimulate interest in these potentially economic deposits.”

In 1958, the directorate was renamed the Overseas Geological Surveys, which later became integrated as the Overseas Division of the Institute of Geological Sciences in 1964. The institute eventually evolved into the British Geological Survey (BGS), which continues to deliver international research and partnerships, in which the present authors are heavily involved. A 1977 review of the work of the Overseas Division noted baldly that “in most newly independent countries, there are few experienced indigenous geologists to staff a geological survey” (IGS Overseas Division 1977). Clearly, this situation was in large part a consequence of the colonial approach, which had offered few, if any, opportunities for local geologists to gain training and experience. For the rest of the twentieth century, the response to this continued to be the secondment of expatriate geologists to work in overseas geological surveys. However, this was accompanied by a gradual increase in training and development opportunities for local colleagues.

At the BGS, we have been working for some time to move on from this colonial legacy. We now focus on building and sustaining partnerships with African geological surveys and their geologists, working together to exchange knowledge, expertise, and skills. However, remnants of the colonial approach undoubtedly still remain across the geosciences and more widely. There is still far too much evidence of “parachute science”, whereby UK and other scientists from the Global North design and win projects, visit African sites, collect data, and write papers without involving African colleagues beyond the arrangement of logistics (North et al. 2020). International support for geological surveys and other geoscience organisations in Africa is all too often short-term: equipment may be purchased and data gathered, but there is limited support for the management, maintenance, and use of those assets once the international funds are no longer flowing. Changes in international aid budgets and focus, for example due to COVID-19 (Brown 2021), can have a significant impact on geoscience organisations in lower- and middle-income countries. There is a need for sustainable, long-term international funding, as illustrated by Swedish support for national research systems (Fellesson and Mählck 2017).

We discussed this text with our colleague Prince Cuffey, Director of the Geological Survey within Sierra Leone’s National Minerals Agency. He agreed with many of the points made here and emphasised that partnerships need sustainable funding to ensure meaningful progress. He also made an important point: he, like many other leaders in African geoscience institutions, has experience across the different sectors, having previously worked for exploration and mining companies. All too often, those companies were headquartered overseas, not in the country where they were actively working; when they closed their operations, their data and information left the country with them. Prince gave the example of Sierra Leone’s carbonatites. As a company geologist, he was involved in the development of a magnetic anomaly from which he identified a marked carbonatite, so he knows the dataset exists, but the company left Sierra Leone without ever submitting their data to the Geological Survey. This happens time and again, and it is vital that geoscientists ensure that datasets collected in one country are also delivered to the appropriate institution in that country.

The “decolonisation” of geoscience calls for us all to address the factors over which we have influence, i.e., those that may sustain or create additional inequalities. This is an opportunity for geoscience organisations—including the BGS—to critically reflect on how UK colonial history shaped our discipline, and on subsequent progress. We also need to consider the attitudes and challenges that remain today in our organisations and the way in which we undertake our work in former colonial countries. Many of us have inadvertently made mistakes at times, which we need to recognise, reflect on, and learn from. Developing this deeper understanding of the issue, and openly acknowledging our history, will enable us to confront unequal power relations and inequality in accessing knowledge, data, and resources. It will also improve our organisational practice in equality, diversity, and inclusion, as well as our engagement with external partners in science that itself can support international development. Ultimately, we aspire to sustainable, equitable partnerships with African geoscience organisations, so that together we can continue excellent research—on carbonatites and on many other topics!

**REFERENCES**


During my doctoral studies, in the late 1980s, I realised that the Italian kamafugites (kalsilite melilitites) had to be related to carbonatite magmatism. I started a detailed study of the kamafugitic sites, and I explored remote areas deep in Italy’s Apennine mountains. When I found the Polino carbonatite, I put a few drops of acid on it, and the rock reacted. I have a vivid memory of my heart beating faster. I had found it! My fellow geologists were somewhat sceptical, but the late Professor Giorgio Marinelli (1922–1993) encouraged me and predicted many new carbonatite discoveries. He was right. Overcoming my Latin temperament, I focused on the concept that carbonatites, however unusual as rocks, cannot be dismissed as simple geological oddities but require detailed and comprehensive study. I am fond of all the history that marked my latest 40 years of life, and it reminds me of the many friends and mentors that I have had, especially when I was a young researcher. Sadly, some of them are no longer with us. I am so grateful to them, and I consider it a life-changing experience when I was a young researcher. Sadly, some of them are no longer with us. I am so grateful to them, and I consider it a life-changing experience when I was a young researcher.

**CARBONATITES: BACKGROUND**

The “carbonatite saga” parallels the Plutonist vs. Neptunist _quercia_ of the 18th and 19th centuries concerning the pyrogenic versus chemical origins of igneous rocks. In the mid-19th century, minerals in alkaline rocks attracted mineralogists, who considered them fascinating examples of rocks containing minerals that combined calcium silicates and carbonates. These minerals occur in skarns, which are thermally metamorphosed rocks formed at contacts between silicate magma and limestone. Skarns may contain perfectly faceted crystals and, despite their marginal importance and volume, monopolised European mineralogical studies. On this basis, the concept of magma–limestone interactions was applied to carbonatitic and alkaline igneous rocks, which related sub-alkaline rocks to carbonatites. The thermodynamic study of mantle metasomatism has developed. Carbonatite specialists from Europe, Russia, North America, Brazil, and China met at the EuroCarb workshops, which were held in Italy, the Canary Islands, and the Kola Peninsula in 2002 and 2003. These meetings started an international discussion that is ongoing and have promoted new ideas about the economic potential of European carbonatites (e.g., Stoppa et al. 2016).

Limestone assimilation became a fashionable model. Most distinguished geologists of the day discussed the role of limestone in the origin of felspathoidal rocks. For example, Alfred Rittmann (1893–1980) proposed that Mount Vesuvius volcano leucitites form by dolomitic limestone assimilation into a trachytic magma. Not everyone agreed: Whitman Cross (1854–1949) rejected Daly’s model based on the geological observation that the melilite-bearing rocks of Hawaii (USA) formed in the absence of limestones and sub-alkaline rocks.

The person often credited with the first compelling hypothesis that these limestones are, in fact, igneous was Waldermar Brøgger (1851–1940). Although Brøgger was initially a proponent of Daly’s assimilation model, he changed his mind after studying the Norway’s Fen alkaline complex. He advanced the idea that limestones associated with alkaline silicate rocks are not sedimentary. Instead, he proposed them to be igneous rocks that he referred to as carbonatites. This was a radical idea that was strongly opposed. James Shand (1882–1957), one of the most famous alkaline rock petrologists of the time, did not believe in the igneous origin of carbonatites. Norman Bowen (1887–1956) suggested that carbonatites are non-igneous metasomatic and hydrothermal rocks. Likewise, William Pecora (1913–1972) concluded that carbonatites formed by carbonate solutions derived from alkaline magmas. Nevertheless, the field evidence overwhelmingly supported the idea that carbonatites were igneous, and an increasing number of “limestones” were recognised as igneous carbonatites.

**THE CARBONATITE GOLDEN AGE: 1960–2000**

The most intense effort in studying carbonatites took place between 1950 and 2000. Based on experimental petrology, an increasing number of Russian and US scientists became supporters of the carbonatite magmatic origin. Field observations of carbonatites on Alnö Island (Sweden) by Harry von Eckermann (1886–1969) supported the seminal experimental work of Peter Wyllie and his co-authors, leading to the conclusion that wollastonite and calcite can crystallise in a magmatic environment. Numerous geological, mineralogical, petrographic, geochemical, and isotope studies confirmed the magmatic genesis of carbonatites and their associated alkaline rocks, such as melilitites and foidites. Many experimental studies have suggested that carbonatites can be generated in several different ways, including by primary mantle melting, differentiation of carbonate from silicate melts, liquid immiscibility, and crystal fractionation. Beginning in the late 1970s, a new generation of scientists demonstrated that carbonate-composed melts are largely immiscible at crustal pressures and form conjugate pairs, with silicate liquids starting from CO2-rich, mafic-carbonate parent melts. The thermobarometric and stable isotope studies of Russian petrologists on melt inclusions in carbonatite-hosted minerals was particularly important in demonstrating the igneous genesis of alkaline silicate and carbonatites rocks. Mantle metasomatism plays a considerable role in the evolution of carbonatites, and for many years it was believed that metasomatism involved solely the lithosphere. In recent decades, based on the study of mantle xenoliths and inclusions in diamonds, the idea of deep mantle metasomatism has developed. Carbonatite specialists from Europe, Russia, North America, Brazil, and China met at the EuroCarb workshops, which were held in Italy, the Canary Islands, and the Kola Peninsula in 2002 and 2003. These meetings started an international discussion that is ongoing and have promoted new ideas about the economic potential of European carbonatites (e.g., Stoppa et al. 2016).
THE IMPORTANCE OF THE EXTRUSIVE CARBONATITES: THE CASE HISTORY OF ITALY

A completely new insight into the origins of carbonatites came from observations of extrusive carbonatite volcanism, including the 1960 eruption of Oldoinyo Lengai (Tanzania), the discovery of tear-drop lapilli-stone at Kaiserstuhl (Germany), and the carbonatitic tuffs and bombs found at Fort Portal and Katwe-Kikorongo (both in Uganda). These studies corroborated the decades-earlier intuition of David Bailey (1931–2012) concerning the existence of extrusive carbonatites at Rufunsa (Zambia). Extrusive carbonatites preserve astonishing evidence of rapid cooling from high-temperature carbonate liquids, as well as having high-pressure aragonite inclusions. Studies of volcanic carbonatites have revealed a new type of alkaline carbonatite consisting of sodium- and potassium-rich calcium carbonates. The rapid transformation of these ephemeral phases to form Ca-carbonatites led to the generalisation that initially all extrusive carbonatites were alkaline. Supporting evidence now includes the existence of wide alkali-rich fenite aureoles around most carbonatite intrusions and alkali-carbonate inclusions in extrusive carbonatite minerals.

Although carbonatites are now accepted as igneous, the role played by mantle and crustal silicate material reaction and contamination was somewhat forgotten or ignored, overshadowed by the new enthusiasm that all carbonatites are igneous. Calcite carbonatite rocks were often erroneously interpreted as forming from melts of equivalent composition, and any oxide or silicate crystals were inferred as having crystallised from the carbonatite magma itself, without clear evidence. The unexpected discovery of extrusive carbonatites in Italy, within the Quaternary extensional intermountain belt, opened a new front of discussion. These rocks are very primitive silica-rich carbonatites with high Cr–Ni contents, mantle nodules, and high incompatible element contents. As deduced by the presence of abundant mantle debris, the magmas were initially propelled, at the mantle level, by violent CO2 release with sufficient force to bring the magma and xenoliths to the surface at high speeds. This produces a fluidised mantle-rock breccia immersed in an immiscible mixture of mafic alkaline silicate and carbonate droplets. Passing through the lithosphere, specific concentric-shelled lapilli are formed in the conduit by the attachment of melt droplets to mantle xenolith fragments. These silica-rich carbonatites are important for their primitive character (high-Mg content and abundant mantle debris), because most experimental work indicates that melting of carbonated peridotite produces magnesian carbonatite melts with silica. The so-called “Italian silicocarbonatites”, with their primitive compositions, are invariably associated with potassic undersaturated rocks called kamaufugites, while the geochemical and isotopic equilibrium between the two rock types indicates genesis by immiscibility at crustal levels. Notably, Italian carbonatites contain monticellite and wollastonite as mantle debris and carbonatite-liquid low-pressure reaction minerals. This is consistent with experimental work showing assimilation of silicate rock by carbonatite magma.

A more recent discovery is that Italian late-stage carbonatites are strongly enriched in fluorite, baryte, light rare earth elements, Nb, V, and Sc (FIG. 1) (Stoppa et al. 2019). The discovery of carbonatites in Italy initiated vigorous discussion about their geodynamic context. Strong opinions arose from those who consider that Italian alkaline magmatism is related to subduction, because carbonatites are typically associated with intracontinental rifting but only rarely with intraplate oceanic islands. However, most of the papers about Italian carbonatites attribute this magmatism to upwelling of mantle asthenosphere and stretching of the lithosphere that is related to the Tyrrhenian opening, possibly controlled by a mantle plume of deep origin. Some authors have invoked Reginald Daly’s petrogenetic theory for these rocks; others oppose that view.

A FINAL SURPRISE

Recent studies have proffered the idea that carbonatites can react with silicates (accidental mantle and crustal debris or felsic country rocks) to produce a suite of calcium silicate minerals that include diopside, wollastonite, monticellite, and andradite: assemblages that are typically found in skarns. However, whilst these minerals often appear to be phenocrysts that crystallised directly from the carbonatite melt, it seems more likely that the carbonatite melt was instead a diffusive medium in which SiO2 derived from the silicate rocks was transported into the carbonatite system and sequestered in the skarn-like mineral assemblage. In this model, carbonatite rocks are hybrid rocks that result from a traditional magmatic crystallisation of carbonate minerals and from contamination by silicate material. This model now better explains field and thin-section observations and reverses Daly’s hypothesis based on reactions proposed by Rittman. It explains the specific crystal chemistry of the carbonatite minerals and their textural relationship, which are entirely different from those of skarns. The reactions that form the carbonatite-hosted skarn assemblages follow the same thermodynamics that govern the formation of true skarns hosted in sedimentary carbonate rocks. However, there is a fundamental difference: the liquid magma is carbonatitic, not siliceous. Essentially, this is not a skarn per se, but rather an “antiskarn”.

Sometimes there are circular thoughts in science, which reconcile old theories with new ones but that acknowledge observations developed over a century. In the end, one of the processes concomitant to the formation of calc-silicate assemblages in carbonatites is a metasomatic antiskarn reaction, which is precisely the opposite of what was proposed a century ago by Daly.

REFERENCES

Meet the Authors

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Carbonatites: Contrasting, Complex, and Controversial

Vadim S. Kamenetsky1,2, Anna G. Doroshkevich3, Holly A. L. Elliott4, and Anatoly N. Zaitsev5,6

INTRODUCTION

First reported in 1870, carbonatites are now known from more than 600 localities, are found on all continents, are found in different tectonic settings (mostly on cratons, where they are associated with large-scale faults; but also in continental rifts, orogenic belts, and oceanic islands), and can have ages from the Archaean to present (Woolley and Kjarsgaard 2008; Jones et al. 2013). Most carbonatites are restricted to continental areas where the thickened lithosphere and crust are favourable to the production of CO2-rich melts (Humphreys-Williams and Zahirovic 2021; however, they are, in fact, extremely diverse rocks. They are present in alkaline magmatic provinces, are genetically related to a wide range of ultrabasic and alkaline silicate rocks (Woolley and Kjarsgaard 2008), and occur in intrusive complexes as plugs, pipes, cone sheets, dykes and veins, as well as in volcanic environments as lavas and pyroclastic-fall deposits. Plutonic occurrences are much more common than volcanic. The sizes of carbonatite bodies are variable, from a hundred square metres to several tens of square kilometres in outcrop area. Volcanic carbonatites are known from ~50 localities (Woolley and Church 2005), but only the Oldoinyo Lengai Volcano in the Gregory Rift (part of the East African Rift System; Tanzania) is active, with several historic eruptions of lava, ash and lapilli in the 20th century (Keller et al. 2010). Carbonatite lavas were also erupted in recent geological times and are still preserved as extinct volcanoes, such as at Kerimasi (Tanzania), Tindere (Kenya), Kaisersuhl (Germany), Khanneshin (Afghanistan), and Catanda (Angola) (e.g., Woolley and Church 2005).

The International Union of Geological Sciences’ definition of carbonatite implies igneous rocks that are largely composed of carbonate minerals, but it does not take into account rocks formed under so-called ‘carbothermal’ and/or ‘carbohydrothermal’ conditions. The varieties and origins of carbonatite compositions are summarized by Mitchell (2005), who defined bona fide magmatic, mantle-related carbonatites, and fractionation-related ‘carbothermal’ derivates of “diverse, and commonly unidentified, parental magmas” represented by REE–F-rich carbonate rocks. The existence of carbonatic magmas is witnessed by lava and scoria at the Oldoinyo Lengai Volcano and is further supported by studies of extinct volcanoes (e.g., Keller 1989). On the other hand, compositions of plutonic carbonatites do not represent the composition of their melts: they are typically controlled by processes such as crystal
fractionation, loss of alkali-rich fluids, and post-magmatic re-crystallization and reaction with ground waters and host rocks. Some well-studied carbonatite complexes, like those from the Devonian Kola Alkaline Province (Russia), had a multistage origin that involved magmatic and late- and post-magmatic ‘carbohydrothermal’ liquids and fluids (Wall and Zaitsev 2004). A general concern in the literature is that carbonate-rich rocks formed in the crust (e.g., sediments, marbles, skarns, purely hydrothermal crustal anatectic melts) should not be considered together with magmatic and magmatic-carbothermal/carbohydrothermal carbonatite types (Mitchell 2005).

CARBONATITE NOMENCLATURE AND CLASSIFICATION

“Carbonatite” is a name that reflects the dominance of one or several carbonate minerals in an igneous rock (Woolley and Kempe 1989). The exact proportion of carbonate minerals required to match a definition of carbonatite (e.g., >50 vol% or >30 vol%) remains a matter of debate (Le Maitre 2002; Mitchell 2005). In contrast to other igneous rock classifications, the term “carbonatite” is applicable to both plutonic and volcanic suites.

Currently, there are three approaches to carbonatite description. Rare, but still in use, are older terms such as søvite/sövite (coarse-grained calcite carbonatite), alvikite (fine-grained calcite carbonatite), rauhaugite (coarse-grained dolomite carbonatite), and beforsite (fine-grained dolomite carbonatite). More commonly accepted carbonatite nomenclature is based on rock mineralogy. Carbonatites contain mineral species from all the major mineral classes, including native elements, sulfides, oxides, carbonates, phosphates, sulfates, and halides. Highlighting the mineralogical composition of a particular rock can be done by prefacing “carbonatite” with one, two, or even more mineral names as qualifiers, such as ‘calcite carbonatite’, ‘dolomite carbonatite’, or ‘apatite–calcite carbonatite’ (Fig. 1). Whole-rock chemical compositions are often used for the chemical classification of carbonatites, where rocks with relatively high wt% contents of CaO, MgO, or (FeO + Fe₂O₃ + MnO) are referred to as ‘calcio-’, ‘magnesio-’ or ‘ferro-carbonatites’, respectively (Woolley and Kempe 1989). A revised, though generally similar, chemical classification is based on molar proportions rather than weight percent, of oxides (Gittins and Harmer 1997). The chemical term ‘natrocarbonatite’ is applied to a rock “consisting essentially of the Na–Ca–K carbonate minerals, nyerereite and gregoryite” (Le Maitre 1997). The chemical term ‘natrocarbonatite’ is applicable to a rock “consisting essentially of the Na–Ca–K carbonate minerals, nyerereite and gregoryite” (Le Maitre 1997).

Spatially, temporally, and genetically linked to carbonatites are the following lithologies: phoscorites [magnetite–apatite–silicate (olivine, clinopyroxene, or mica) ± carbonate (calcite, dolomite)]; diverse hydrothermal veins; and metasomatic mica- and/or amphibole-rich rocks known as fenites, which have been proposed to belong to “the rocks of carbonatite series” (Bulakh and Ivanikov 1984). Similarly, the term ‘carbonatite’ can be also “applied to a complex of related carbonate and silicate rocks in a magmatic or extrusive complex” (Mitchell 2005).

CARBONATITE GEOCHEMISTRY

Major and Trace Elements

Variable mineralogy of carbonatites, hydrothermal alteration, and non-uniformity of textures and grain-size (Fig. 1) make it difficult to obtain representative chemical analyses and compare the composition of rocks even from the same outcrop. Chemical classification based on molar proportion of oxides (Gittins and Harmer 1997) closely, but not entirely (see above), relates to the modal mineralogy of the carbonatites. For example, calcite-rich, dolomite-rich and siderite-rich carbonatite can be assigned chemical names as calcio carbonatite, magnesiocarbonatite, and ferrocarbonatite, respectively (Fig. 1). The abundances of the major oxides CaO, MgO, and FeO in bulk rock compositions also reflect amounts of non-carbonate minerals, such as forsterite, and the pyroxene-, amphibole- and mica-group minerals, magnetite, apatite, etc. The silicate minerals are in control of Al₂O₃ and SiO₂ components, whereas oxide minerals and apatite are responsible for Fe₂O₃, TiO₂, and P₂O₅, respectively.

Abundances of alkali elements in carbonatites worldwide are very low (on average K₂O + Na₂O = 0.6 and 0.7 wt% in plutonic and volcanic carbonatites, respectively) with the exception of the Oldoinyo Lengai natrocarbonatite, which is dominated by alkali elements (up to 41.5 wt% K₂O and Na₂O). Some carbonatites, such as Khibina and Vuoriyivarvi (Kola alkaline province, Russia), contain significant mafic and ultramafic rocks. The rock chemistry of carbonatites is controlled by the K₂O/SiO₂ ratio, which is high in the Khibina and Vuoriyivarvi complexes (see below) (Walter et al. 2021). Similarly, studies of solid, melt, and fluid inclusions in carbonatite minerals (see below) imply that primary and parental melts of magmatic carbonatite rocks initially contained significant amounts of alkalis.
Many carbonatites and adjacent fenitized rocks contain highly elevated concentrations of incompatible trace elements, such as Ba, Sr, REEs, Th, U, Nb, Zr (e.g., Chakhmouradian 2006), and the majority of these elements are economically important. The enrichment of certain elements in carbonatites is extraordinary compared to their abundances in other terrestrial rocks, and has strong mineralogical control (e.g., monazite and apatite are responsible for P and REEs; perovskite for Ti, Nb, and REEs; pyrochlore for Nb and Ta). High abundances of REEs (~10 wt% and even higher) in some carbonatites reflect the presence of a wide variety of REE minerals (e.g., burbankite, synchysite, bastnäsite, monazite) that form during magmatic crystallization, deuteric or hydrothermal remobilization, and/or weathering. The overall enrichment in the lithophile trace elements is comparable in plutonic and volcanic carbonatites but varies strongly for rocks in the same complex and even on the scale of an outcrop.

Most carbonatites show very strong fractionation among the lithophile trace elements, which can have wide ranges: La<sub>2</sub>O/Sm<sub>2</sub>O ratios can be 4–100, and Gd<sub>2</sub>O/Yb<sub>2</sub>O ratios can be 2–50 (Jones et al. 2013).

Fluorine can reside in fluorapatite, fluorite, and fluorarbonates and is represented in higher abundances than Cl in plutonic carbonatite minerals, averaging 0.5 wt% and 0.03 wt%, respectively. In contrast, the Oldoinyo Lengai volcanic carbonatites are significantly more enriched in the halogens, and Cl dominates over F (cf., 1.2–5.9 wt% Cl vs 1.2–3.6 wt% F) (Mangler et al. 2014 and references herein).

Most compatible trace elements (i.e., those that preferentially concentrate into solids vs. co-existing melts), such as Co, Cr, Ni, and V, are generally very low (<100 ppm) in all carbonatites, but some chalcophile metals (e.g., Cu in the Phalaborwa carbonatite–phoscorite complex in South Africa) can even make economic deposits.
Stable and Radiogenic Isotopes

Syn- and post-magmatic alteration of carbonatites is well known to affect compositions of stable and radiogenic isotope ratios, with magnitudes that depend on the particular isotope, overall abundances of the element in question, abundance ratios of a parent–daughter pair involving radioactive decay, host mineral, mineral assemblage, type of alteration, and age of the rocks.

The reconstruction of original (magmatic) carbon and oxygen isotope ratios in carbonate minerals from carbonatites is a challenging task because they are prone to recrystallization in subsolidus and hydrothermal conditions. For example, δ18O values of the Oldoinyo Lengai natrocarbonatite lavas increase from +6.5‰ to +11.8‰–12.4‰ within days of eruption, concomitant with partial subsolidus replacement of magmatic carbonates by hydrous Na–Ca carbonates (Keller and Zaitsev 2006). As equilibration with atmospheric moisture progresses, δ18O of these lavas increases even more, reaching +15.5‰ to +18‰ in the hydrated carbonate with perisoméite [Na2Ca(CO3)2·2(H2O)] and +23‰ to +27‰ in the calcite carbonatites (Keller and Zaitsev 2006). Similarly, altered natrocarbonatite lavas from ancient Tinderet and Kerimasi volcanoes are characterised by higher δ18O values (+16.2‰ to +22.6‰) compared to primary calcite phenocrysts (+7.4‰ to +8.1‰) (Zaitsev et al. 2013). Similarly, a narrow range of δ13C (~−6.3‰ to −7.1‰) in fresh Oldoinyo Lengai natrocarbonatites is significantly extended to higher values in altered rocks (~−1.5‰) (Keller and Zaitsev, 2006), and such higher δ13C values are also common in other carbonatites worldwide. Isotopic shifts may be explained by isotopic exchange between carbonatites and H2O–CO2 fluids at different temperatures and with different H2O:CO2 ratios, assimilation, and other processes occurring in early stage magmatic carbonatites through to sub-solidus fractionated carbonatites and finally to the subsolidus hydrothermal stage.

Bona fide magmatic carbonatites usually preserve their original radiogenic isotope ratios because of extreme enrichment in the elements in question (e.g., Sr, Nd, Pb) as part of a general pattern of incompatible trace element enrichment, and because of the conservative behaviour of some of these elements during subsolidus alteration (e.g., Nd, Hf). In general, the radiogenic Nd and Hf isotope signatures of mantle-derived carbonatite melts is not affected by crustal contamination. Thus, carbonatites from Archean to present may provide reliable insights into the isotopic evolution of the Earth’s mantle. Most carbonatites are characterised by relatively radiogenic Nd and Hf and non-radiogenic Sr isotope compositions, implying depleted or slightly enriched mantle sources (Bell and Simonetti 2010; Jones et al. 2013 and references therein). In this respect, carbonatites contrast with certain areas of alkaline magmatism, such as the Roman Comagmatic Province (Italy), which are characterized by crust-like isotope compositions.

TEMPORAL AND SPATIAL ASSOCIATIONS OF CARBONATITES

The majority (76%) of carbonatites occur in close temporal and spatial association with diverse ultrabasic and alkaline silicate rocks (Woolley and Kjarsgaard 2008). Our knowledge of associated rocks in a particular carbonatitic complex strongly depends on that complex’s erosion level and on the results of drilling and mining activities. Associations of silicate rocks typically found with carbonatite in a plutonic complex may include olivinite, peridotite, pyroxenite, melilitolite, jiolite, and nepheline syenite. Carbonatites in volcanic complexes may associate with olivine melilitolite/olivine nephelinite, nephelinitite, phonolite, and trachyte. Notably, carbonatite–silicate associations may include only one, or a combination of, several of the rock types stated above. The association of carbonatites with silicate rocks has received several explanations in almost every publication on this topic, ranging from co-genetic to circumstantial links. The most frequently proposed hypotheses for the occurrence of carbonatites in ultrabasic to alkaline complexes call on crystallization from a residual melt after extensive fractionation of carbonated silicate magmas and related carbonate–silicate liquid immiscibility (Fig. 2C) (Jones et al. 2013), or primary melts of a CO2-bearing mantle utilising the same alkaline–silicate plumbing system (Gittins and Hamer 2003).

Fenite: Metasomatic Alteration Aureoles

Carbonatite and alkaline melts expel multiple pulses of alkali-rich fluids as they ascend, cool, and crystallize, and these expulsions alter the surrounding country rock through a process called fenitization (e.g., Le Bas 2008; Elliott et al. 2018; Walter et al. 2021). This metasomatic process forms aureoles of altered rock (fenite) that can extend over scales from centimetres to several kilometres away from the source, depending on factors such as porosity, permeability, and element concentration gradients between the fluid and the country rock (Elliott et al. 2018). Fenites typically consist of a potassic aureole proximal to the intrusion, surrounded by a distal sodic aureole. Fluid migration to the outer fenite aureole is facilitated by a well-developed vein network, which is typically formed by hydraulic fracturing early during the fenitization process. These veins restrict the volume of country rock interacting with the fluid (Fig. 3A), allowing element concentration gradients to be maintained over large distances (Elliott et al. 2018; Walter et al. 2021).
Fenitization typically involves the removal of silica and addition of alkalis (Na$_2$O + K$_2$O). Fenitization causes an increase in alkalis (0.5–10 wt%) and a decrease in silica (0.5–29 wt%) when comparing protolith and fenite (Elliott et al. 2018). However, the magnitude of this alkali–silica exchange is protolith dependent, the greatest fenitization occurring when there is a large alkali concentration gradient between the fluids and protolith, or are there high proportions of less stable minerals. Therefore, protoliths such as granite or meta-sediments are typically more intensely fenitized compared to quartz- or carbonate-dominated rocks, such as sandstone or limestone. The fate of the silica removed during fenitization is still debated, with some authors arguing that silica migrates down a concentration gradient from the country rock towards the intrusion, leading to the often-observed silicified carbonatites. Alternatively, common late-stage quartz veins and fenite silicification may indicate that silica is transported to the outer zones of the fenite. Silica mobilization during fenitization is often associated with a substantial volume loss ranging from 6% to 20% (e.g., at Alnö, Sweden) (Morogan 1989).

**CARBONATITE CONTROVERSY: ROCKS VS MAGMAS**

Strong chemical and textural syn- and post-magmatic modifications in intrusive carbonatites are mirrored by observations on modern carbonatitic lavas at Oldoinyo Lengai Volcano that degrade within several weeks of emplacement (Zaitsev and Keller 2006). Prior to alteration, these low-temperature (<600 °C) gregoryite–nye-reite carbonatites are strongly enriched in Na$_2$O and K$_2$O (total of 38–41.5 wt%) and halogens (up to 4.5 wt% F and 5.7 wt% Cl), and have low Ca (15 wt%) and insignificant Mg–Fe contents (<1 wt%), compared to the Ca–Mg-dominated compositions typical of intrusive calcite or dolomite carbonatites (Fig. 1). The exceptional alkali-rich compositions at the only active carbonatite volcano, coupled with petrographic and geochemical evidence of alkali-rich compositions in prehistoric extrusive carbonatites (Zaitsev et al. 2013) and geochemical halos (i.e., fenite) around many intrusive carbonatites, suggest that most common Ca–Mg-dominated compositions of carbonatites in the rock record may not represent primary liquid compositions but are magmatic crystal cumulates and/or residues left after syn- and post-magmatic alteration by deuteritic and meteoric fluids (e.g., Le Bas 2008; Elliott et al. 2018; Walter et al. 2021). Thus, using bulk rock analyses effectively prohibits reconstruction of parental carbonatite melt compositions.

**Inclusions in Carbonatite Minerals**

Study of inclusions (crystal, melt, and fluid) in igneous minerals aids in constraining the liquidus assemblage, chemistry, volatile content, temperature, and evolutionary paths of their parental melts, because primary and pseudosecondary inclusions in phenocrysts largely retain magmatic qualities. Comprehensive studies of inclusions hosted in minerals have been undertaken at carbonatite complexes, including at Oka (Quebec, Canada) (Chen et al. 2013), at Afrikanda (Kola alkaline province, NW Russia) (Potter et al. 2020), and at Kerimasi (Gregory Rift, Tanzania) (e.g., Guzmics et al. 2012).

Host oxide minerals in studied carbonatites are abundant, large in size, chemically and mechanically robust, and contain numerous primary inclusions (Fig. 4). However, the opacity of oxide hosts hinders common approaches to studying individual inclusions: this can be efficiently dealt with only by special techniques (e.g., water-free grinding and polishing) (Chen et al. 2013; Potter et al. 2020).

Inclusions are typically crystalline and consist of various carbonate, anhydrous and hydrous silicate, oxide, halide, sulfate, sulfide, and phosphate minerals (Fig. 5) (Table 1). Individual inclusions up to 100 μm across can be as simple as a single mineral or as complex as 12 different phases (Fig. 5) (Table 1). Neighbouring inclusions may not contain the same assemblage of minerals (Fig. 5F), and the phase...
proportions can be highly variable. The inclusions’ phase assemblages are distinct for different carbonatites and even between samples in the same carbonatite; however, alkali carbonates (shortite and nyerereite), calcite, and apatite are common in every sample and are often dominant (Table 1).

The original interpretation of the magnetite-hosted, multiphase inclusions in the Oka carbonatite was that they were bona fide crystallised melt inclusions (Chen et al. 2013). However, random proportions of co-trapped immiscible alkali–silicate, alkali–carbonate and Cu–Fe sulfide melts and even micro-emulsions of these liquids in a suite of heated and quenched perovskite-hosted multiphase inclusions in the Kerimasi intrusive rock (afrikandite) strongly point to a highly heterogeneous environment of crystallization (Guzmics et al. 2012). Furthermore, entrapment of a single parental carbonatite liquid was challenged by the study of multiphase inclusions in perovskite and magnetite from Afrikanda rocks (Potter et al. 2020). There are five arguments in favour of their non-magmatic origin: 1) the textural characteristics of the host oxide minerals, which show sintering of individual grains, dissolution, and recrystallization; 2) a mismatch between phases and their assemblages inside inclusions and those in the host rocks; 3) the presence of minerals that are not expected to arise through magmatic crystallization (e.g., pectolite, andradite, wollastonite, brucite, chlorides, baryte); 4) there are variable mineral assemblages and bulk compositions of inclusions in the same grains; 5) a failure of inclusions to homogenise on heating, even at temperatures likely higher than any natural carbonatite magma (Potter et al. 2020).

The preferred model for the polymineralic inclusions in the Afrikanda perovskite (Potter et al. 2020) and magnetite from other carbonatites (Fig. 5) is random trapping of magmatic and post-magmatic minerals that were interstitially present during coalescence (or sintering) and recrystallization of magmatic oxide grains at subsolidus conditions.

Clearly, the use of multiphase inclusions has so far failed to adequately address the original compositions of carbonatite magmas. On the other hand, the observed mineral inclusion assemblages are undoubtedly carbonate-rich, silica-undersaturated and dominated by alkali and alkali-earth elements, all traits that constrain the origins in the mantle and evolution in the crust of plutonic carbonatites.

**Figure 4** (A) Backscattered electron image showing ‘sintering’ textures of perovskite and magnetite in the silico-carbonatitie from the Afrikanda deposit (the Kola alkaline igneous province, NW Russia). (B–D) Sintering textures from the carbonatite of the Afrikanda deposit as seen by transmitted-light optical microscopy. Note large abundances of polycrystalline inclusions in the cores of the perovskites and the diverse mineral assemblages (see also Figs. 5E and F) in the neighbouring inclusions; intergrown magnetite is largely inclusion-free. The scale bar is 150 μm.

**Figure 5** Backscattered electron images showing an unprecedented variety of different mineral phases in the inclusions hosted by magnetite in carbonatites. (A) Polymineralic phases from the Kovdor carbonatite (Russia). (B) Polymineralic phases from the Guli carbonatite (Russia). (C, D) Polymineralic phases from the Oka carbonatite (Quebec, Canada). (E, F) Polymineralic phases from the silico-carbonatites Afrikanda carbonatite (Russia) hosted by perovskite. The numbered individual phases are as follows: 1–calcite, 2–shortite, 3–nyerereite, 4–eitelite, 5–burbankite, 6–bradleyite, 7–sylvite, 8–thenardite, 9–apatite, 10–pyrochlore, 11–magnetite, 12–spinel, 13–baddeleyite, 14–columbite, 15–brucite, 16–phlogopite, 17–(Ba)-phlogopite, 18–sodalite, 19–pectolite, 20–diopside, 21–andradite, 22–cuspidine, 23–unknown Na–Mg-carbonate.
OUTLOOK FOR THE CARBONATITE STORY

Today, carbonatites are widely accepted to be mantle-derived or evolved from mantle-derived melts, although their primary (or parental) melt compositions and ultimate genesis are still controversial. The geochemical and mineralogical diversity among different carbonatite complexes around the world is governed by compositions of parent magmas, the temperatures and pressures of melt generation, liquid immiscibility and fractional crystallization, the extent of wall-rock assimilation, and the loss of alkali and volatile elements to fenitization. The greatest discrepancy is that between Ca-rich (calcite) or Ca–Mg-rich (dolomite) compositions of the >600 carbonatite complexes worldwide (Fig. 1) and the halogen-rich natrocarbonatite magmas at the modern Oldoinyo Lengai Volcano (Fig. 2): this raises the imperative question as to why plutonic carbonatite complexes are deficient in alkalis (most notably Na and K), chlorine, and fluorine. Therefore, the petrogenetic significance of the Oldoinyo Lengai natrocarbonatite lavas for identifying the ‘true’ chemical composition of parental carbonatite magmas, and the applicability of this to other plutonic and volcanic carbonatites, is still pertinent. One way we might understand this disparity could be that alkalis are generally a major component of carbonatitic magma, but are usually lost during melt evolution and crystallization, leaving behind calcitic or/dolomitic residues that eventually solidify to form the plutonic carbonatites and drive fenitization of the surrounding country rocks.

Attempts to better understand primary carbonatite magmas have turned to the study of the multiphase inclusions in the oxide minerals of carbonatites (Figs. 4, 5) (Table 1). However, the great diversity and complexity of these inclusions has attracted contrasting interpretations, possibly because they reflect chemical and mineralogical evolution that stretches across both magmatic and subsolidus recrystallization processes.

The take-home message is that there are no two identical carbonatite rocks in the world: they have variable mineral and chemical compositions that are controlled by many factors, including post-magmatic alteration. There are many indications (modern natrocarbonatite magma, associated silicate rocks, alkali-rich fenite, and mineral-hosted inclusions) that the original carbonatite magma chemically differed from that recorded by the bulk compositions of carbonatite rocks. We need to diversify the methodologies and techniques, and even sample selection, in order to better understand carbonatite magmas. The application of melt and fluid inclusion studies to unravel the details of carbonatite primitive melts requires critical choices of samples, and the further analysis of all inclusion types (melt, fluid, and crystal) within a comprehensive range of carbonatite minerals.

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Evolution of Carbonatite Magmas in the Upper Mantle and Crust

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Carbonatites are the most silica-poor magmas known and are amongst Earth’s most enigmatic igneous rocks. They crystallise to rocks dominated by the carbonate minerals calcite and dolomite. We review models for carbonatite petrogenesis, including direct partial melting of mantle lithologies, exsolution from silica-undersaturated alkali silicate melts, or direct fractionation of carbonated silicate melts to carbonate-rich residual melts. We also briefly discuss carbonatite–mantle wall-rock reactions and other processes at mid- to upper crustal depths, including fenitisation, overprinting by carbohydrothermal fluids, and reaction between carbonatite melt and crustal lithologies.

Keywords: carbonatite; partial mantle melts; liquid immiscibility; fractionation; SiO2-undersaturated melts.

INTRODUCTION

Carbonatites are silica-poor igneous rocks composed predominantly of primary carbonate minerals, typically >50% modal calcite and dolomite. They are the most silica-undersaturated magmas in the Earth’s crust. The bulk of the world’s supply of rare earth elements (REEs) and Nb is derived from carbonatites. The Earth has approximately 600 known occurrences of carbonatites (Humphreys-Williams and Zahirovic 2021 this issue) that range in age from Archean to the present day, and are found on all continents and, in rare cases, on oceanic islands with atypically thick lithosphere [i.e., the Canary Islands (Spain) and Cape Verde]. The most common geodynamic setting for carbonatites is within intraplate regions, commonly cratonic margins, and many are associated with the early stages of rifting and plate separation. Carbonatites have been linked to mantle plumes and the formation of large igneous provinces (Bell and Simonetti 2010).

Carbonatites are a diverse group of rocks that include extrusive, intrusive, and carbohydrothermal varieties (formed by reaction with CO2 + H2O–rich fluids). The only known currently active carbonatite volcano is Oldoinyo Lengai (Tanzania), which historically erupted natrocarbonatite. However, there are ~50 examples of carbonatite extrusives reaching back to 1.8 Ga in the geological record.

The majority of carbonatites (74%) are associated with a wide variety of alkaline igneous silicate rocks that range from ultramafic to felsic (e.g., lamprophyres, olivine melilitites, olivine nephelinites, phonolites, syenites, and their intrusive equivalents). The most common are nephelinite, syenite, and melilitite, the parental melts of which could have been derived by small degrees of partial melting of the hydrous-and-carbonate-bearing mantle (Woolley and Kjarsgaard 2008). Progress towards understanding the formation and evolution of carbonatite magmas has been complicated by their petrological diversity and that of the associated silicate rocks, and by the common presence of cumulate, flow banded, and rheomorphic textures in carbonatites. Field, petrological, and geochemical studies have shown strong links between carbonatites and their associated alkaline silicate rocks. These carbonatite–alkali–silicate complexes could be related by liquid immiscibility, or by extensive fractionation of CO2-bearing silicate melts that have left residual carbonate-rich liquids. Alternatively, some carbonatites occur without associated silicate rocks and/or carry mantle xenoliths and xenocrysts and are inferred to be derived directly from the mantle (Harmer and Gittins 1997). These carbonatites crystallise magnesian calcite as the liquidus phase at low pressures (Harmer and Gittins 1997) and this, coupled with field and textural evidence for cumulates and crystal mushes, lends support for a primary mantle origin for some carbonatites. Furthermore, these primary carbonatites may sometimes be spatially ‘associated’ with primary alkali silicate rocks, but have no genetic relationship to them.

Despite their diversity in mineralogy and lithological association, most carbonatites have stable (carbon and oxygen) and radiogenic isotopic compositions that unequivocally indicate a mantle origin for their parental magmas (e.g., Bell and Simonetti 2010). Moreover, young (<200 Ma) carbonatites have Sr, Nd, and Pb isotopes that closely resemble those of oceanic islands basalts, with HIMU (‘high μ’, where μ = 238U/204Pb) and EM1 (‘enriched mantle type 1’) being the dominant mantle endmembers. This suggests they contain significant components that originated in the sub-lithospheric mantle. Noble gas and N isotopic compositions also indicate a sub-lithospheric source for the parental melts, associated with either upwelling asthenospheric mantle or with plumes arising from the deeper mantle (Bell and Simonetti 2010).

The aim of this article is to review models for the petrogenesis of carbonatites and their evolution before and during crustal intrusion or eruption. Current models for the genesis of carbonatites are illustrated in Figure 1 and include the following:

1. Primary carbonatite magmas emplaced into the crust directly from their mantle sources. Partial melting of
carbonate-bearing peridotite or eclogite in the mantle has been shown to produce alkali-bearing, dolomitic to calcio-dolomitic melts (e.g., Wallace and Green 1988; Yaxley and Brey 2004).

2. Separation of an immiscible carbonatite magma from CO₂-bearing, silica-undersaturated, silicate magmas (e.g., Freestone and Hamilton 1980). Immiscibility is induced by fractionation of the parental primary or evolved liquid, driving its composition to a two-liquid solvus leading to separation of silica-undersaturated silicate melt and carbonatite melt (Kjarsgaard and Peterson 1991; Brooker and Kjarsgaard 2011).

3. Residual melts from the fractional crystallization of evolved, carbonated, undersaturated, alkali-rich silicate liquids without immiscibility (Watkinson and Wyllie 1971).

In any of these three cases, the parental carbonatite and alkali silicate melts may be further modified in the upper mantle or crust by fractional crystallization, reaction with and/or assimilation of wall rock, and loss of alkali-rich fluids to surrounding crust via a process referred to as fenitisation. Extended fractionation of sodic or potassic alkaline silicate magmas (and of carbonatites themselves) can produce low-temperature CO₂, H₂O-rich (and F-rich) residual fluids, commonly referred to as carbonatite melts are of very low density and viscosity and are able to weat silicate grain boundaries at melt fractions as low as 0.02% (Hunter and McKenzie 1989). They can, therefore, segregate from their sources at near-solidus conditions and, being buoyant, can migrate rapidly along silicate grain boundaries by porous flow. If dolomitic carbonatites ascend at such low melt fractions, they are likely to migrate along P–T paths close to the local geotherm, rather than along liquid adiabats. When they intersect Reaction (1), the dolomite component in the carbonatite melt will react with, and replace, orthopyroxene in the wall rock to produce metasomatic olivine and clinopyroxene, releasing a CO₂-rich fluid. This process may even eliminate orthopyroxene locally, leading to the formation of apatite-bearing wehrlite, as has been documented in spinel-peridotite xenolith suites from eastern Africa and southeastern Australia (Yaxley et al. 1991; Rudnick et al. 1993).

Clearly, in this situation, Reaction (1) represents a barrier to migration through, and the extraction of, carbonatites and carbonated undersaturated silicate melts from Iherzolitic or harzburgitic mantle. However, Dalton and Wood (1993) showed that the conversion of peridotite to wehrlite, which can result from Reaction (1), may armor magma conduits and pathways and thereby allow their ascent, without intersecting Reaction (1). Instead, dolomitic carbonatite melts can evolve to more CaCO₃-rich compositions by reacting with the wehrlite wall rock (Dalton and Wood 1993) (Reaction 3).

Melting of carbonate peridotite near its solidus to produce carbonate melts is limited to pressures ≥ 2.0 GPa, where the reaction

$$4\text{MgSiO}_3(\text{oliv}) + \text{CaMg(CO}_3)_2(\text{melt}) = 2\text{Mg}_2\text{SiO}_4(\text{ol}) + \text{CaMgSi}_2\text{O}_6(\text{ol}) + 2\text{CO}_2(\text{fluid})$$  (1)

intersects the peridotite + CO₂ ± H₂O solidus and limits dolomite stability relative to CO₂-rich fluid at lower pressures (Fig. 2). At higher pressures and subsolidus temperatures, magnesite forms via the vapour-absent reaction

$$\text{CaMg(CO}_3)_2(\text{dolomite}) + 2\text{MgSiO}_3(\text{ol}) = \text{CaMgSi}_2\text{O}_6(\text{ol}) + 2\text{MgCO}_3(\text{magnesite})$$  (2)

Near-solidus melts from 2 to 6 GPa are dolomitic to calcio-dolomitic, with SiO₂ > 5%–10%, Ca/Mg < 1, and a total alkali content of typically 5–7 wt% (Wallace and Green 1988; Dasgupta et al. 2004) (Fig. 2).

Evidence from high-pressure experimental petrology, geology, and geochemistry for these models (Fig. 1) and demonstrate that they all apply in different situations.

**CARBONATE MELTS FROM THE MANTLE**

Evidence from high-pressure experimental petrology has shown unequivocally that in both compositionally simple systems such as Na₂O–CaO–MgO–SiO₂–CO₂ and in “complex” natural systems with ≥ 10 major and minor components, low degrees of melting of carbonate-bearing peridotite or eclogite can produce alkali-bearing, dolomitic, and calcio-dolomitic carbonate melts. The melts form at a pressure (P) ≥ 2 GPa (Fig. 2) and a temperature (T) and oxygen fugacity that occurs along oceanic and continental upper mantle conductive geotherms (Wallace and Green 1988; Dasgupta et al. 2004).

**Figure 1** Schematic diagrams illustrating three models for carbonatite formation. (A) Partial melting of amphibole carbonatite peridotite induced by heat influx from upwelling asthenospheric mantle forms ephemeral sodic dolomitic carbonatite melt, which ascends and reacts with lithospheric orthopyroxene, forming a wehrlite layer. If wehrlite armours the magma conduits then dolomitic carbonatite may reach the crust. Reaction of dolomitic carbonatite and wehrlite can generate calcio-carbonates that may also reach the crust. Alternatively, rapid ascent through lithosphere-scale fractures (thick black lines) may allow direct crustal emplacement. (B) Fractional crystallisation involving olivine (quadrilaterals, no cleavage), clinopyroxene (hexagons, oblique cleavage), and nepheline (elongate octagons, orthogonal cleavage) in a silica-undersaturated, carbonated silicate melt drives the liquid to a two-liquid solvus, allowing carbonatite liquid to unmix and segregate. The outer patterned margin of the carbonatite represents fenite (and fenitisation) in the crust and metasomatism of a magma conduit in the mantle. (C) Fractional crystallisation of a silica-undersaturated, carbonated silicate melt leads to highly evolved, carbonatite liquid without intersecting a solvus. The indicated crystals are as for Figure 1B but with the addition of calcite (rhombs with oblique cleavage).
Carbonatite liquids can form from carbonated silicate magmas if such magmas reach the two-liquid solvus that separates carbonate and silicate liquids. Melting of peridotite with only a few 1,000 ppm C, at low melt fractions and high pressures (>2.5–3.5 GPa) yields carbonated, SiO₂-undersaturated silicate melts, such as olivine melilitite or olivine nepheline (Green 2015), with several wt% dissolved CO₂. Segregation and migration of these melts into the crust, coupled with crystallization of silicate phases, increases CO₂ in the residual silicate liquid such that a carbonate liquid is exsolved. Thus, a carbonatite magma forms, with its associated conjugate silica-undersaturated silicate magma (e.g., Kjarsgaard et al. 1995; Weidendorfer et al. 2016).

There have been numerous experimental studies on the immiscibility of silicate–carbonate liquids at crustal and upper mantle pressures (see Brooker and Kjarsgaard 2011 and references therein). These studies have been broadly aimed at understanding the effects of variable bulk compositional parameters [alkali, SiO₂ and H₂O contents, Ca/Mg, Fe/Mg, pressure (including PCO₂) and temperature] on the extent of the carbonate–silicate two-liquid field, and the compositions of liquids and solid phases.

Experimental studies at crustal pressures using natural rock powders have shown that immiscibility between silicate and carbonatite melts can reproduce compositions closely resembling those found in nature (Freestone and Hamilton 1980; Kjarsgaard and Peterson 1991). These compositions used as starting material in the two-liquid experimental studies include nepheline or phonolite combined with natrocarbonatite from Oldoinyo Lengai (Freestone and Hamilton 1980; Kjarsgaard et al. 1995) and nephelinites from the Shombole Volcano (Kjarsgaard and Peterson 1991). These studies indicate that the immiscibility field closes off at low alkali contents with the production of conjugate Na-bearing calcic carbonatites and nephelinites. They also indicated that the two-liquid field narrows in compositional space with increasing temperature and decreasing pressure (Fig. 3). Notably, liquid immiscibility, while feasible at mantle pressures (2–3 GPa), is favoured at moderate pressures (mid-crust to lower-crust). At mantle pressures, high CO₂ solubility in the silicate melt may preclude CO₂-saturation and immiscibility (Brooker and Kjarsgaard 2011).

Strong support for the important role of liquid immiscibility in the generation of carbonatites associated with alkaline silicate magmas is provided by an analysis of ocean island volcanics by Schmidt and Weidendorfer (2018), who showed that the formation of carbonatites is restricted to those hotspot islands which have lavas with the lowest Si- and highest alkali-contents among their primitive melts (Cape Verde and Canary Islands). In these cases, crystal fractionation of strongly silica-undersaturated primitive melts having high alkali contents drives the evolving melts into the silicate–carbonatite miscibility gap, whereas less alkaline magmas fractionate toward the alkali-feldspar thermal divide and do not exsolve a carbonate.

The carbonatite lavas erupted from Oldoinyo Lengai are also considered to result from liquid immiscibility with the carbonatite exsolved from parental nepheline magma (Potter et al. 2017). Supporting evidence is found in melt inclusions trapped in minerals crystallising from the lavas (e.g., gregoryite, schorlomite, nepheline, clinopyroxene) which preserve clear textural evidence of immiscibility between nephelinitic and carbonatite (halide) liquids (Potter et al. 2017). The lavas erupted at Oldoinyo Lengai contain phenocrysts of gregoryite [(Na₂K₂Ca)CO₃] and nephene carbonate solid solutions, Na₂CO₃, khanneshite, fluorite, Na-sylvite, K-halite, apatite, nepheline, sulfides, and other phases (Potter et al. 2017; Weidendorfer et al. 2017; Kamenetsky et al. 2021 this issue). The origin of the carbonatite lavas ultimately relates to liquid immiscibility from parental nepheline magma that exsolved alkali-carbonate liquid.
The highly sodic carbonatite lavas at Oldoinyo Lengai are commonly viewed as anomalous because they do not resemble any other carbonatites, which are typically much lower in Na₂CO₃ and richer in CaCO₃. The majority of carbonatites are alkali-depleted due to many possible processes, e.g., accumulation of crystallized calcite or dolomite, alkali loss to exsolved fluids or late-stage melts, or even weathering. The lavas of Oldoinyo Lengai are notoriously unstable under atmospheric conditions and are difficult to preserve in the surficial environment because of the H₂O-soluble nature of the sodic carbonate minerals they crystallize. The lavas have been observed to evolve very rapidly after eruption as a result of alkali leaching, leaving residual calcic carbonate rocks, with the primary melt compositions only preserved as inclusions in minerals.

An example of carbonatite formation by silicate–carbonate liquid immiscibility as recorded in melt inclusions is the Kerimasi Volcano (Tanzania), only a few kilometres south of Oldoinyo Lengai. At Kerimasi, melt inclusions trapped in perovskites consist of immiscible silicate–carbonate pairs: melilitite and conjugate alkali-bearing (7–10 wt %) calcio-carbonatites (Guzmics et al. 2015). However, silicate and carbonate melt inclusions in nepheline, apatite, and magnetite further reveal a range of compositions, including melt inclusions similar to the natrocarbonatites that erupted from Oldoinyo Lengai (Guzmics et al. 2015). The difference in exsolved carbonate compositions is attributed to the more calcic parental melilitite at Kerimasi Volcano compared with the peralkaline nephelinite parent at Oldoinyo Lengai. This illustrates the important effects of the parental undersaturated alkali silicate melt composition on the nature of the exsolved conjugate carbonate liquids (Kjarsgaard and Peterson 1991).

**FRACTIONAL CRYSTALLISATION OF SILICATE MELTS LEADING TO RESIDUAL CARBONATITE MELTS**

In some cases, silica-undersaturated alkali melts may undergo fractional crystallisation without intersecting a two-liquid field. Fractionation may proceed sufficiently to produce an evolved, residual carbonatitic liquid. Experimental studies of this process are rare. Watkinson and Wyllie (1971) investigated the nepheline–calcite join at 25 wt% H₂O and showed that a H₂O-bearing liquid with a composition of 90% nepheline + 10% calcite at ~0.1 GPa could undergo fractionation with a successive assemblage of nepheline, melilitite, and hydroxyhaüyne or cancrinite, leading to a calcite-rich residual liquid. This was a way to explain the sequence of rock-types observed in the Oka carbonatite complex in Québec (Canada), where nepheline-, melilitite + nepheline-, melilitite + hydroxyhaüyne or cancrinite-, and calcite + cancrinite + melilite-bearing rocks correspond, respectively, to the ijolite, nepheline-okaite, okaite, and carbonatite. Further experimental work is necessary to assess the characteristics of CO₂- and H₂O-bearing silicate melt compositions, their fractionating phases, and the pressure–temperature conditions that might allow for liquid lines of descent that do not intersect a two-liquid solvus, thereby evolving all the way to residual carbonatite liquids without immiscibility.

**CARBONATITE MAGMA DIFFERENTIATION**

The fact that many carbonatites in the Earth’s crust are rich in CaCO₃ (sövites, or calcio-carbonatites) is consistent with their derivation as calcite cumulates from broadly dolomitic parental melts (Harmer and Gittins 1997). As described earlier, melts parental to carbonatites that formed in the

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**Figure 3**

(A) Silicate–carbonate two-liquid fields, as determined from experiments, plotted on the Hamilton ternary, projected from CO₂ (± H₂O). The Oldoinyo Lengai (Tanzania) two-liquid field for moderate- to high-alkali compositions at fixed P (0.3 GPa) and T (1,100 °C) is shown by filled stars connected by conjugation (tie) lines. Decreasing temperature from 1,250 °C to 900 °C (open stars) at fixed P and T illustrates the widening of the two-liquid field. Data from Freestone and Hamilton (1980). The low-alkali Shombole (Kenya) two-liquid solvus at 0.5 GPa (polythermal, 1,025–900 °C), and a 2–3 GPa, 1,250 °C mantle pressure solvus illustrates the increased size of the two-liquid field with increasing pressure from 0.3 to 3 GPa. Data from Kjarsgaard (1998) and Brooker and Kjarsgaard (2011).

(B) Carbonate liquid (CL) compositions plotted on the K-poor part of the CaCO₃–Na₂CO₃–K₂CO₃ ternary at 0.1 GPa. The calcio-carbonatite to natrocarbonatite differentiation trend (illustrated by a red dashed line + arrow) is due to suppression of the calcite–nyerereite cotectic and nayerereite–fairchildite thermal divide in a natural system. Modified after Kjarsgaard and Peterson (1991) and Weidendorfer et al. (2017). Calcite-saturated carbonate liquid experimental data after Weidendorfer et al. (2017); carbonate liquids from Kerimasi melt inclusions from Guzmics et al. (2015); carbonate liquids from two-liquid fields from Freestone and Hamilton (1980) and Kjarsgaard (1998). Image of experimental run product showing quenched immiscible carbonate liquid (SL) and carbonate liquid (CL) from an experiment run at 1.5 GPa, 1,275 °C in the system SiO₂–Na₂O–Al₂O₃–CO₂. Courtesy of Richard Brooker. (D) Image of experimental run with immiscible silicate liquid (SL) and carbonate liquid (CL) and crystals of clinoxyroxene (Cpx) and calcite (cross polarized light). From Shombole nephelinite run BK290; B.A. Kjarsgaard, unpublished.
mantle are likely to be alkali-dolomitic to calcio-dolomitic in composition. Liquids close to the compositional join \( \text{CaCO}_3 - \text{MgCO}_3 \) are unlikely to crystallize dolomite as a liquidus or sub-liquidus phase at low pressures.

Experimental studies of the alkali carbonate–\( \text{CaCO}_3 \) systems (Weidendorfer et al. 2017 and references therein) have shown that calcite (and apatite) is a crystallisating phase over a large compositional and temperature range. Formation of Na-rich carbonatite (similar to those erupted at Oldoinyo Lengai) from a more calcic parental carbonatite melt was long considered highly controversial because of the existence of a thermal barrier in the \( \text{Na}_2\text{CO}_3 - \text{K}_2\text{CO}_3 - \text{CaCO}_3 \) system at low pressures (see Fig. 3). In this system, Na-bearing calcic carbonatite liquids was expected to crystallise calcite as the liquidus phase and evolve to a eutectic liquid with \(<10\text{ mol}\% \text{Na}_2\text{CO}_3\) at about 800 °C, a substantially lower \( \text{Na}_2\text{CO}_3\) content and higher temperature than the erupted lavas at Oldoinyo Lengai (490–595 °C).

However, Weidendorfer et al. (2017) have elegantly demonstrated that when this system includes additional volatile and other components known to be present in the natural lavas, such as Cl, F and \( \text{P}_2\text{O}_5 \), the thermal divide is suppressed. They demonstrated that low-pressure crystallisation of 47.7 wt% calcite, 11.9 wt% apatite and minor clinopyroxene from a calcitic carbonate liquid with 8–9 wt% \( \text{Na}_2\text{O} + \text{K}_2\text{O} \) and as little as 2.7 wt% F and 4 wt% Cl will terminate at a lower temperature eutectic (~500 °C) where a natrocarbonatite melt is saturated in \( \text{Na}_2\text{CO}_3\) and nyereite.

This raises the possibility that Oldoinyo Lengai’s highly sodic lavas are, in fact, not particularly anomalous. The processes of immiscibility and fractional crystallisation inferred or observed in this complex may, in fact, be broadly representative of other Na-poor, calcio-carbonatites which are associated with silica-undersaturated silicate magmas and were emplaced in the crust in the geological past. The low alkali contents of most carbonatites and the rarity of natrocarbonatites such as those of Oldoinyo Lengai simply reflects their likely origins as calcite-rich cumulates; a loss of Na-rich fluids to the surrounding wall rock during fenitization (see next section); the unstable nature of sodic compositions and their susceptibility to syn- and postmagmatic crystallization and fluid alteration, and especially to weathering and leaching, which may have removed evidence of their former highly sodic character.

In Figure 4, we illustrate highly simplified versions of possible scenarios in which carbonatites may be produced, including by immiscibility from a range of silica-under- saturated silicate magmas, and in settings associated with rifting, mantle plumes, and crustal margins. In general, the compositions of the associated silicate rocks are determined by the thickness of the overlying lithosphere, which limits the depth and degree of partial melting.

**SECONDARY PROCESSES AND CRUSTAL INTERACTIONS WITH CARBONATITES**

Understanding carbonatites and their genesis and evolution is further complicated by the fact that carbonatites emplaced at shallow levels in the crust can undergo extensive re-equilibration and interaction with carbohydrothermal and other aqueous fluids, including meteoric waters, and also with the crust into which they are emplaced. A classic version of these processes is referred to as ‘fenitisation’, whereby an alkali-rich fluid is expelled from the carbon-silicate melt into the surrounding country rock and metasomatizes it, forming Na- or K-rich silicate minerals such as pyroxenes, amphiboles, and alkali feldspars.

Carbonatites commonly display complex multistage evolutionary histories that can involve magmatic, carbohydrothermal, and hydrothermal stages, which can be identified by detailed petrological and geochemical study. Many carbonatites of magmatic origin have been modified by late-stage magmatic and/or sub-solidus metasomatic processes involving \( \text{CO}_2\)-rich and water-rich fluids. These fluids can lead to the remobilization and formation of secondary phases and the concentration of REEs, P, Sr, Ba and F. Experimental studies have shown that REEs are readily concentrated by hydrothermal processes and that transport and deposition of REEs is facilitated by formation of alkali-REE complexes having ligands of \( \text{Cl}^- , \text{F}^- \) or \( \text{CO}_3^{2-} \) (Anenburg et al. 2020a). In addition to fenitization, some carbonatites have been inferred to have interacted so extensively with crustal rocks that they were ephemeral, effectively reacting out of existence (Anenburg et al. 2020b).

Hydrothermal processes involving chloride- and carbonate-rich fluids are thought to have played an important role in the formation of iron-rich carbonatites (siderite- or ankerite-bearing carbonatites aka ‘ferrocarbonatites’). However, iron-rich residual carbonate could also form by extended fractional crystallisation of Ca–Mg carbonate melts, because Fe is highly soluble in residual chloride- and water-rich carbonate melts. Ferrocarbonatites likely formed by multistage processes during their crystallization, notably involving late overprinting by carbonate- and chloride-rich hydrothermal fluids and pervasive fenitization of the country rock. Similarly, it is clear that multistage processes involving magmatic carbonatite overprinted by later carbo-hydrothermal and/or hydrothermal events commonly play an important role in the development of REE and other associated mineral deposits.

**CONCLUSIONS AND FUTURE DIRECTIONS**

Carbonatites can have multiple origins and complex evolutionary histories. Most carbonatites are directly associated with sodic alkaline silicate rocks (nephelinites, melilitites) and the case for their formation by liquid immiscibility is well supported. Much of the compositional diversity of the more primitive sodic alkaline rock types associated with carbonatites that formed by liquid immiscibility (i.e., aillikite, melilitite, nephelinite, basanite) can be explained in terms of depth and degree of partial melting of the mantle. Other more evolved rock types (e.g., syenites) may reflect more extensive crystal fractionation prior to separation of an immiscible carbonatite melt. Alternatively, extended fractionation of evolved carbonated silicate magmas may result in the formation of carbonatitic rocks from residual melts, without immiscible separation of carbon from silicate melts. Within this broad spectrum of ‘carbonatitic’ rocks are the REE–F-rich carbonate rocks that may...
be precipitates from COH fluids. These rocks can be of significant economic interest due to their enrichment in REEs and other metals, such as Nb; however, formation of these ores typically involves multiple stages of enrichment.

Experimental petrology has shown that primary carbonatite melts of alkali-rich, dolomitic to calcio-dolomitic carbonate composition can be formed by low degrees of partial melting of carbonate-bearing peridotite and eclogite at pressures greater than about 2 GPa. But, because these carbonatites are intrusive (plutonic) and were modified by crystal accumulation from the primary melts, clear evidence for a primary mantle origin may be absent. Possibly as much as a quarter of known carbonate occurrences are not associated with putative conjugate silicate magmas (Woolley and Kjarsgaard 2008) and, therefore, arguably do not present evidence of formation by liquid immiscibility. Carbonatites without associated silicate rocks and which carry mantle xenoliths and xenocrysts have been inferred to be derived directly from the mantle (Harmer and Gittins 1997), as per Figure 1.

Advances in in situ age determinations using the U–Pb isotope system in perovskite and high-precision 40Ar/39Ar and Sr–Nd–Hf–Pb and carbon and oxygen isotopic analyses coupled with trace element analysis of mineral phases continue to better define the temporal and chemical relationships between coexisting carbonatite and silicate rocks. For example, are the associated rocks coogenic, or comagmatic, or simply coeval? Isotope systematics also give important information about the likely sources of melts parental to carbonatites. They are also key to deciphering the complex history of carbonatite-related ore deposits. Such integrated studies are providing new insights into the nature and origin of the diverse spectrum of carbonatites, the role of carbonate in the mantle, and the sources of carbon in carbonatites. Similarly, Ca isotopic compositions of carbonatites (Amsellem et al. 2020) and chemical and isotopic compositions of inclusions and their diamond host (e.g., using O isotopes) (Timmerman et al. 2021 this issue) are providing increasing evidence of recycling of crustal carbonates during subduction into the deep, convecting mantle as a major source of carbon in carbonatite rocks.

REFERENCES


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Carbonatitic high-density fluids and carbonate mineral inclusions in lithospheric and sub-lithospheric diamonds reveal comparable compositions to crustal carbonatites and, thus, support the presence of carbonatitic melts to depths of at least the mantle transition zone (~410–660 km depth). Diamonds and high pressure–high temperature (HP–HT) experiments confirm the stability of lower mantle carbonates. Experiments also show that carbonate melts have extremely low viscosity in the upper mantle. Hence, carbonatitic melts may participate in the deep (mantle) carbon cycle and be highly effective metasomatic agents. Deep carbon in the upper mantle can be mobilized by metasomatic carbonatitic melts, which may have become increasingly volumetrically significant since the onset of carbonate subduction (~3 Ga) to the present day.

KEYWORDS: carbonatitic melt; diamond; viscosity; metasomatism; carbon cycle; carbonate

INTRODUCTION
Diamonds provide direct samples of the mantle and most are formed in the sub-continental lithospheric mantle at depths of ~140–220 km. Uncommon “superdeep” diamonds with higher pressure inclusions are interpreted to have formed in the lower parts of the upper mantle and upper parts of the lower mantle, at ~300–800 km depth (Stachel et al. 2005). Diamonds are delivered to the surface by kimberlitic magmas and associated magmas, such as orangeites, lamproites, and lamprophyres: volatile-rich, fast-ascending, low-degree mantle melts. Carbonatite rocks are igneous rocks with >50 vol% primary carbonate minerals (Kamenetsky et al. 2021 this issue and references therein); their parental mantle-derived carbonatitic melts lie on a chemical continuum with kimberlitic melts (kibemelites have higher Mg and Si but lower Ca and CO₂). Carbonatite rocks are found in continental settings, with 75% being emplaced within 600 km of cratons (Humphreys-Williams and Zahirovic 2021 this issue), and they have been spatially connected to kimberlites (Snap Lake, Canada; Premier, South Africa) and to ultramafic lamprophyres (Alnö, Sweden; Kandalaksha, Russia; Aillik Bay, Canada).

The rare occurrences of diamonds in carbonatites (Chagatai, Uzbekistan; Dalihu, China) and the widespread finds of carbonate mineral inclusions and carbonatitic high-density fluid (HDF) inclusions in lithospheric and sub-lithospheric diamonds suggest that at least some carbonatitic melts are formed at great mantle depths (>120 km) and are involved in diamond growth. Here, we review the connection between diamond, carbonatite rocks, and the metasomatic, deep-probing nature of carbonatitic melts in the mantle from the perspectives of both experimental and natural samples. The stability of carbon phases and melts, and diamond formation reactions and their dependence on P, T and fO₂, have been studied through thermodynamic models and high pressure–high temperature (HP–HT) multi-anvil and piston-cylinder experiments. Variations in the laboratory starting compositions (CO₂, Na₂O, K₂O, MgO, CaO, FeO contents)—reflecting the major element variations of natural carbonatites—have a significant effect on the peridotite solidus temperature and implied mobility of carbonatitic melt. The major elements, trace elements, and isotopic compositions of carbonatitic HDFs in diamonds and carbonatitic melts overlap.

THE CARBONATITE–DIAMOND CONNECTION

Carbonatitic High-Density Fluids in Lithospheric Diamonds
Diamond can trap both crystalline solids and the parental fluid (the HDF) during growth in the mantle (Kleins-BenDavid et al. 2009). A range of mantle carbonatitic melt compositions can be inferred from Mg-rich to Fe-rich micro-inclusions of magnesite (MgCO₃), siderite (FeCO₃), and dolomite in diamonds from different Kimberlite localities (Diavik, Northwest Territories, Canada; Panda, Northwest Territories, Canada; Internationalaya, Sakha, Russia). The first recognition of inclusions of alkaline carbon at with water was reported in cloudy and fibrous diamonds from the lithospheric mantle by Navon et al. (1988), whose group subsequently classified HDF compositions into four endmembers: hydrous siliceous; low-Mg carbonatitic; high-Mg carbonatitic; and hydrous saline. The low-Mg and high-Mg carbonatitic HDFs bear similarities with carbonatitic melts from HP–HT experiments and will be the main focus for chemical comparison here.
Major and Trace Element Compositions of Carbonatitic Melts

High-density fluid inclusions in diamonds can be used to reconstruct compositions of high-pressure carbonatitic melts. The inclusions are measured unexposed to avoid contamination and loss of the fluid and volatiles: this results in low analytical totals (<10%) and, thus, unknown amounts of CO₂ and H₂O. Water and CO₂ contents are reconstructed from Fourier transform infrared (FTIR) spectra and cation (CO₃²⁻) contents from inclusions measured by electron probe microanalysis (EPMA) and/or scanning electron microscopy (SEM), and volatiles are proposed to make up ~40 wt% (Navon et al. 1988).

The carbonatitic HDF endmembers in diamonds are rich in Mg, Ca, K; are enriched in incompatible elements relative to primitive mantle compositions; are low in Si and Al; and are low in Sr, Ti, and Y relative to the middle rare earth elements (MREEs) and heavy rare earth elements (HREEs). Low-Mg carbonatitic HDFs have <14 wt% MgO. High-Mg carbonatitic HDFs (>14 wt% MgO) have higher Na₂O and BaO relative to low-Mg carbonatitic HDFs, on a volatile-free basis (Klein-BenDavid et al. 2009). Although HDF compositions are often compared to solid crustal carbonatite rocks, it is important to remember that the latter are susceptible to late-stage modification by magmatic processes and alteration (Kamenetsky et al. 2021 this volume). Coarse-grained plutonic carbonatites are often cumulate in nature, and carbonatitic melts lose soluble alkalis to hydrothermal, magmatic, or meteoric fluids during cooling. Thus, crustal carbonatites do not represent the compositions of the carbonatitic melts that led to their formation.

As shown in Figure 1A, high-Mg carbonatitic HDFs overlap compositionally with carbonatitic melts formed by partial melting of peridotite in HP–HT experiments, demonstrating that both diamonds and carbonatite rocks can crystallize from comparable liquids. Both low-Mg and high-Mg carbonatitic HDFs show similarities, such as trace element enrichment, with carbonatite rocks and kimberlites (Fig. 1B). The high-Mg carbonatitic HDFs are related to a peridotitic paragenesis and have mostly been found in diamonds from Udachnaya on the Siberian craton, and Kankan on the West African craton. Low-Mg carbonatitic HDFs display a continuous compositional trend with silicic fluids and are associated with an eclogitic paragenesis based on mineral inclusions such as coesite, omphacite, and garnet (pyrope–almandine–grossular with 6–32 wt% CaO and <1 wt% Cr₂O₃) within the same diamonds. The high-Mg HDFs exhibit lower alkalis, Zr, Hf, Ti, and Y, and higher Nb, Ta, and Ba–Th–U/alkali, light rare earth element (LREE)/MREE, and LREE/HREE ratios compared to the low-Mg carbonatitic HDFs (Fig. 1B) (Weiss et al. 2009).

Formation Models and Isotopic Insights

Since the discovery of HDFs in diamond by Navon et al. (1988), ideas around the formation of these diamond-forming fluids have evolved significantly. Initial models tried to explain the saline–carbonatitic–silicic compositions by evolution from a single parental carbonatitic fluid. Precipitation of carbonate and apatite would drive the fluid into an immiscible field, separating the fluid into separate saline and silicic components (Weiss et al. 2009 and references therein). While experiments in the diopside–carbonate–chloride system confirmed the miscibility gap, they did not evolve from saline to carbonatitic compositions upon cooling, 2) similar REE incompatibility in carbonate and apatite, but large LREE/HREE variation in HDF, 3) evolution of fluid compositions into different directions in single diamonds (Weiss et al. 2009), and 4) the discovery of the distinction between low-Mg and high-Mg carbonatitic end-members, all argue against an immiscibility and fractionation model to explain all fluid compositions. One current view is that a hydrous saline parental fluid forms through partial melting of subducted basaltic crust and that the product fluid interacts either with hydrous carbonated eclogite to form low-Mg carbonatic to silicic compositions, or reacts with carbonated peridotite (possibly with magnesite metasomes) to form high-Mg carbonatitic fluids (Weiss et al. 2015).

Partial melts produced in experiments of carbonated eclogite and carbonated peridotite closely resemble the major-element chemistry of low-Mg carbonatic and high-Mg carbonatitic fluids, respectively (Hammouda and Keshav 2015). Thus, a model of partial melting of carbonated eclogite and peridotite to form carbonatic melts could explain many compositions observed in HDFs in diamonds (Fig. 1A). However, most partial melting experiments were carried out with much lower K contents than are observed in HDFs, which are enriched in K compared to carbonatic melts and carbonatitic rocks. Processes other than partial melting are needed to accumulate the higher K and trace element patterns with elevated Ba–U–Th–LREE and depleted Nb–Ta–alkalis (Fig. 1B), such as interaction with, or infiltration of, chloride–potassium-rich (saline) fluids or interaction with a previously metasomatized (now phlogopite-rich) lithosphere. Phlogopite is a mica mineral with high Rb/Sr ratios that evolves to exceptionally high ⁸⁷Sr/⁸⁶Sr ratios with time due to decay of ⁸⁷Rb to ⁸⁷Sr; this characteristic may explain why silicic and saline HDFs in diamonds have higher initial ⁸⁷Sr/⁸⁶Sr ratios than most carbonatitic rocks. Strontium isotope data are extremely limited (only 7 analyses to date), but the majority of existing Sr isotope measurements of high-Mg carbonatitic HDFs are comparable to the low ⁸⁷Sr/⁸⁶Sr initial ratios of magnesio-carbonate rocks (Fig. 2) which have Rb/Sr ratios below that of the bulk silicate Earth.
Experimental Constraints on the Conditions of Diamond Growth in the Lithosphere

Not all diamond growth is related to carbonatitic fluids. Diamond formation in the sub-continental lithospheric mantle has been suggested to occur in one of three ways: 1) pH changes during a reaction between CHO fluids and coesite + kyanite-bearing eclogite; 2) redox reactions between CHO fluids and wall rock (eclogite, peridotite, pyroxenite); 3) precipitation from cooling or ascending CHO fluids (Stachel et al. 2017 and references therein). Here, we focus on the mechanisms of diamond formation from carbonatitic melts, which involves reduction of carbonate or CO₂ and cooling of oxidized CHO fluids to low-degree partial melts. The stabilities of the various forms of carbon—either oxidized as solid carbonates, or carbonatitic melts, or as subsolidus CO₂ or CO₃²⁻ fluids; or reduced as for diamond and graphite—are determined by pressure, temperature and fO₂. In the case of a cratonic geotherm, diamond is stable deeper than ~135 km and at conditions more oxidized than +0.1 to +0.6 log units of fO₂ greater than the iron–wüstite redox buffer reaction (given as ‘∆IW’, which signifies the log of fO₂, in the sample relative to the log of fO₂ in the iron–wüstite buffer) and more reduced than the fO₂’s at which carbonate melts become stable [−1IW+2.9 to +4.1, or, equivalently, 1–2 orders of magnitude more reduced than the fayalite–magnetite–quartz (FMQ) redox buffer, or ‘∆FMQ’ to −1] (Stagno 2019). The stability of carbonate melts expands to lower fO₂ with the addition of a silicate component to those melts (Stagno et al. 2020 and reference therein). In the upper part of the mantle (~250 km), fO₂ is broadly determined by Fe²⁺/Fe³⁺ equilibria in silicate minerals (Fig. 3). However, in harzburgitic environments where fO₂ may be buffered by fluid, diamond precipitation likely does not occur via redox reactions but instead via a reaction between coexisting CO₂ and CH₄ (→ 2C + 2H₂O) during cooling of CHO fluids (decreasing the carbon solubility) (Stachel et al. 2017).

Experimental growth of diamond from alkali-carbonate melt is fast. The first HP–HT experiments to be performed on hydrous carbonate compositions showed that CHO fluids are formed and that diamond can both nucleate and grow on seeds in such systems at 5.7 GPa and 1,150–1,420 °C, with alkalis (Na, K) acting as catalysts (Pal’yanov et al. 1999). Further HP–HT carbonate experiments have included silicate components and confirmed that diamond can grow in several different morphologies resembling natural forms—fibrous, coated, polycrystalline, and monocrystalline. The HP–HT experiments performed at 7.7 GPa and 1,500–1,800 °C in a graphite-free system with Ca,Mg-carbonate + silica provided direct evidence for the crystallization of diamond via reduction of carbon in carbonatitic melts (Arima et al. 2002).

Sub-Lithospheric Diamond Formation from Carbonatitic Melts

Like some lithospheric mantle diamonds, deeper sub-lithospheric diamonds can contain nano- and micro-inclusions, macro-inclusions, and voidites (faceted void-like defects containing a solid phase). Some nano- and micro-inclusions in superdeep diamonds (300–800 km depth) were found to be rich in solid molecular nitrogen without evidence for water and carbonate (Navon et al. 2017). Not all superdeep diamonds crystalized from the same fluids or under the same redox conditions, based on observed solidified inclusions of reduced Fe–Ni–C–S liquids in CLIPPIR (which stands for ‘Cullinan-like, large, inclusion poor, pure, irregular, resorbed’) diamonds and carbonate (identified by FTIR) in cloudy He-bearing transition-zone diamonds. Though major element compositions of such carbonate-bearing micro-inclusion-rich parts of diamonds are yet to be determined, trace element abundances and oxygen isotopes (δ¹⁸O) of majoritic garnet and Ca,Ti-perovskite mineral inclusions in superdeep diamonds are consistent with crystallization from a low-degree alkali-rich carbonatitic melt derived from subducted and altered oceanic crust in the deeper part of the upper mantle (Thomson et al. 2016; Regier et al. 2020). Superdeep diamonds with carbonate mineral inclusions confirm the stability of carbonate to depths of the transition zone and perhaps lower mantle.
Experimental data on the phase state of simple and multi-component carbonate systems let us assess the stability of carbonatitic melts at mantle conditions. The HP–HT experiments simulating diamond growth at sub-lithospheric pressures (10–20 GPa) show that both metallic (Fe,Ni) melts and carbonate-melts yield very fast growth (>1 μm/min) of diamonds that trap melt inclusions (Tomlinson et al. 2011). It has been suggested that f₀₂ likely decreases with increasing depth in the Earth’s upper mantle (Stagno 1999), so that environments more reduced than the lithosphere and upper asthenosphere are expected in the transition zone and lower mantle. The CLIPPIR diamonds are believed to come from such great depth and may derive from metallic liquids. In contrast, oxidized conditions in subducting slabs could provide a very high-pressure environment where crustal-derived carbonates (CaCO₃ and MgCO₃) might be stable and melt congruently down to depths of the Earth’s lower mantle (Litaso et al. 2020).

The HP–HT multi-anvil experiments on mid-ocean-ridge basalt (MORB) eclogites with added CaCO₃ indicate that aragonite, magnesite, and alkali-rich carbonates are stable at shallower depths (below 1,300 °C, or at ~9–13 GPa), whereas calcite–magnesite and alkali–calcite carbonate solid solutions are formed at deeper depths (Kiseeva et al. 2013). Upon thermal relaxation of a subducting slab, partial melting can occur in carbonated, fertile mantle at near-adiabatic temperatures (Thomson et al. 2016). The formed carbonatitic melts are unstable when percolating into the more reduced surrounding mantle, resulting in diamond formation through ‘redox-freezing’ (Rohrbach and Schmidt 2011). Both HP–HT experiments and natural inclusions in superdeep diamonds show evidence for the coexistence of diamond and carbonates or carbonatitic melts (Kiseeva et al. 2013) at oxygen fugacities of ΔIW+0.5 to +2.5 (Stagno 2019) at relatively shallow mantle pressures, declining to ΔIW+1.2 at 14 GPa and 23 GPa, where carbonate may be reduced to form diamond (Thomson et al. 2016). Inspired by evidence that cooling of a CHO fluid might result in diamond precipitation in the lithosphere, new HP–HT experiments were carried out to test whether this mechanism also operates at sub-lithospheric depths. Cooling of silicate-rich and oxide-rich carbonatitic melts at 24–26 GPa (Si–Mg–Fe–Ca–Na–C–O₂ system) (Spivak and Litvin 2019) leads to fractional crystallization of diamond followed by a sequence of assemblages of ferropericlase ± bridgmanite ± other phases (Fig. 4), some of which have been observed in natural superdeep diamonds. However, as not all of these assemblages have been observed in natural samples (yet), and the ambient mantle has a higher temperature than the subducting slabs that serve as the sources of the oxidized carbonatitic and CO₂ fluids, it remains to be determined if cooling and fractional crystallization leads to sub-lithospheric diamond formation in nature as it does in the laboratory.

**CARBONATITIC METASOMATISM**

**Carbonatitic Mantle Metasomatism**

The high mobility of carbonatitic melts, which have low viscosity and which wet silicate grain surfaces, implies that they would make effective metasomatic agents (Green and Wallace 1988). Experiments that examine carbonatitic melts interacting with lherzolite and harzburgite at pressures corresponding to shallow mantle depths (<90 km) produce wehrlitic assemblages (olivine + clinopyroxene). Reactions taking place have the following form:

1. orthopyroxene (enstatite) + carbonate/Ca–Mg carbonatitic melt → olivine (forsterite) + clinopyroxene (jadeite/diopside) + CO₂ (fluid) (+ Ca-carbonatitic melt)
2. orthopyroxene (enstatite) + spinel + clinopyroxene + Na-carbonatitic melt → amphibole (pargasite) + olivine (forsterite) + CO₂ (Yaxley et al. 1991)

The reaction of carbonatitic melt with orthopyroxene in depleted harzburgite or lherzolite likely produces a more Ca-rich carbonatitic melt plus wehrlite at decreasing pressures, whereas reaction of carbonatitic melt with fertile lherzolite results in a more Na-rich carbonatitic melt. Equilibrated wehlrites that form by carbonatitic metasomatism in the mantle are characterized by well-crystallized olivine and clinopyroxene minerals, whereas the same reactions in unequilibrated mantle xenoliths instead contain fine-grained olivine and clinopyroxene, sometimes on rims of remnant orthopyroxene, with possible interstitial anhedralapatite on grain boundaries (Yaxley et al. 1991).

The interaction of a carbonatitic melt with the surrounding mantle results in a local fractionation of trace elements, enrichment in large ion lithophile elements (LILs), LREEs, Ca, and P compared to high field-strength elements (HFSEs) such as Ti in the lithospheric rocks through which carbonatite moves, with the most pronounced enrichments in depleted harzburgite and dunite. Consequently, metasomatized xenoliths may display high Ca/Al, high Zr/Hf (above primitive mantle; >36), high La/Yb ratios, and Ti/Eu ratios below primitive mantle. Carbonatitic metasomatism can be distinguished from silicate metasomatism by the decoupling of LILs and LREEs (which are enriched) from Ti (which is not) and by the lack of Fe–Al–Na enrichment in the rims of garnets and other minerals.

The conversion of orthopyroxene to olivine and clinopyroxene through the metasomatic process of carbonatitic melt–lithosphere interaction may not be important in the deeper lithosphere and asthenosphere, given the
rarity of wehrlitic xenoliths and wehrlitic garnets in diamonds (Aulbach et al. 2020). However, other, more cryptic, evidence indicates that carbonatitic metasomatism occurs at depths in the deep lithosphere and below the lithosphere/asthenosphere boundary. Sinusoidal REE patterns in Cr-rich garnets can be created by carbonatitic metasomatism and are observed in harzburgitic and lherzolitic garnet inclusions in diamonds, providing support for carbonatitic metasomatism in the diamond stability field. Metasomatism in (sub-)lithospheric settings likely occurs in an open system via melt-channelized flow and a dissolution–precipitation process and, although we are unsure of the length-scales in natural deep systems, fast diamond growth appears to result from carbon-rich fluids transported along grain boundaries to diamond seeds. Included in these processes would be rapid growth of fibrous diamond and trapping of fluids that are out of chemical equilibrium with their host rocks.

**Viscosity and Density Properties of Carbonatitic Melts**

The first precise measurements of viscosity and density of carbonate melts at high $P$ (2–5.5 GPa) and high $T$ ($530–1,500 \, ^\circ C$) were made using a falling sphere observed in situ with synchrotron X-rays (references in Jones et al. 2013). This reduced and extended the range of viscosity estimates from previous research (see Jones et al. 2013 and references therein) and established that viscosities of pure carbonate melts that have a range of chemical compositions lie between $1.5 \times 10^{-2}$ to $5 \times 10^{-3} \, Pa\cdot s$. These laboratory carbonate melts are reasonable analogues for mantle-derived carbonatitic melts, confirming that the latter have the lowest viscosities of known terrestrial magmas (Jones et al. 2013). Basaltic melts, for example, have viscosities $>2.5 \, Pa\cdot s$ at pressures of $2–6 \, GPa$. The extreme physical properties and inferred mobility of carbonatitic melts support their likely role in the flux of mantle carbon through the processes of melting and mantle metasomatism.

In natural systems, both in the crust and in the mantle, carbonatitic melts have been considered as ideal metasomatic agents, because their intrinsically low viscosities permit them to migrate along grain boundaries (Green and Wallace 1988). However, in natural rock systems, ‘impure’ carbonate melts (i.e., those containing silicate) may be less mobile than the predictions based on viscosities measured for pure carbonate melts, due to higher polymerization of the silicate-bearing melt. For example, experimental measurements of viscosities of carbonate–silicate and melilitic melts intermediate in composition between carbonatite and silicate liquids at pressures of 2.4–5.3 GPa and temperatures of 1,565–2,155 °C yield viscosities between 0.02 Pa·s and 0.08 Pa·s (Stagno et al. 2020). These values are low compared to common silicate melts, but one to two orders of magnitude higher than those of pure carbonate melts. Carbonatite melt may also be less mobile through silicate rocks where immiscibility separates that melt into co-existing silicate-rich and carbonate-rich melt phases; this is because silicate melt preferentially wets grain boundaries, preventing the carbonatite melt from migrating (Minarik 1998).

Prior to experimental measurements at much higher pressures, it was conjectured that carbonate melts would retain their low viscosity melt properties deep into the mantle. However, recent experiments above 40 GPa using carbonate glasses as analogues to carbonatitic melts reveal a surprising increase in viscosity by at least 3 orders of magnitude ($>20 \, Pa\cdot s$) (Fig. 5); these viscosities are $>1,000\times$ higher than those of iron silicate liquids that could contain and move carbon in the lower mantle. Hence, the extremely low viscosity that characterizes carbonate melts in the crust and lithosphere may not extend down into the transition zone, and almost certainly not into the lower mantle. Instead, carbonate melts below the transition zone are likely to be much less mobile, with implications for the long-term storage and mobility of carbon in the deep Earth.

**CARBONATITES AS TRACERS OF DEEP MANTLE PROCESSES**

Both laboratory HP–HT experiments and observations of natural diamonds and mantle xenoliths confirm the stability of carbonate minerals and carbonatitic melts over a large depth range in the upper mantle. Constraining the relative contributions of carbonatites and diamond to the deep carbon cycle through time is not an easy task. Over the past ten years, major advances in our understanding of carbon on Earth have been made, especially through the DeepCarbon Observatory consortium. The uncertainty in the abundance of carbon on Earth has now been reduced, but still varies over a range of ~50–180 ppm for average upper mantle (Marty et al. 2016). The total amount of carbon brought to the Earth’s surface in the past ~3 Gy is estimated at 7.35 billion carats ($0.00147 \, Mt \, C$) (Kimberley diamond : statistics) and, thus, diamond is not a significant carrier of carbon from the mantle to the surface compared to, for example, mid-ocean ridges that can have a degassing rate of 13–30 Mt C y$^{-1}$ (Fig. 5). It will take a multidisciplinary effort to constrain the diffuse degassing of CO$2$ from the continental lithosphere by the passage of magmas such as carbonatites, kimberlites, and CO$2$-bearing silicate melts by combining effusive gas measurements; geological reconstructions of the sizes of past riffs, basins, and fault systems; and more studies on wehrlitic xenoliths. Estimates from the proportion of rock affected by wehrlitization suggest this process contributes between 1.4 ± 0.1 Mt CO$2$ y$^{-1}$ and 70 ± 58 Mt CO$2$ y$^{-1}$ of cryptic CO$2$ degassing per continental rift area (Aulbach et al. 2020).

Large uncertainties in the nature of deep carbon reservoirs, their temporal distributions, and the fluxes of carbon between them present challenges for future studies of Earth’s carbon cycle. Nevertheless, carbonatite volcanism demonstrates connectivity and mobility between the mantle and the surface, coordinated on the scale of plate tectonics. We recognize the chemical fingerprint of ephemeral carbonatites in samples of lithosphere retrieved.

**FIGURE 5** Schematic diagram showing the contributions of carbonate or carbonatite and diamond to the mobility of carbon between the mantle and the surface, representative of the last 200 My. Open diamond symbols = diamonds; MOR = mid-ocean ridge. FOR DATA SOURCES SEE HTTP://ELEMENTSMAGAZINE.ORG/SUPPLEMENTS/.
as xenoliths, and they are implicated in delivering carbon to sites of crystallization of some diamonds in which HDs are trapped. It is currently poorly known how the fraction of C mobility and degassing from carbonatites compares to those from other CO\textsubscript{2}-rich melts, or how different the fractionation of carbonates compared to erupting carbonatites, or the relative amounts of carbon stored in the sub-continentlithospheric mantle versus the sub-lithospheric mantle (Fig. 5). Nevertheless, carbonatites in the geological record attest to the importance for the carbon cycle to be tracked, because that is an indicator of this important class of CO\textsubscript{2}-rich magmatism. There are 609 known occurrences of carbonatite (Humphreys-Williams and Zahirovic 2021 this issue). These carbonatites have been emplaced since the Archean and appear more frequent since ~1.2 Ga, especially in the Mesozoic (as is the case for kimberlites) (Tappe et al. 2018; Humphreys-Williams and Zahirovic 2021 this issue). This temporal trend may be influenced by poor preservation of small-volume crustal carbonatite deposits. However, the increasing frequency of carbonatites through time could be linked to the following three factors: 1) the onset of subduction ~3 Ga, coinciding with the formation of eclogitic diamonds; 2) the development of possibly more oxidizing conditions in the upper mantle in the first billion years of Earth’s history (Shirey et al. 2013 and references therein); 3) more abundant carbonates in subducting slabs since the Mesozoic. The more abundant presence of carbonates is caused by the emergence of abundant skeletal life as oceanic calcifiers and the formation of platform carbonates in the Mesozoic (Galvez and PUBellier 2019).

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**REFERENCES**


Formation of Rare Earth Deposits in Carbonatites

Michael Anenburg, Sam Broom-Fendley, and Wei Chen

Carbonatites and related rocks are the premier source for light rare earth element (LREE) deposits. Here, we outline an ore formation model for LREE-mineralised carbonatites, reconciling field and petrological observations with recent experimental and isotopic advances. The LREEs can strongly partition to carbonatite melts, which are either directly mantle-derived or immiscible from silicate melts. As carbonatite melts evolve, alkalis and LREEs concentrate in the residual melt due to their incompatibility in early crystallising minerals. In most carbonatites, additional fractionation of calcite or ferroan dolomite leads to evolution of the residual liquid into a mobile alkaline "brine-melt" from which primary alkali REE carbonates can form. These primary carbonates are rarely preserved owing to dissolution by later fluids, and are replaced in-situ by monazite and alkali-free REE-(fluor)carbonates.

KEYWORDS: brine-melt; burbankite; critical metals; rare earths; alkaline complexes

INTRODUCTION

Carbonatites are one of the most prospective rock types on Earth. Almost 10% of carbonatite occurrences host an active or former mine and a further 10% are defined as a mineral resource (Simandl and Paradis 2018). The principal commodities mined from carbonatites include phosphate, niobium, fluoride, rare earth elements (REEs), vermiculite, iron, and zirconium, as well as their (often underappreciated) use as a limestone source for aggregate, cement, and agricultural purposes. Despite this abundance of commodities, carbonatites are probably best known for REE mineralisation. The REEs continue to be topical owing to their requirement in the production of high-strength permanent magnets for electric vehicles and wind turbines, among a myriad of other high-tech uses. Carbonatites host most REE mines and are the focus of many exploration projects due to exceptional ore enrichment, with the REEs commonly contained in minerals with well-established extraction methods. Nearly all carbonatites are dominated by the four lightest REEs (the light rare earth elements, LREEs: La, Ce, Pr, and Nd), of which Nd and Pr are particularly marketable. The remaining REEs (the heavy rare earth elements, HREEs: Sm to Lu) are more valuable, but typically comprise less than 1% of the REE content in these rocks.

In the last ten years, continued interest in REE deposits has led to an increase in published descriptions of carbonatite-hosted REE mineralisation. In this paper, we reconcile some of the field and petrological observations with recent experimental and isotopic advances to outline a conceptual model for the formation of carbonatite-associated rare earth deposits (Fig. 1).

MANTLE FORMATION AND INITIAL REE PARTITIONING

Most carbonatites trace their origins to mantle melting (Fig. 1A). Radiogenic isotopic compositions of carbonatite-associated REE deposits suggest an origin from enriched mantle domains (enriched mantle type 1, EM1; enriched mantle type 2, EM2; and HIMU type, i.e., high “μ”, where μ = 238U/204Pb). Carbonate melts enriched in REEs originate from mantle sources that were previously refertilised by different components. For instance, it has been suggested that North American carbonatites, such as Bear Lodge (Wyoming, USA), derive from an asthenospheric mantle plume that was composed of depleted mantle refertilised by a subduction-derived EM1 component (Moore et al. 2015). In another example, the Manning-Dechang REE deposits in China are derived from previously metasomatised subcontinental lithospheric mantle: prior to carbonatite formation, this mantle domain was enriched by REE-rich and CO2-rich fluids that were themselves derived from subducted marine sediments, leading to a final radiogenic isotope signature intermediate between the EM1 and EM2 end members (Hou et al. 2015). Continental rift zones, such as the East African Rift, are another tectonic setting which is conducive to the formation of REE deposits associated with carbonatites and that derive from mantle having radiogenic isotope compositions intermediate between the EM1 and HIMU end members (Bell and Simonetti 2010).

This apparent variety in mantle sources and tectonic settings indicates that there is no single source for carbonatites and that these REE-rich melts can form in any CO2-enriched mantle, regardless of how the enrichment occurred. Fertilisation of that mantle with other chemical constituents (e.g., Na, K, P, S, and F) does not have to immediately precede the partial melting that generates carbonatite magmas. In fact, these two events can be separated by hundreds of millions of years (Anenburg et al. 2020a). Carbonatite melts are typically emplaced during continental rifting (Bell and Simonetti 2010), although a number of complexes are associated with syn- to post-collisional tectonic environments (Hou et al. 2015).
Carbonatite melts are most commonly thought to form either by direct mantle melting or to evolve from carbonate-bearing alkaline silicate melts by immiscibility or fractionation (Fig. 1A). All of these processes potentially lead to REE-enrichment. Carbonatites formed by very-low degrees of melting of carbonated mantle will concentrate LREEs relative to silicous higher-degree melts generated from the same source (Foley et al. 2009). Immiscible separation of carbonate and silicate melts from carbonatite silicates can also lead to partitioning of LREEs to carbonate melts. Carbonatite–silicate partition coefficients for the LREEs, Ba, Sr, F, P, and Cl are highest when the immiscible silicate melt is highly polymerised, Ca-poor, and hydrous (Nabyl et al. 2020). Carbonatite–silicate partition coefficients are low for the LREEs in deep mantle–derived alkali-silicate melts, substantial REE partitioning to conjugate carbonatites being only achieved after prolonged fractionation, leading to LREE enrichment of carbonatites, thus, requires immiscibility to occur very late in the evolution of an alkaline magma batch when the conjugate silicate melt is phonolitic (Nabyl et al. 2020). The common spatial association of the plutonic chemical equivalent of phonolite (nepheline syenite) with REE-mineralised carbonatites (e.g., Moore et al. 2015; Doroshkevich et al. 2016) circumstantially supports their petrogenetic link. The two immiscible melts are unlikely to rise together due to their differing physical properties; thus, the close association between carbonatite and nepheline syenite indicates that their emplacement was immediately preceded by immiscibility, temporally and spatially. Nevertheless, the immiscibility origin for some carbonatite–silicate rock associations is questionable (Gittins and Harmer, 2003), while others are not accompanied by cogenetic silicate rocks (e.g., Kangankunde in Malawi; Nkombwa in Zambia). Therefore, liquid immiscibility may not always be a prerequisite for carbonatite melt formation and, by extension, economic mineralisation.

Carbonatites are fully endowed with their REE budget during the initial short-lived magmatic intrusion event and do not accumulate additional REEs over time via...
metamorphic or hydrothermal processes, although these may modify mineral assemblages or chemical signatures (overprinting) and result in local REE redistribution. A particularly extreme example is the Bayan Obo deposit (China) where Nd isotope compositions of monazite crystals reflect that Mesoproterozoic carbonatite magmatism, followed by protracted 1 Gyr history of later fluids recording recrystallisation and locally limited remobilisation of REEs (Song et al. 2018). Owing to the fact that carbonatites can seemingly be derived via more than one route, yet all routes can lead to a REE deposit, we consider processes that modify carbonatite melts after their generation to be the dominant controls for generating most carbonatite-associated REE deposits. That is, enrichment of REEs in the carbonatite source is needed, particularly for the largest economic deposits, but must be accompanied by one or more key processes during carbonatite evolution.

**IGNEOUS FRACTIONATION (>600 °C)**

Crystallisation of REE-poor minerals from a carbonatite melt is crucial for REE enrichment in the residual melt. Field relationships and experimental evidence on carbonate rocks indicate that a carbonatite melt typically first crystallises calcite, followed by dolomite, then Fe-rich dolomite (sometimes referred to as ankerite in the carbonatite literature, even if not always strictly ankerite according to its composition), and, locally, siderite (Fig. 1B). This crystallisation sequence is manifested in the concentric rings of many carbonatite complexes, where an Fe-rich and REE-rich dolomite carbonatite occupy a central position which is enveloped by REE-barren Fe-poor dolomite or calcite carbonatite (e.g. Chilwa Island in Malawi; Karasug in Russia) (Prokopiev et al. 2016; Dowman et al. 2017). The observed sequence of calcite followed by dolomite followed by Fe-rich dolomite is consistent with carbonatite fractionation experiments (Anenburg et al. 2020b) and with the predicted stability ranges of Ca-, Mg-, and Fe-carbonates derived from thermodynamic data.

It is important to be aware of the compositions of different carbonatite rocks (calcite carbonatite, dolomite carbonatite, siderite carbonatite) are not representative of a carbonatite melt. Rather, these are crystal cumulates of an alkali- and volatile-bearing carbonatite melt. The most compelling evidence for the high alkali content of carbonatite melts is the presence of fenites—metasomatised rocks predominantly composed of Na-K-silicates (Elliott et al. 2018)—which occur around almost all carbonatite complexes. In addition, Na-rich carbonatite melt inclusions are common in minerals hosted in Na-poor carbonatite rocks (e.g., Prokopiev et al. 2016), with experimental evidence further supporting alkali-rich carbonatite melts in equilibrium with alkali-poor cumulates (Weidendorfer et al. 2017; Anenburg et al. 2020b).

The REEs are incompatible (i.e., they partition into the liquid rather than solid) during high-temperature igneous crystallisation of carbonatite melts. The principal early crystallising minerals are magnetite, olivine, and clinopyroxene, all of which exclude REEs, and particularly LREEs, from their crystal structures. Once the melts are calcite-saturated and voluminous carbonate cumulates form, the REEs are strongly enriched in the liquid owing to their incompleteness in calcite (Chebotarev et al. 2019). Additionally, fluorapatite is common throughout the entire crystallisation sequence of carbonate liquids. Although REEs can be compatible in (i.e., partition into) fluorapatite, with REE uptake controlled by coupled substitutions with either Na⁺ or Si⁴⁺, formation of REE-fluorapatite is unlikely in high-temperature carbonatite systems. Experimental evidence indicates that high-temperature fluorapatite will not concentrate REEs regardless of Na contents in the melt (Anenburg et al. 2020b). Furthermore, silica activities in high-temperature carbonatite melts are not typically high enough to allow REEs + Si substitution into fluorapatite. Only in rare circumstances, such as carbonatite intrusion into silica-saturated rocks (e.g., granites) and exceptional silica assimilation efficiency, can substantial incorporation of REEs into early high-temperature fluorapatite occur. In these unusual cases, fluorapatite can be the REE ore in its own right (e.g., the Nolans Bore fluorapatite vein deposit in the Northern Territory, Australia) (Anenburg et al. 2020a).

**BRINE-MELT STAGE (600–400 °C)**

As carbonate melts evolve to more Mg- and Fe-rich compositions, several components are retained in the melt, such as Na⁺, K⁺, H₂O, sulfate, chloride, and fluoride, and these act as fluxes (Prokopiev et al. 2016; Weidendorfer et al. 2017). These fluxes strongly depress the solubility and melt transitions to a Na-K-carbonate ± chloride ± sulfate brine with no clear boundary or distinct exsolution of fluids, as evident by a lack of immiscible carbonate melts and REE-rich alkali brines in studies of fluid and melt inclusions (Xie et al. 2015; Walter et al. 2021). Limited fluid and melt inclusion homogenisation data point to a transition that a calcite-dominant melt can reach up to several metres in width (Fig. 2A). However, REEs do not significantly partition into this aqueous phase and remain dissolved in the brine-melt (Song et al. 2016).

At this stage, REEs are sufficiently concentrated in the residual brine-melt to form REE-minerals (top of Fig. 1B), such as monazite and alkali REE carbonates from the Burbankite and carbocernaite groups (Zaitsev et al. 2002; Anenburg et al. 2020b). These alkali REE carbonate minerals are not in the lexicon of the average mineralogist for good reason—they are extremely ephemeral. However, in a few localities, they are preserved as euhedral or subhedral phases, associated with carbonate, or as inclusions in dolomite, fluorapatite, and perovskite (Zaitsev et al. 2002; Moore et al. 2015). Similar carbon and oxygen isotope values for burbankite and its host carbonate minerals demonstrate that they are derived from the same source (Zaitsev et al. 2002). Burbankite also occurs in REE-rich dolomite-carbonatite pegmatites, forming large euhedral hexagonal crystals exhibiting spectacular unidirectional crystallisation. These pegmatites locally form some of the highest REE concentrations found anywhere on the planet and can reach up to several metres in width (Fig. 2A).

In cases where a carbonatite melt is silica-rich, perhaps through melt–wall rock interaction (Xie et al. 2015; Giele et al. 2019), crystallisation of alkali-silicates such as phlogopite or aegirine, can suppress the formation of alkali REE carbonate minerals, leading to high-temperature pseudomagmatic bastnäsite or monazite instead (Anenburg et al. 2020b). Fluorapatite forming at the brine-melt stage can incorporate substantial LREE contents owing to the greater availability of charge-balancing Na⁺ from the alkaline brine-melt. Furthermore, the low temperature leads to an increase in silica activity, permitting substitution of the Si + REE “britholite” component into fluorapatite (Chakhmouradian et al. 2017; Anenburg et al. 2020b). Often, this brine-melt fluorapatite has a texture suggesting that it forms by hydrothermal replacement of earlier
REE-poor fluorapatite (Chakhmouradian et al. 2017), but it can also form as thin veins and stringers (Broom-Fendley et al. 2017).

In contrast to LREEs, HREEs are still largely incompatible during the brine-melt stage, and remain dissolved in the residual brine-melt (Anenburg et al. 2020b). The highly evolved brine-melt has extremely low viscosity and low wetting angles and can infiltrate wall rock. This process removes HREEs from the carbonatite body, further contributing to the extreme fractionation of LREEs from HREEs typical of carbonatites. These alkali fluids are highly corrosive and, once in contact with the surrounding silicate rocks, will strongly alter them into fenite (Elliott et al. 2018). Fenite alteration zones can extend up to several kilometres from their host carbonatites, and occasionally contain sub-economic amounts of REE-bearing minerals, such as xenotime, Y-enriched fluorapatite, and REE-(fluor) carbonates with elevated HREE/LREE ratios (Andersen et al. 2017; Broom-Fendley et al. 2017; Dowman et al. 2017).

HYDROTHERMAL FLUID

During late-stage evolution of carbonatite systems, the brine-melt evolves into something resembling a more conventional hydrothermal fluid, with salinity diluted by an increasing H2O content. Fluid inclusions and stable isotope data point to a diverse range of evolutionary paths, depending on carbonatite emplacement depth, as well as the effects of cooling, mixing, and fluid–rock reaction (Walter et al. 2021). Carbonatite-derived fluids show a temperature of up to 400 °C, whereas externally derived fluids are typically cooler (up to 250 °C). In particular, the aqueous and carbonic components may exsolve, or boil, from the carbonatite melt, possibly many times, leading to a complex mixture of low-density and high-density inclusions (“vapour” and “liquid”, respectively). Boiling can lead to fracturing of the surrounding country rock, facilitating further dilution of the carbonatite-derived fluid by meteoric water (Walter et al. 2021).

Whether wholly derived from the carbonatite brine-melt or mixed with a meteoric component, hydrothermal fluids can back-react with alkali–REE-carbonates, such as burbankite and carbocernaite. In this process, alkalis are removed and the original minerals are replaced by an assemblage of less-soluble REE-(fluor) carbonates (ancylite, synchysite, parsite, bastnäsite) or monazite, accompanied by strontianite, baryte, and, locally, low-Sr calcite and quartz (Figs. 2B, 3A–B) (Andersen et al. 2017; Giebel et al. 2017). This replacement reaction results in a significant reduction in volume, propagating further hydrothermal input and dissolution of alkali–REE-carbonates. Preservation of alkali–REE-carbonates is scarce and only observed in a handful of localities. In most cases, evidence for the formation of burbankite is indicated only by the preservation of hexagonal pseudomorphs, now containing a variety of Ca, REE, Ba, and Sr minerals (Fig. 2B–C). If burbankite, carbocernaite, or any other alkali–REE-carbonates did not form euhedral phases during the brine-melt stage, then evidence for their former presence is often erased, with only scarce mineral inclusions offering any hint to the former presence of these minerals (Fig. 3C). The local abundance of quartz in hydrothermal assemblages attests...
to the substantial involvement of externally derived fluids, as silica solubility is low in earlier carbonatite magmas and brine-melts.

It is the REE-(fluor)carbonate ± monazite mineral assemblage that is most typical in mineralised carbonatites, commonly occurring as stringers or vug-like accumulations (Fig. 3). The vug-like mineralisation habit, in particular, has led many authors to interpret such REE mineralisation as the result of direct precipitation from a hydrothermal fluid. Although it is possible for REE-carbonates to form without an alkali precursor, carbonatite liquids are invariably alkaline and crystallisation of alkali-free carbonates as primary precipitates is unlikely to be the principal mineralisation process in nature. Therefore, we propose that such mineralisation results from the in situ replacement of the primary precipitates is unlikely to be the principal mineralisation process in nature. Therefore, we propose that such mineralisation results from the in situ replacement of the alkali–REE-carbonates (such as burlankite and carbocerntaite), which were formed during the brine-melt stage, by a less-briny and more mixed hydrothermal fluid that existed during the post-magmatic stages of the carbonatite system, diluted by external fluids (Fig. 1C). In other words, low-temperature fluids do not directly precipitate REE minerals but re-crystallise existing, highly soluble, alkali–REE-carbonates into less soluble, often calcic, phases.

Although we propose here that REE enrichment reaches its apex during the brine-melt stage, it is evident that REEs can be mobilised on the local scale by low-temperature hydrothermal fluids, resulting in further redistribution of the REEs (Broom-Fendley et al. 2016). Rare earth element minerals can be related to the dissolution of other primary REE-bearing minerals, such as fluorapatite or calcite (Chakhmouradian et al. 2017; Giebel et al. 2017; Cangelois et al. 2020; Ying et al. 2020). The REEs contained within these minerals are then reprecipitated as REE minerals in close proximity to the original host (Fig. 4). Depending on the composition of the low-temperature fluid, protracted fluid fluxing can lead to fractionation of the light from the heavy REEs owing to the preferential stability of LREE–chloride complexes in the fluid (Migdisov et al. 2016). Dissolution–reprecipitation of REE-bearing minerals is likely to occur on a small scale in all cases of carbonatite-hosted REE mineralisation, especially where breakdown of magmatic calcite is evident. However, as carbonates only contain trace amounts of REEs, even dissolution of large amounts of calcite can only account for a small volume of REE mineralisation (Ying et al. 2020).

The C and O isotope composition of primary igneous carbonatite is often considered to fall within ranges of δ18O from 6‰ to 10‰ (VSMOW, or Vienna Standard Mean Ocean Water) and δ13C from −8‰ to −4‰ (VPDB, or Vienna Pee Dee Belemnite). Similar values can be obtained for calcite and dolomite associated with REE mineralisation, indicating crystallisation from the carbonatite melt or brine-melt occurs at a sufficiently high temperature that there is minimal isotopic fractionation between these minerals and their parental melt or brine-melt (Zaitsev et al. 2002). Interaction of these minerals with hydrothermal fluids causes complex shifts in C and O isotope compositions, because the carbonates are subject to recrystallisation by circulating low-temperature fluids that post-date the brine-melt stage (Moore et al. 2015; Doroshkevich et al. 2016). This results in a wide spread of isotopic compositions, especially to higher δ18O, attributable to interaction with cooling deuteric or basinal fluids. However, it is rarely clear whether these higher δ18O values are attributable to REE mineralisation or if they are a result of subsequent recrystallisation: reported C and O isotope data are often overly reliant on bulk analyses that blur together compositions of multiple minerals of different origin. Dissolution of primary carbonates, and the formation of late, Sr-poor calcite is common in carbonatites on a range of scales (e.g., Fig. 4B). Careful analyses of carbonates using in situ methods on properly mapped minerals (e.g., using cathodoluminescence or high-contrast backscattered electron imaging) (Anenburg et al. 2020a) are crucial to untangle primary magmatic signatures from later recrystallisation.

**WEATHERING**

As with hydrothermal dissolution–reprecipitation, weathering can also result in the breakdown of primary REE phases and the transport of REEs into newly formed REE phases. Indeed, on a local scale, it can be difficult to differentiate the two processes. Protracted weathering increases REE grade (i.e., whole-rock concentration) through dissolution of carbonate and so chemically removing the bulk of the rock (e.g., Andersen et al. 2017). In some cases, this can make the difference between whether mining is economical or not, such as the case of the Mount Weld (Western Australia), Tomtor (Russia), and Zandkopsdrift (South Africa) carbonatite-derived laterites. While advantageous, protracted weathering can also result in the formation of complex Al–REE-phosphates (e.g., florencite), which are currently not suitable for economic extraction.

**UNKNOWNS AND FUTURE STUDY**

While we have tried to summarise here the key steps we consider important to forming carbonatite-hosted REE deposits, the model (Fig. 1) is by no means complete. The variables that influence carbonatite evolution predictions are too sensitive and too numerous to find a model that fits perfectly in every case. For every example we can think of where the above mineralisation mechanism fits, it is possible to think of one or two more where it does not.

As an example, crystallisation of alkali–REE-carbonates can also occur in association with calcite carbonatite (e.g., Bear Lodge) (Moore et al. 2015), diverging from the process of late-stage REE concentration in dolomite and ankerite carbonatites we outlined above. Additionally, the calcite–dolomite–ankerite sequence may only be apparent in small carbonatites where the entire crystallisation sequence is visible at the surface.

Owing to the poor preservation of minerals which form during the brine-melt stage, the temperature and composition of such mineralising fluids is challenging to quantify and still represents a significant knowledge gap in our understanding of REE mineralisation. Detailed study of
primary fluid inclusions in LREE-rich apatite linked to the brine-melt stage may be a fruitful avenue to further clarify the fluid temperature and composition.

Consider this paper to be a call to focus greater attention to the brine-melt stage in carbonatites, and on understanding the formation of the alkali–REE-carbonates (as well as rare primary monazite and REE-fluorcarbonates), rather than the post-magmatic processes which we consider as merely recrystallisation of alkali–REE-carbonates. Hydrothermal fluids do not transport the LREEs in carbonatites on a significant scale but simply muddy the water with respect to our understanding of how REE-deposits in carbonatite form. The conditions at which a carbonatite melt transitions to a brine-melt and then a hydrothermal fluid, however, remain poorly constrained, as are the finer details regarding which phases are crystallised to make a residual REE-rich ferroan dolomite carbonatite melt. Any future work which promotes the fundamental understanding of REE deposit formation in carbonatites and its regional geological context will likely be useful for exploration and exploitation of these valuable resources, ensuring that metal supply for zero-emission technology is met.

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REFERENCES


The distinctive mineralogy of carbonatites

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The mineralogy of carbonatites reflects both the diversity of the sources of their parent magmas and their unusual chemistry. Carbonatites contain diverse suites of both primary magmatic minerals and later hydrothermal products. We present a summary of the variety of minerals found in carbonatites, and note the economic importance of some of them, particularly those that are major sources of “critical elements”, such as Nb and rare earth elements (REEs), which are essential for modern technological applications. Selected mineral groups are then discussed in detail: the REE carbonates, the alkali-rich ephemeral minerals that are rarely preserved but that may be important in the petrogenesis of carbonatites and their metasomatic haloes in adjacent rocks, and the Nb-rich oxides of the pyrochlore supergroup.

**KEYWORDS:** carbonate minerals; rare-earth carbonates; ephemeral minerals; pyrochlore; critical elements

**GENERAL INTRODUCTION**

Mitchell (2005) recommended defining “carbonatite” as an igneous rock containing 30% or more of primary igneous carbonate, expanding beyond the current lower limit of 50% accepted by the International Union of Geosciences in order to better capture the sheer diversity of such rocks. Such rocks may form from deep-sourced primary partial melts, from magmas that are residues of subsequent crystallization or immiscibility separation, or by precipitation from sub-solidus, carbohydrothermal residual fluids. The carbonate content of carbonatite may be primary (inherited from volatile-rich mantle) or secondary (obtained by assimilation much nearer the Earth’s surface). Modal ratios of carbonate:silicate vary widely in carbonatites and associated rocks.

The chemistries of carbonatites lead to distinctive properties and mineralologies. The counter-ion to carbonate in carbonate minerals found in carbonatites is dominantly Ca²⁺, although Mg²⁺ and Fe²⁺ can also be important, and the alkalis Na⁺ and K⁺ may play more important roles than are generally evident from the geological record, as indicated by ephemeral alkali carbonates. The relatively poorly polymerized nature and low solidus temperatures of carbonate magmas (Litasov et al. 2013) makes them highly mobile. While their trace element contents reflect those of their sources, the frequent association of carbonatites with highly differentiated peralkaline melts leads to enrichment in large-ion lithophile elements such as Ba and Sr and high field-strength elements such as Nb and the light REEs (LREEs = La to Sm), to the point that minerals containing these elements crystallize as primary magmatic phases. The unusual bulk chemistry and primary mineralogy also leads to a diverse suite of secondary phases that are distinctive among igneous rocks.

The REEs form a variety of magmatic and secondary REE-enriched minerals in carbonatites. These are usually carbonates, although cations from the smaller, heavy REEs (HREEs = Eu to Lu) are more compatible in phosphate phases such as members of the apatite group and xenotime, (Y,HREE)PO₄. These elements are in constantly increasing demand, particularly for applications such as high-strength magnets and luminescent phosphors.

We present here a general overview of the minerals and mineral parageneses that are found in carbonatites, including sections that focus on specific groups of minerals that are economically important but are otherwise unusual. We also discuss the elusive “ephemeral minerals” that are too reactive with water, air, or surrounding rocks to persist over geological time but that may, nevertheless, play a major role in the evolution of carbonate magmas and fluids. For reference, we provide a supplementary table of all species mentioned by name in this article, with formulae and classification data (see http://elementsmagazine.org/supplements).
More than 250 minerals occur in carbonatites, in distinctive and complex parageneses. The enrichment of carbonatites in otherwise rare elements (strong enrichments in Nb, Zr, Sr, Ba, light LREEs, with subordinate Y, HREEs, Th, U, Sc, and Ta) in combination with the abundance of carbonate, CaO, MgO, Na₂O, and P₂O₅ strongly influence the “mineralogical portrait” of carbonatites. Carbonates, silicates and, to a lesser degree, oxides are the most diverse chemical classes of carbonatite minerals. The main rock-forming phases are carbonates (calcite, dolomite, ankerite or siderite, benstonite, Na–Ca carbonates, and others) and Mg-rich silicates such as forsterite, diopside, (Na)–Ca–Mg amphiboles, phlogopite–biotite mica and paragenetically late clinopyroxene, and serpentines or vermiculite ± magnetite, fluorapatite–hydroxylapatite-series phosphates, and fluorite (Woolley 2019 and references therein). Distinctive silicate minerals in these rocks can include the Al-poor mica tetraferrophlogopite, Ti-enriched and/or Zr-enriched silicate oxide garnets of the anradite–schorlomite–kimzeyite–kerimasite system, and Ca-rich but Si-poor phases such as perovskite, melilite, and monticellite.

One of the most outstanding mineralogical features of carbonatites is the character of zirconium mineralization: unlike other geological formations in which Zr is mainly concentrated in zircon or (in appaitic rocks) in sodium zirconosilicates, oxides are the major Zr phases of carbonatites: baddeleyite, zirconolite/zirkelite-like minerals, and calzirite. Niobium and titanium minerals are also mainly represented by oxides in carbonatites. The major paragenetically early Nb minerals are Na–Ca pyrochlore-group members, Nb-enriched zirconolites, and perovskite-group oxides (typically Nb-bearing perovskite, less often luiehsite or latrappite), with other niobates playing a minor role [colombite-(Fe), fergusonite-(Ce), fersmite, etc.].

A very important feature of carbonatites is the concentration of REEs, Sr, and Ba, mainly in carbonate minerals. Carbonatites are “record-holders” among rock types in both modal abundance and diversity of REE carbonate minerals. In some deposits, baryte–celestine series sulfates are also important concentrations of Ba and Sr. The species diversity of sulfides in some carbonatites is significant. However, only pyrrhotite, pyrite, and sometimes chalcopyrite and/or sphalerite are known to occur in large amounts, while other sulfides (as well as other chalcogenides, native metals, and intermetallicides) are typically minor microminerals (Rudashevsky et al. 2004).

**LATE HYDROTHERMAL MINERALIZATION IN CARBONATITES**

The diversity of the carbonatite “mineralogical portrait” is vastly enhanced by late, relatively low-temperature hydrothermal mineralization, which is found in the majority of carbonatite complexes. Although the products of paragenetically early and late mineral-forming stages in carbonatite systems can be similar in gross geochemistry, they are quite different from one another in mineral composition and crystal chemistry. More than twenty carbonates, phosphates, silicates, and oxides are exclusive to carbonatites: the majority of these are hydrated, late-crystallizing species. Other unusual minerals are shared with associated siliceous igneous rocks and also with skarns and other metasomatized country rocks.

The greatest diversity is found in the alkali-rich and incompatible-rich carbonatites associated with highly differentiated appaitic nepheline syenites. The typical minerals there are zeolite-like hydrous Na-rich and/or K-rich zircono-

**Figure 1** A complex high field-strength element silicate–oxide association in a hydrothermally altered carbonatite (Kovdor, Russia). The minerals present are as follows: color-zoned prisms of the Nb–Ti silicate labuntsovite-Mg; beige pseudo-hexagonal tablets of the Zr silicate catapleiite (more common on the left side of photo); small dark blue anatase crystals (right side of photo). Photo credit: Igor Pekov
is sensitive to crystallization conditions (Zhitova et al. 2018). Synthetic layered double hydroxides, with their high specific surface areas and exchangeable interlayer contents, have many applications as catalysts, sequestering agents, and drug delivery media (Mills et al. 2012).

Phosphates are typically represented only by apatite-group minerals in early assemblages in carbonatites but show a great diversity in late hydrothermal parageneses and weathering profiles. The most spectacular example is the assemblage of more than twenty phosphates found at Kovdor. The majority of them, apart from fluorapatite, are hydrous species containing essential Mg, Fe, Na, Ba, Sr, Ca or Sc, but without REEs. Almost half of these species are unique to this deposit.

**RARE-EARTH CARBONATES**

Partitioning of REEs into carbonatites increases dramatically with the degree of crystallization and differentiation of the alkaline silicate magmas from which the carbonatitic melts unmix by immiscibility. Rare-earth carbonates represent one of the major sources of REEs in carbonatites, the other one being the phosphate mineral monazite. As mentioned above, burbankite/calcioburbankite can be primary magmatic REE carbonate minerals. Burbankite is formally a solid solution between (Na2Ca)Sr3(CO3)3 and Na3 (Sr2LREE)(CO3)3, while calcioburbankite has Ca replacing the Sr. Recent laboratory studies (Anenburg et al. 2020) have shown that related species even richer in Na and REEs can crystallize from melts and that other Na-rich, but nominally REE-free, carbonates can also incorporate significant REEs. The work of Anenburg and colleagues demonstrates that the presence of alkali cations (Na+, K+) in addition to anions is essential for high concentrations of REEs in the melt. Note that such very alkali-rich phases are likely to be highly soluble and imprecise in nature.

Burbankite-group minerals can become replaced by a range of secondary REE carbonate species, typically carbocernaite in the first instance (Zaitsev et al. 2002; Chakhmouradian et al. 2017). Carbocernaite is (Ca,Na)(Sr,LREE)(CO3)2, formally a solid solution between CaSr(CO3)2 and Na3LREE (CO3)3. The various natural occurrences could probably be reclassified as more than one mineral species, depending on the dominant end-member. Both burbankite and carbocernaite are subject to replacement by other carbonate, such as bastnäsite and strontianite, and the sulfate mineral baryte.

Other common secondary REE carbonates are members of the ancylite group, which contain in their structure one site occupied by a variety of cations: REE3+, Ca2+, and Sr2+. In general, in order to identify the predominant REE in a particular crystallographic site, Alfred Levinson’s 1966 rule-based nomenclature is used: “the species name is obtained by appending the chemical symbol of the predominant rare-earth element to the group name”. For instance, ancylite-(Ce) is a mineral with Ce playing the role of the species-defining REE. The ancylite-group minerals, unlike the burbankite group, contain OH− and in some species also H2O groups, consistent with their late hydrothermal origin. The crystal structures of the minerals of the burbankite and ancylite groups, as well as that of carbocernaite, are best described as arrays of large, heavy cations with carbonate groups in the interstices.

The most remarkable REE carbonates, in terms of chemical and structural phenomena, are those of the bastnäsite–synchysite series, which contain at least nineteen recognized, and many potentially new, mineral species. The archetypal end members of the series are bastnäsite-(Ce) [Ce(CO3)F] with a crystal structure type denoted as B below, and synchysite-(Ce) [CaCe(CO3)2F] denoted as S (the dominant REE may differ, and F may be replaced by OH) (Fig. 3). Intermediate members of the series have crystal structures made from slices (modules) of the B structure and S structure stacked together in different proportions n:m to give a range of species with different compositions BSnm (polysomes). In addition to the bastnäsite and synchysite groups, the recognized mineral species are those of the parasite group corresponding to the symbol BS (n = m = 1), and röntgenite-(Ce), the BS2 member (n = 1, m = 2).

The species of this series are very similar to one another physically, and they frequently form intergrowths. The difficulty of distinguishing the rarer members from relatively common bastnäsite and parasite is reflected in the names: “synchysite” (from the Ancient Greek “synchysis”, meaning “confounding”) and “röntgenite” (after Wilhelm Röntgen, the discoverer of X-rays, X-rays being required to identify them as a new mineral). The original bastnäsite was named more conventionally after its type locality in the metasomatic Fe–Cu–REE deposit at Bastnäs (Sweden), and parasite after Señor J. J. Paris, who was the manager of the mine at Muzo (Colombia) where it was first found but which is better known for producing many of the world’s finest emeralds. Well-crystallized parasite and emerald sometimes grow together. The origin of the rare minerals at Muzo is unique and remains mysterious. There are no known associated igneous sources for the unusual elements Be, Cr, V, and REE, which may have been extracted from clays and organic complexes in the surrounding sediments.

The crystal structure of bastnäsite-(Ce) is based upon [CeF] sheets alternating with the sheets of carbonate groups oriented perpendicular to the plane of the [CeF] layer (“edge-on”). Thus, the B module contains two sheets and has the total formula [(CeF)(CO3)]BS. The crystal structure of synchysite-(Ce) is composed from the B modules separated by the additional sheet of Ca2+ cations and another sheet of “edge-on” (CO3)3 layers, all together forming the [(CeF) (CO3)(Ca)(CO3)]BS module. A structure with only Ca2+ cation layers would essentially be that of the metastable CaCO3 polymorph vaterite. No other ordered sequences are known which are richer in Ca than synchysite, but the layer sequences for bastnäsite, synchysite, and their intermediates are shown in Figure 3.

The sequence of the B and S modules in a member of the polysomatic series may be ordered on different scales or totally disordered, very similar to the situation observed...
in other layered minerals such as micas and the layered double hydroxides. In many cases, X-ray diffraction fails to decipher the sequence due to the twinning, stacking, and “polysomatic” faults, which result in intense streaking and diffuse scattering of XRD patterns: the crystal structure of röntgenite-(Ce), for example, has not yet been fully characterized. The most appropriate experimental technique for characterizing layer-by-layer stacking is high-resolution transmission electron microscopy. This technique has revealed many polysomes that occur as intergrown lamellae but that have never been found as single crystals, such as $B_2S$, $B_3S_2$, and $B_3S_4$ (Ciobanu et al. 2017; Zeug et al. 2020).

Even for the same polysome, additional structure variability can arise through polytypism. This can involve different patterns of relative sideways shift of different modules to give structures with different crystallographic symmetries, or changing the exact sequence of $B$ and $S$ modules. For example, whereas parisite-(Ce) is usually identified as the $BS$ polysome with the ordered $\ldots BSBSBS\ldots$ sequence, Capitani (2019) recently described lamellae up to 20 nm thick of a new polytype with the $\ldots BBSSBBSS\ldots$ sequence.

The exceptional crystal-chemical complexity of the bastnäsite–synchysite polysomatic series is comparable to that observed in sheet silicates; more information is provided in reports by Capitani (2019), Zeug et al. (2020), and references therein. From the genetic point of view, the formation of ordered/disordered sequences in the series is related to different kinetic regimes of crystallization (Ciobanu et al. 2017).

**EPHEMERAL MINERALS OF CARBONATITES**

The Earth’s only currently active source of carbonatite lava, Oldoinyo Lengai in Tanzania, is unique in that it produces natrocarbonatite flows of a type that would not be preserved in the geological record. The major phenocryst phases in these lavas are tablets of nyerereite $[\alpha-(Na,K)\text{Ca}(CO_3)_2]$ and rounded crystals of gregoryite ($\alpha-Na_6CO_3$). Gregoryite is known only from this locality. These minerals are high-temperature polymorphs of, respectively, zemkorite (a poorly studied mineral which needs further investigation) and natrite, both of which are unstable in moist air at room temperature. On eruption, they react in hours to form a succession of other Na–K–Ca carbonates which are also water-soluble or partially so (Zaitsev and Keller 2006). The lava groundmass is rich in halides, including soluble sylvite and halite (Zaitsev et al. 2009). Within days of eruption, only relict insoluble phases, such as calcite and fluorite, remain, the overall composition bearing little resemblance to that which originally erupted.

The dissolved Na$^+$ and carbonate ions drain into Lake Natron, only 20 km to the north of Oldoinyo Lengai, where the high temperature and evaporation rate can result in the pH of the water exceeding 12. This highly saline, alkaline environment supports a community of halophilic cyanobacteria which impart a red, orange, or pink color to the water, to the salt crusts, and to the flocks of millions of flamingos which feed on the microbes.

Relationships between many of these minerals in lapilli from Oldoinyo Lengai are described by Mitchell (2006). A phase of approximate composition $Na_{3.4}PO_4(CO_3,F,Cl)$ occurred in those lapilli as small crystals and aggregates in replacements after gregoryite. It was found to decompose within six months even when kept in a desiccator. It still defies full description and approval as a new mineral.

Elsewhere, there is considerable evidence for the presence of similar carbonate phases at depth, but they are preserved only as inclusions in insoluble mineral hosts. Nyerereite occurs as inclusions in magnetite from the extinct Tanzanian Quaternary volcano Kerimasi (Zaitsev et al. 2009). Nyerereite and zemkorite have been found in kimberlites (Sharygin et al. 2008). Nyerereite and shortite
[Na$_2$Ca$_2$(CO$_3$)$_3$] have also been found as inclusions in refractory oxide minerals such as perovskite, magnetite, and ilmenite in lithospherically derived calcite–amphibole–pyroxenite rocks of the Afrikanda complex (Kola Peninsula) and elsewhere (Chakhmouradian and Zaitsev 2004). Natrocarbonatite-like assemblages have been found as inclusions in magnetite in the calcite-dominated Okha complex of Canada (Chen et al. 2013). The experimental work of Litasov et al. (2013) demonstrated that Na and K can lower the solidus temperatures of carbonatite melts by 400–500 °C under upper mantle conditions and that these alkalis can partition into those melts. The melts then crystallize a range of Na- and K-rich carbonate phases, including some not yet described as minerals.

We note that the name “nyereite” is after Julius Nyerere, President of Tanganyika and subsequently Tanzania, 1964–1985. This makes it a rare exception to the International Mineralogical Association (IMA) guideline that minerals not be named after political figures.

PYROCHLOR-SUPERGROUP MINERALS OF CARBONATITES

The high field-strength elements (HFSEs) Ti, Zr, Hf, Nb, and Ta are present in a wide range of concentrations in carbonatites and their associated rocks (Chakhmouradian 2006). The HFSEs are particularly elevated in phosphorites (ultramafic rocks consisting mainly of magnetite, apatite, and a Mg-rich silicate) and silicocarbonatites (>20% SiO$_2$) (Mitchell 2005). The HFSEs are lower in calcio- and magnesiocarbonatites, but even here their concentrations can be sufficiently high for them to crystallize as major elements in magmatic phases: the largest-producing Nb source at Araxá (Brazil) is a dolomite–calcite carbonatite. The low overall silica activity means that Nb is generally hosted by oxide minerals in those rocks. A distinctive feature of carbonatitic HFSEs is a high Nb/Ta ratio. This may be due to the greater stability of carbonate complexes for the lighter HFSEs (Chakhmouradian and Williams 2004) or that they are derived from a source that is already enriched in Nb over Ta. Along with the non-silicate nature of the Nb minerals, this feature makes carbonatitic Nb oxides attractive as an economic source of Nb for applications such as high-performance alloys and superconducting magnets.

The Nb contents of carbonatites are largely hosted in minerals of the pyrochlore group. The archetypal ideal formula of pyrochlore is (NaCa)Nb$_2$O$_6$F, which lies on the border between the species fluorapatopyrochlore (Na > Ca) and fluorcalcipyrochlore (Ca > Na) as currently classified by the IMA. This is an example of a general formula $A_2B_2X_6Y$, where $A$ sites contain large cations in 8-fold coordination and $B$ sites contain smaller 6-fold coordinated cations that link via octahedral corners to form a framework of cubic symmetry. A very wide range of cations of appropriate size but various valences can occupy the $A$ and $B$ sites, allowing for extensive and complex homovalent and coupled heterovalent solid solutions. The anion X is largely O$_2^−$. However, the $Y$ site can be occupied by an anion (OH$^−$, F$^−$, O$_2^−$) or H$_2$O, or be vacant, or sometimes contain a large cation such as K$^+$. The current mineral species nomenclature scheme determines that names use the dominant constituents of the dominant valence in each of the $Y$, $A$, and $B$ sites (Atencio et al. 2010). The crystal-chemical flexibility and general stability of pyrochlore-structure oxides makes them phases of great interest for radioactive waste containment (Laverov et al. 2010).

Pyrochlore-group minerals (Fig. 4) may have a long crystallization history in carbonatic systems, which is reflected in the mineral composition. Most primary (i.e., magmatic) carbonatitic pyrochlore compositions lie in the fluorcalcipyrochlore field but show complex oscillatory zonation that provides a record of magma evolution. Pyrochlores may also record both a pre-carbonatite and a late alteration history. Walter et al. (2018) described partially resorbed cores of uncharacteristically high U and Ta content, which may be xenocrysts acquired from associated syenites, and late hydrothermal rims that are enriched in Th and REEs. The phenocrysts examined by Chebotarev et al. (2017) have patchy zonation due to late hydrothermal and supergene alteration, where $A$-site cations and $Y$ anions are lost to give keno- or hydropyrochlore compositions, and the remnant cations are enriched in Sr, Ba, and Pb to the point that Sr can predominate over Ca. Chakhmouradian and Williams (2004) discuss several other examples of paragenetically early (U,Ta,Ti)-enriched pyrochlores (some with Ti > (Nb + Ta), putting them in the betafite field), as well as inclusions in magnetite in the calcite–carbonate mineral assemblage. Original micrographs and analytical data are courtesy of Dr. Taras Panikorovskii (Kola Science center, Russian Academy of Sciences).
as oscillatory zoned pyrochlore proper, and post-magmatic zones that have A sites that are depleted in Na and Ca but that may be enriched in Sr, Ba, Pb, U, Th, and REEs.

CONCLUDING REMARKS

The juxtaposition of a wide range of unusual chemical elements at high concentrations is one key to the diversity of carbonatite minerals. The complexity of their petrogenesis and subsequent alteration is another. Carbonatites are exceptional natural laboratories for demonstrating the ways in which large-ion lithophiles, high field-strength elements and rare earths can combine to form solid phases that are often unique to the carbonatite setting. Observational and experimental studies of these phases, their crystal structures, paragenetic relations, and associated fluids are only beginning to elucidate how some technologically vital critical elements are mobilized and concentrated to form economically important deposits.

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Carbonatites have formed for at least the past three billion years. But over the past 700 My the incidence of carbonatites have significantly increased. We compile an updated list of 609 carbonatite occurrences and plot 387 of known age on plate tectonic reconstructions. Plate reconstructions from Devonian to present show that 75% of carbonatites are emplaced within 600 km of craton edges. Carbonatites are also associated with large igneous provinces, orogenies, and rift zones, suggesting that carbonatite magmatism is restricted to discrete geotectonic environments that can overlap in space and time. Temporal constraints indicate carbonatites and related magmas may form an ephemeral but significant flux of carbon between the mantle and atmosphere.

Keywords: carbonatites; global tectonics; mantle carbon; cratons; LIPs; orogenic magmatism

INTRODUCTION

Magmas parental to carbonatites have been generated for at least two-thirds of Earth’s history: the oldest known carbonatite is the Mesoarchean 3.01 Ga carbonatite Tupertalik in Greenland (Bizzarro et al. 2002). The only currently active carbonatite volcano is Oldoinyo Lengai (Tanzania), which erupts alkali-rich carbonatite and is unique within the rock record (excluding compositionally similar minerals and melt inclusions). Carbonatites are largely confined to the continental lithosphere (Fig. 1) with a few examples occurring on older, thicker, oceanic lithosphere, associated with ocean island basalt (OIB) volcanism. Carbonatites occur in a variety of tectonic settings, including stable intraplate areas and in association with rifts, lithospheric highs, and orogenies (Woolley 1989; Simandl and Paradis 2018). The emplacement of carbonatites is largely continuous throughout Earth’s history from 3 Ga, but exhibits a significant increase in the number of occurrences with time (Fig. 2) (Woolley 1989; Woolley and Kjarsgaard 2008; Kogarko and Veselovskiy 2019).

Carbonatites are the products of low-degree partial melting of an enriched (relative to ambient upper mantle) or metasomatised mantle. Mantle metasomatism is the sub-solidus chemical change of a rock and is observed in much of the continental lithospheric mantle. Carbonatites may be directly erupted from their mantle source or, more frequently, emplaced after protracted modification within the lithosphere (Woolley and Kjarsgaard 2008). Carbonatites are diverse rocks formed through eruption, intrusion, or carbohydrothermal fluid activity (Mitchell 2005; Woolley and Kjarsgaard 2008). Isotopic studies of selected carbonatites may indicate a temporally isolated mantle source for the magmas (Nelson et al. 1988; Bell and Simonetti 2010), and their association with large igneous provinces (LIPs) has been used to suggest an association with deep mantle phenomena (Ernst and Bell 2010).

The number of carbonatites through time is an expression of how their mantle source conditions have changed, combined with the effects of selective preservation in the geological record. Carbonatites require specific physico-chemical conditions within the asthenospheric and/or lithospheric mantle source to generate their parental low-degree melts, but they also require favourable tectonic regimes to promote transport of such low-volume melts through the lithosphere.

The contribution of carbonatites as a flux of carbon between the mantle and the atmosphere has historically been regarded as insignificant due to the rarity of carbonatites (e.g., Woolley 1989) and the low volume of carbonatite magmatism at any one occurrence. However, recent work suggests carbonate-rich magmas may be important in transporting carbon from the mantle to the atmosphere (Foley and Fischer 2017; Paulsen et al. 2017; Yaxley et al. 2019). The recognition of their association with other CO₂-rich magmas suggests that the overall flux of CO₂ may be significant, at least on geologically short timescales.

We collate an up-to-date list of 609 carbonatites and present a model detailing the distribution of 387 of known age (Fig. 1), which takes into consideration plate-tectonic reconstruction models for the last 410 My. We focus on understanding the relationship between the spatial and temporal occurrences of carbonatites and relevant geotectonic features through time (Fig. 3, the example at 130 Ma). Specifically, we place the history of carbonatite magmatism within the context of the Young et al. (2018) model for tectonic history ~410–250 Ma, which we modified along western North America to improve the kinematic evolution of terrane accretions, linked to data in Müller et al. (2019) for the period 250–0 Ma, and to a newly derived, optimised, mantle reference frame using the open-source GPlates platform (www.gplates.org).
CARBONATITES AND THE LITHOSPHERE

The close spatial and temporal association of carbonatites with alkaline rocks, along with mineralogical affinities and incompatible element (including light rare earth element) enrichment, suggests a close petrogenetic relationship between the rock types: 76% of known occurrences of carbonatites are associated with some form of alkaline rock (Woolley and Kjarsgaard 2008). Although generally confined to continental areas, some carbonatites occur in oceanic settings (Fig. 1) (Schmidt and Weidendorfer 2018), whereas alkaline rocks are abundant on the continental and the oceanic lithosphere. It is, therefore, possible to generate alkaline magmas from below the sub-oceanic lithosphere, but much rarer to generate carbonatite-forming magmas in oceanic settings.

The association of carbonatites with cratonic lithosphere was recognised from early studies in Africa, but compilations of global datasets showed the association is consistent across all continents (Woolley 1989; Woolley and Kjarsgaard 2008; Simandl and Paradis 2018). Our analysis shows the closest spatial association is between carbonatites and the edges of cratons (Fig. 4). This association may partly reflect the proportion of the continental crust occupied by cratons and their dimensions, but also suggests that the optimal extraction conditions for carbonatites occur along the significant boundaries that exist within the lithosphere between the cratonic and non-cratonic lithosphere.

Carbonatites are often associated with rifts (e.g., Foley and Fischer 2017); however, our data show that only ~25% of carbonatites are found within ~1,000 km of major modern or palaeo-rifts (Fig. 4). Rifting (or extensional tectonic regimes) can be associated with major plate reconfiguration, large igneous province eruption, or may result from more local-scale changes in the stress regime over a plate. Therefore, the factors controlling rifting likely influence the local mantle conditions (e.g., temperature, composition, and depth of the lithosphere–asthenosphere boundary), and, thus, the propensity to generate carbonatite-forming melts.

Continental lithospheric control on carbonate spatial distribution is demonstrated when examining the repetition of carbonate occurrences through time. In several regions around the world—including Eastern Africa, Greenland, and Southern Africa—carbonatites are repeatedly emplaced through time (Woolley and Bailey 2012). Foley and Fischer (2017) present modelling of the deep lithospheric budget of carbon and suggest that the lithosphere acts as a vast store for carbon at depth, both from incompatible melts generated from the asthenospheric mantle, which accumulate through time, but also from plume-derived material. Carbon stored at the base of the lithosphere can be remobilised through redox reactions and decompression melting, concentrated in regions dictated by the architecture of the lithosphere–asthenosphere boundary (Foley and Fischer 2017) and the presence, or reactivation, of faults and lineaments in the lithosphere. Carbon-rich regions may then be reactivated repeatedly through time to generate carbonatites, carbon-rich magmatism, and associated degassing.

MANTLE CONDITIONS FOR Generating CARBONATITIC MELTS

The mantle conditions required to generate carbonatitic melts are strict. Low-degree melting (<1%) is crucial to matching major and trace element compositions of carbonatites, implying that the mantle temperatures in carbonatite-melt source regions are at, or close to, the CO2-bearing peridotite (or eclogite) solidus. Carbonatites are not known from the geological record before 3.01 Ga; alkaline rocks appear in the geological record at 2.79 Ga, and kimberlites at ~2.85 Ga (Tappe et al. 2018). This implies either that the physico-chemical conditions required for generating melts parental to carbonatite were not established prior to this time (Woolley 1989; Tappe et al. 2018) or that previously formed rocks have been lost from the geologic record.

Magma volumes, coupled with incompatible element enrichment and metasomatised mantle xenoliths entrained in carbonatitic volcanism, and carbon-rich alkaline volcanic provinces both indicate a metasomatised mantle source region for carbonatitic magmatism (Woolley and Kjarsgaard 2008; Hutchison et al. 2019). Metasomatism of the lithospheric mantle results from the fluxing of low-degree, ephemeral melts that have been derived from the melting of ambient upwelling asthenospheric mantle, from above subducting oceanic lithosphere, and from the peripheries of upwelling thermal anomalies in the mantle. Dating of metasomatic minerals (e.g., amphibole, plagioclase, apatite, sulfides) in mantle xenoliths entrained in carbon-rich magmatism shows the process is dynamic and cumulative over geological time and can both be concurrent with and predate magmatism by many hundreds of millions of years.

Radiogenic isotopic studies (using Sr, Nd, and Pb) of carbonatites have helped to establish that carbonatites are mantle-derived melts (Nelson et al. 1988; Bell and Bleeker 1999). The isotopic ratios of carbonatites are distinct from mid-ocean-ridge basalt (MORB, which is assumed to reflect
the isotopic composition of the depleted upper mantle); carbonatites that are younger than 200 Ma are similar to ocean island basalt (OIB) compositions.

Stable isotope studies of carbonatites and alkaline rocks indicate that the mantle source is metasomatised lithosphere or recycled material in mantle plumes (e.g., Hutchison et al. 2019; Amsellem et al. 2020). Hutchison et al. (2019) demonstrate that there is a temporal change in the sulfur isotope composition of sources of alkaline rocks and carbonatites, and this could reflect changes in the composition of the lithospheric mantle and/or billion-year timescales of deep crustal recycling. Amsellem et al. (2020) show that carbonatites have isotopically lighter Ca than basalts and suggest that this is evidence for the recycling of isotopically light sediments into the mantle, creating hybrid carbonatite sources rich in a component of recycled sediment. Carbon isotopes in many carbonatites overlap with the average value of the asthenospheric upper mantle: δ13C = −5‰ (Deines 2002). Deviations in individual carbonatites are ascribed to either variations in the carbon isotope content of the mantle source of the magmas (e.g., a recycled source component), assimilation of host rocks, post-magmatic hydrothermal fluid flow, or magmatic degassing.

**CHANGES IN MANTLE CONDITIONS AND THE GENERATION OF CARBONATITES**

Several studies using increasing numbers of carbonatite occurrences of known age (Woolley 1989 [n = 148]; Woolley and Kjarsgaard 2008 [n = 155]; Kogarko and Veselovskiy 2019 [n = 180]; Woolley and Bailey 2012 [n = 274]; this study [n = 367]) have shown an increase in carbonatite abundance through time. This has also been demonstrated for alkaline igneous rocks (Kogarko 1996) and kimberlites (Tappe et al. 2018). The change in abundance of carbonatites with time was initially argued by Woolley (1989) as evidence for a change in the physical conditions of melt-forming regions. The change may also reflect the preservation biases of the geological record. Destruction of the lithosphere (e.g., burial, erosion, and metamorphism) is expected to have some effect on the carbonatite record. However, there is strong evidence to suggest that physical conditions within the lithosphere and asthenosphere have changed with time to promote the generation of small-fraction partial melts, parental to carbonatites. Figure 2 details carbonatite occurrences from the Mesoarchean to the present day, including a comparison with an estimate of the proportion of continental crust of Precambrian age, including exposed Precambrian (dark grey) and exposed-plus-buried (light grey) (Goodwin 1996). The estimates of the age of the exposed present-day crust can be taken as a proxy for the preservation record, i.e., the oldest rocks (>650 Ma) form <15% of the total exposed continental crust and, thus, carbonatites older than 650 Ma are equally unlikely to be preserved in the rock record. However, the distribution of carbonatites exhibits greater variability than the current surface area age distribution: for example, the period of 150–500 Ma has less carbonatites, and there are significant “pulses” of carbonatite activity from the Neoarchean to present that would not be predicted by surface area age distribution alone. Tappe et al. (2018) observe a general increase in the abundance of kimberlites since ~2 Ga (similar to the overall increase in the frequency of carbonatites since 3 Ga) and conclude that the abundance reflects changes in the mantle temperature and oxidation state with time. Thus, preservation is not the sole factor influencing the distribution of carbonatites through time. Other variables must be considered to explain the temporal variation of carbonatites.

**Figure 2** Histogram of carbonatites of known age (n = 387). Kimberlites and alkaline rock ages shown for comparison; note varying y-axis scales. Dashed lines show percentage age distribution at the present day (dark = exposed; light = exposed plus buried). From Goodwin (1996).

The origin and abundance of carbon within the early Earth was affected by processes, including planetesimal accretion, core formation, giant impacts, the moon-forming impact, and the late veneer of meteoritic material (Dasgupta 2013). The initial concentration of carbon in the Earth’s mantle is affected by volatile loss during planetary accretion and differentiation into the core. Subsequently, due to high temperatures in the early Earth (if the mantle was oxidising enough), much of the mantle would be at or above the carbonated peridotite solidus and, therefore, carbon would be rapidly extracted and lost to the atmosphere and/or space. The late veneer of meteorites likely increased the concentration of carbon in the mantle. Continued modification of the carbon concentration of the mantle results from the balance of carbon subducted into the deep mantle and carbon degassed from volcanism. 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The ability of the mantle to retain carbon is also bound to the oxidation state of the mantle, where reduced carbon phases (such as graphite, diamond, and methane) act as long-term repositories for carbon. Prior to 3 Ga, it is unclear what the oxidation state of the Earth’s mantle was: some evidence suggests more reducing than present, other evidence suggests a stable mantle oxidation state since the...
CARBONATITES AND THE (DEEP) MANTLE

Large igneous provinces (LIPs) are often attributed to mantle plumes with a deep mantle origin, based on evidence from primordial isotopic ratios (e.g., $^{3}$He/$^{4}$He). The impact of a plume on the lithosphere generates a large volume (>10$^{5}$–10$^{6}$ km$^{3}$) of magma, typically forming flood basalts and some minor felsic magmatism, within geologically short timescales (0.1–1 Ma). There are temporal and spatial correlations between LIPs and carbonatites, which date back as far as 2.06 Ga (Bushveld Igneous Complex, South Africa) (Ernst and Bell 2010). Depending on the LIP thermal regime, carbonatites have been documented to occur prior to, during, or after LIP magmatism. Our data show a weak temporal and spatial correlation between carbonatites and LIPs (Fig. 4) which may be explained by the relatively short duration of the active LIP magmatism in our models versus the much longer heating of the lithosphere that enables the generation of carbonatitic melts pre- and post-LIP magmatism.

Kogarko and Veselovskiy (2019) modelled the emplacement of 155 carbonatites on plate reconstructions to show the spatial association between selected carbonatites and a large low shear-wave velocity province (LLSVP) at the core-mantle boundary. The reconstructions show that 66% of the carbonatites studied can be linked to one LLSVP largely beneath Africa; however, the other significant LLSVP (which currently resides under the Pacific Ocean) was not linked to any carbonatites, and the remaining 34% were not associated with either LLSVP. Our data show that there is a spatial relationship between present-day LLSVP outlines and carbonatites (Fig. 4), but it is not as strong as other geotectonic settings studied (e.g., cratons and orogens). Our approach also assumes fixed and unchanging LLSVPs with carbonatites may be valid where they can be linked to both an LLSVP and LIP magmatism.

Kimberlites are arguably related to carbonatites (particularly the rapidly erupted, diatremic carbonatites) in that both are formed from low-degree melts of metasomatized mantle. Kimberlites are largely confined to the cratons, and some have entrained diamonds containing high-pressure mineral inclusions that indicate an origin from deep
within the mantle. However, Tappe et al. (2020) studied the tungsten isotope composition of a variety of kimberlites across Africa, which have been linked to plumes and the LLSVP, finding that kimberlites across Africa do not carry a primitive or LLSVP signature; instead, they have tungsten isotopic compositions that are indistinguishable from modern ambient mantle (i.e., a depleted MORB source).

Melts parental to carbonatites can be generated in the sub-lithospheric mantle (see Timmerman et al. 2021 this issue; Yaxley et al. 2021 this issue and references therein). These asthenosphere-derived melts (Fig. 5) are likely to be the source for both the metasomatism of the lower lithospheric mantle and a potential heat source for melting metasomatised lithosphere, or the parental melts to carbonatite magmas themselves. However, the extent to which most carbonatitic melts have interacted with the lithosphere on ascent means that tracing this original source is extremely challenging.

**THE ROLE OF CARBONATITES IN THE GLOBAL CARBON CYCLE**

Carbonatites have historically been considered unusual, rare rocks that are confined to stable intraplate areas. However, we know them to occur across a range of lithosphere types and to be associated with CO\(_2\)-rich alkaline magmas and mantle source regions. There are at least 609 carbonatites and, when considered with carbon-rich alkaline rocks (\(n = 2,586\)) (Humphreys-Williams and Woolley, unpublished data) and kimberlites (\(n = -5,652\)) (Tappe et al. 2018) (there are around 8,847 occurrences of CO\(_2\)-rich magmatic rocks. This is a conservative estimate because collations often contain complexes or volcanic fields as one entry and the geological record is incomplete; thus, a complete count of such CO\(_2\)-rich igneous rocks would underestimate their production over Earth history. The CO\(_2\)-rich magmatism (although volumetrically small in many cases) is associated with significant degassing of mantle-derived CO\(_2\) both pre- and post-volcanism. Carbonatites and related rocks also contribute to the flux of CO\(_2\) from the mantle to the lithosphere through magmas that intrude the lithosphere but that fail to erupt. As proposed by Sleep (2009), kimberlite melts which fail to reach the Earth’s surface have been frozen in the deep lithosphere, so forming a significant CO\(_2\) reservoir. It is entirely plausible that a whole spectrum of CO\(_2\)-rich small-fraction partial melts (alkaline, carbonatitic, kimberlitic) may be trapped in the lithosphere and that carbonatite-rich metasomatism may be near-ubiquitous in the deep lithospheric mantle.

Due to degassing, igneous rocks do not retain a reliable record of the CO\(_2\) budget of the primitive magmas from which they were derived, and carbonatites are no exception. Despite carbonate minerals being stable and crystallising a proportion of the magmatic CO\(_2\), much more is expected to be lost either through magmatic degassing, fenite-forming processes, and/or decarbonation reactions. Paulsen et al. (2017) provide evidence for the impact of CO\(_2\) derived from carbonatitic and alkaline magmatism and demonstrate that there is a temporal correlation between a proposed mantle cooling event prior to the Ediacaran and a subsequent spike in carbonatitic and alkaline magmatism (as determined through detrital zircon chemistry), which then led to an increase in volcanic CO\(_2\) and so promoted global warming. Degassing of CO\(_2\) from active rift environments associated with carbonatites is higher than previously thought (Foley and Fischer 2017). Other regions, such as small monogenetic volcanic fields containing carbonatites and other carbon-rich alkaline basaltic magmas, may also have a significant role in the carbon flux from the mantle to the crust and atmosphere. Carbon-rich alcali basaltic magmas typically erupt as volumetrically small products (maars or cinder cones) but are associated with passive degassing of mantle-derived CO\(_2\) for millions of years past the cessation of volcanism. This volcanism typically entrains xenoliths of highly metasomatised mantle, suggesting parts of the non-cratonic lithosphere (away from major rifts) contain significant stores of CO\(_2\), which is released when lithospheric stress regimes permit. The impact of CO\(_2\) degassing at such volcanic fields has not been considered in long-term estimates of carbon degassing from the mantle due to poor constraints on the flux of CO\(_2\) from these fields and due to the relatively recent acknowledgement of carbonatitic volcanism in these provinces. Critically, it may be possible that the impact of carbon-rich magmatism on the atmospheric concentrations of CO\(_2\) may be enhanced when the relevant geotectonic environments (Fig. 5) happen simultaneously, optimising the flux of CO\(_2\) from the mantle to the atmosphere.

**SUMMARY**

Carbonatites are derived from low-degree partial melting of an enriched or metasomatised mantle source and are either directly erupted or experience varying degrees of magmatic modification or low-temperature alteration after emplacement or eruption. The increase in carbonatites, alkaline rocks, and kimberlites with time is likely a result of mantle cooling over Earth’s history, the formation and stabilisation of the lithosphere, compositional change of the mantle due to subduction, and the cumulative effect

![Figure 5](image-url)

**Figure 5** Schematic of the most common geotectonic settings of carbonatite magmatism. Note that no temporal relationship between the geotectonic event and the formation of carbonatite magmatism is given, i.e., carbonatite magmatism may happen at any time during the event or may be restricted to discrete periods. Textured area within lithospheric mantle represents regions where cumulative metasomatism at the base of the lithosphere may occur. Wiggly arrows denote asthenosphere-derived, carbon-rich metasomatic melts of varying chemical composition, which may be parental to carbonatitic magmatism, may induce melting, or metasomatised the lithosphere. Vertical lines detail the path of carbonate-rich melts; those with spots are large igneous province (LIP) basalts and related rocks.

(A) Carbonatite magmatism in orogens: where lithospheric stress regime is favourable, carbonatites may be erupted or emplaced. (B) Carbonatites associated with LIP and mantle plumes: carbonatites are typically generated on the periphery of the flood basalts and/or temporally early or late. (C) Carbonatite emplacement in cratons: carbonatites are strongly associated with the edges of cratons where the lithospheric features make effective traversing melts and where volatiles may be concentrated due to the LAB (lithosphere–asthenosphere boundary) topography. (D) Carbonatites erupting around the margin of rifted settings where mantle melting conditions are suitable, i.e., incompatible elements are enriched and melting can occur at low melt fractions.
of metasomatism of the lithospheric mantle through time. Our spatio-temporal analysis suggests a strong association between craton edges and carbonatite occurrences (Fig. 4). This may suggest that most continental regions where carbonatites form have some Archean crustal component, but carbonatites are also an outcome of the conditions necessary for deep lithospheric carbon storage and mobilisation into carbonatite-forming melts. Many carbonatites throughout Africa and South America can be spatially linked to an LLSPV, but there are no known carbonatites above the Pacific LLSPV, suggesting that the nature of the lithosphere (i.e., continental vs. oceanic), and not the deep mantle, is critical in carbonatite genesis.

Three optimal conditions for the generation of carbonatite-forming magmas can be outlined as follows: 1) near-solidus mantle temperatures and a C-rich metasomatised mantle source; 2) extended periods of time to accumulate carbon within the lithosphere; 3) geotectonic event(s) forming appropriate lithospheric stress regimes to mobilise C-rich regions or allow the ascent of C-rich melts. The impact of carbonatitic (and associated alkaline) magmatism on the global carbon cycle is beginning to be recognised, but passive degassing around intraplate volcanic fields requires further attention. New methods for monitoring carbonate and alkaline rock distribution through time (such as detrital zircon studies), and further constraints on the volumes of carbon emitted by carbonatites, alkaline rocks, and associated degassing, potentially over geologically short time periods, will help to illustrate the importance of carbonatites for the transport and storage of carbon between the mantle and the atmosphere and their influence on the global carbon cycle over geological time.

ACKNOWLEDGMENTS

Thanks to John Eiler, Suzette Timmerman and Michael Anenburg for and for editorial handling; Carl Spandler and Sebastian Tappe for positive and constructive reviews; and Yannick Buret for comments on earlier versions of the manuscript. EH-W acknowledges funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement no. 689909). EH-W wishes to thank Alan Woolley for his continued guidance and infectious enthusiasm for carbonatites and alkaline rocks. SZ was supported by Australian Research Council grant DE210100084, a University of Sydney Robinson Fellowship, and Alfred P Sloan grants G-2017-9997 and G-2018-11296. GPlates development is funded by the AusScope National Collaborative Research Infrastructure System (NCRIS) program. Full digital supplement, including data and animations, can be accessed from https://doi.org/10.5281/zenodo.5206007. We acknowledge the assistance of John Cannon in deploying the absolute plate motion optimisation for the Palaeozoic portion of the plate reconstructions.

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All of us had hoped to meet in person in Cracow (Poland) in 2021 after the 3rd European Mineralogical Conference (EMC) meeting had been postponed in 2020. However, the pandemic situation was far from stable and the safer option had to be chosen: to have the conference on-line. We did not get to enjoy an ice-breaker party or have those long scientific discussions in one of Cracow’s many pubs and cafes. We did, however, enjoy good science, almost flawless streaming, and have long scientific discussions via chat box and at virtual poster tables. We can even watch again some of the scientific events, such as the plenary talks and the one social (!) evening – a concert by Pinky Loops (https://youtu.be/i2DW69l32lE). As an afterthought, online conferences have some advantages, such as quick transitions from one session to another (and without the persistent sound of a door closing and opening); but, despite that, we hope to be ‘in person’ for the 4th EMC in 2024.


The 3rd European Mineralogical Conference was organized by the Mineralogical Society of Poland on behalf of the following European mineralogical societies: Deutsche Mineralogische Gesellschaft (DMG), Mineralogical Society of Great Britain and Ireland (MinSoc), Mineralogical Society of Finland, Österreichische Mineralogische Gesellschaft (ÖMG), Russian Mineralogical Society (RMS), Sociedad Española de Mineralogía (SEM), Société Française de Minéralogie et de Cristallographie (SFMC), Società’ Italiana di Mineralogia e Petrologia (SIMP), Swiss Society of Mineralogy and Petrology (SSMP), with the participation of European Mineralogical Union (EMU). The conference was attended by 531 participants (including 136 students) from 34 countries (see Table 1 for details) who presented 325 oral presentations and 129 posters. The meeting lasted five days, the first day being dedicated to two workshops: Workshop on Low Temperature Geochemical Modelling using PHREEQC, which was led by Mark Tyrer, Andy Watson, Vincent

<table>
<thead>
<tr>
<th>Country</th>
<th>No of participants</th>
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<tbody>
<tr>
<td>Germany</td>
<td>120</td>
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<tr>
<td>Italy</td>
<td>116</td>
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<tr>
<td>Poland</td>
<td>90</td>
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<td>Spain</td>
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<td>France</td>
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<td>United Kingdom</td>
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<td>Switzerland</td>
<td>11</td>
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<tr>
<td>Canada</td>
<td>10</td>
</tr>
<tr>
<td>Finland, United States, Greece</td>
<td>9</td>
</tr>
<tr>
<td>Other</td>
<td>46</td>
</tr>
</tbody>
</table>

Thanks to the efforts of many members from all the above-mentioned European mineralogical societies it was possible to prepare a unique scientific event that contained a substantial list of scientific sessions and was accompanied by fruitful discussions, during both the oral and the poster sessions.
President's Letter

**MSA: A Strange Year**

This is my sixth and last message to you as 2021 Mineralogical Society of America (MSA) President. To say the least, it has been a strange year for me as president. All society business has been conducted by Zoom. No in-person meetings for me. No opportunities to meet and congratulate in person those honored by the society. No chance to thank and interact with the myriad volunteers who keep the society on track through their diligent committee work, or with the excellent staff who keep the society functioning. The MSA purred along transforming its outreach activities—short courses, lecture series—to a virtual world, handing out honors and doing business as before, but via Zoom, trying its best to weather the storm. Were these efforts successful? I think largely so, but as the less-personal interaction that happens in the virtual world begins to dominate the affairs of the society, one wonders what the inevitable outcome will be? To my mind, the serendipitous interactions that arise during one-on-one unplanned conversations are the spark that fuels scientific advancement. And, isn’t that kind of interaction why we join a society like the MSA: to seek out and associate with like-minded individuals for mental stimulation and intellectual growth? You don’t get that kind of stimulation from a committee meeting, especially one on Zoom. You are unlikely to benefit in that way from a YouTube video presentation of an MSA lecturer, no matter how talented s/he is, in the same way as going out to dinner or lunch with that lecturer and just having a conversation about how science is done or your joint interests. Virtual short courses are great and reach a larger group of people, but they are no substitute for attending a short course in person, interacting one-on-one with the instructors and participants, and benefitting from the intellectual stimulation that arises from total immersion. The MSA has evolved over the past year to embrace the necessity of virtual interaction, and this has led to many positive outcomes, but when the present health crisis is finally over, we, as a society, must not let efficacy trump the reason for our existence. We must ensure that personal interactions prevail as the dominant expression of the contributions the MSA gives to its members and to the broader community of Earth scientists who prosper because of the generosity of the MSA.

The MSA was founded in the last month of 1919; curiously enough, just prior to the fourth wave of a virus that resulted in another raging global pandemic. Its first president, Edward Kraus, must have been affected by this public health situation. One wonders what the situation was like back then at the University of Michigan, and if travel restrictions prevented him from carrying out his duties as president? Was there a post-war optimism that prevailed over the specter of a fifth and permanent cycle of death and chaos? History demonstrates that the MSA arose from the metaphorical ashes of that pandemic and became an intellectual force in the Earth science community. As members of the MSA, let’s all make sure that happens this time around with the same vigor as before.

My year as MSA President is over, and my only real regret is that I never found myself in a situation where some member could walk up to me and greet me as “El Jefe.”

Mark Ghiorso
2021 MSA President

Consider a Contribution to MSA

Many members contribute to the MSA by including a contribution with their annual dues and/or by responding to special appeals. Depending on the wishes of the member, the money is deposited with the principal of the MSA Endowment Fund, the J. Alexander Speer Outreach Fund, the MSA Mineralogy/Petrology Fund, the B. Thompson Fund, the Edward H. Kraus Crystallographic Research Fund, the F. Donald Bloss Fund, the General Operating Fund, or the new Peter R. Buseck Lecture Fund. The income of these funds is used to support MSA’s research grants in crystallography, mineralogy, and petrology; the MSA Undergraduate Prize; the Mineralogical Society of America Award; the Distinguished Public Service Award; the Dana Medal; the Roebling Medal; the website; and the Distinguished Lecturer program. If you have not done so previously, please consider contributing at the next opportunity.

Msa 2021 Awardes

**Roebling Medal:** Dr. George R. Rossman

Dr. George R. Rossman, Division of Geological and Planetary Sciences, California Institute of Technology (USA) has been awarded the 2021 Roebling Medal. This is the highest award that MSA bestows each year and is a recognition of “scientific eminence as represented primarily by scientific publication of outstanding original research in mineralogy.” Dr. Rossman has 345 publications listed on the Web of Science with an h-index of 66. For many years, he has studied how light elements are incorporated into minerals and has made vital contributions to research into the causes of color in minerals. His work in other areas of mineralogy and spectroscopy has influenced scientists, particularly planetary scientists, in a wide variety of disciplines. The MSA is proud to recognize Dr. Rossman’s seminal achievements by presenting him with the Roebling Medal.

**Dana Medal:** Dr. Sergey V. Krivovichev

Dr. Sergey V. Krivovichev works at the Department of Geology at St. Petersburg State University (Russia) and is the recipient of the 2021 Dana Medal. This medal is “intended to recognize sustained outstanding scientific contributions through original research in the mineralogical sciences by an individual in the midst of his or her career.” Dr. Krivovichev’s laboratory in St. Petersburg has become the primary center for experimental inorganic crystallography in Russia. Dr. Krivovichev’s publication record (many papers, chapters,
and books), as well as his influential work in both experimental and theoretical mineralogy, have earned him the recognition of his community. The MSA is pleased to present him with the 2021 Dana Medal.

**Distinguished Public Service Medal:**
Dr. Denton S. Ebel

Dr. Denton S. Ebel, Curator of Meteorites at the American Museum of Natural History (AMNH), is the 2021 recipient of the Distinguished Public Service Medal. This award is awarded by MSA “to individuals or organizations who have made important contributions to furthering the vitality of the geological sciences, especially, but not necessarily in the fields of mineralogy, geochemistry, petrology, and crystallography.” The award recognizes and celebrates Dr. Ebel’s work in public education at AMNH through lectures, innovative museum exhibitions, scientific meetings, and ground-breaking outreach programs. The MSA is delighted to recognize Dr. Ebel’s many contributions to geoscience education.

**MSA Award:** Dr. Chenguang Sun

Dr. Chenguang Sun of the Department of Earth, Environmental, and Planetary Sciences at Rice University (Texas, USA) has been awarded the 2021 Mineralogical Society of America Award. This award “is intended to recognize outstanding published contributions to the science of mineralogy by relatively young individuals or individuals near the beginning of their professional careers.” Dr. Sun’s research has contributed significantly to knowledge in quantifying trace element distributions in major rock-forming minerals, deducing the thermal history of mafic and ultramafic rocks, and clarifying carbonatite melt and peridotite interactions. For his many achievements, MSA is pleased to award Dr. Sun the 2021 MSA Award.

### MINERALOGY AND OPTICAL MINERALOGY

**Mineralogy and Optical Mineralogy** (2019, Second Edition, by Dyar, Gunter, and Tasa) is now in full color. It is available in both hard copy through the MSA Bookstore and as a PDF version (individual chapters and the entire text) through MinPubs.org. All the illustrations and animations that accompany the text are on the MSA website for free. You can find them at http://www.minsocam.org/msa/DGT_Figures/. Please contact the MSA Business Office at business@minsocam.org for more information.

### 2022 CALENDAR

The title for this year’s calendar, published by Lithographie is *Minerals of Mexico*. This stunning 16-month calendar, published by Lithographie Ltd., is available through the MSA Bookstore for only $12.

### DID YOU KNOW?

There are a variety of videos on MSA’s YouTube channel. These include those from the Centennial Symposium, Minerals Day, Short Courses, and others. Just a few of the titles are “The Mineralogy of Mars”, “Gems and Gemology”, “Triple Oxygen Isotope Geochemistry”, “Wire Silver and Gold Formation”, and many others. Videos for Minerals Day 2021 (October 11) will feature career opportunities in mineralogy and petrology.

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**Société Française de Minéralogie et de Cristallographie**

**GENERAL ASSEMBLY OF THE SFMC**

The General Assembly of the French Society of Mineralogy and Crystallography (i.e., Société Française de Minéralogie et de Cristallographie, or SFMC) was held in a hybrid form 16 June 2021. Members either participated in person at the association’s headquarters or remotely by video conference. The general assembly followed the presentations of the 2021 Hauy-Lacroix Prize for the best thesis, which went to David Bekaert (see below), and the 2020 SFMC Merit Award to Georges Calas (citation published in *Elements* v16n3). As part of the emc2020 awards ceremony, Georges Calas gave a fascinating lecture entitled, “Looking at Minerals and Glasses at a Molecular Scale”.

**The 2021 Haüy–Lacroix Prize**

The French Society of Mineralogy and Crystallography committee awarded its 2021 Haüy–Lacroix Prize to David Bekaert.

**David Bekaert** completed his PhD thesis, entitled “Isotopic Constraints on the Origin and Nature of Primitive Material in the Solar System and on Early Earth”, at the Centre de recherches pétrographiques et géochimiques (Université de Lorraine, France) under the supervision of Bernard Marty and Laurent Tissandier. During his PhD, David studied the origin of volatile elements in the Solar System and the primitive Earth and the processes that govern their distribution. This work is based on the geochemistry of rare gases (He, Ne, Ar, Kr, Xe) which have been used as tracers of these processes. David’s approach combined experimentation with observation of natural samples. A web-seminar given by David at the SFMC General Assembly is available on the SFMC’s website.

**THE SFMC TRAVEL GRANTS**

Each year the SFMC offers several grants to help young researchers participate in schools/workshops, symposiums, and conferences. The following are this year’s recipients:

**Goldschmidt2021 conference** (4–9 July, virtual meeting)

Five grants: Maxime Bertauts, Sarah Figowy, Julie Jonfal, Clément Laskar, Salomé Pannefieu.

**emc2020 conference** (29 August–2 September, virtual meeting)

One grant: Camille Muller.

**BULLETIN DE MINERALogie NOW SCANNED!**

The entire contents of the *Bulletin de Mineralogie* (and its former title incarnations from 1878 to 1988) is now available in digital version and is free access on the Persée portal: see https://www.persee.fr/. This has been made possible thanks to the conscientious validation work of Anne-Marie Boullier, François Guillot, and Christian Chopin. This platform is maintained with the support of the French Ministry for Higher Education and Research and hosts mainly French-language scientific journals in the spirit of open-access. Browsing through the many back issues gives one the opportunity to witness the changes of mineralogy from goniometers to the advent of the petrographic microscope to X-ray diffraction and the electron microscope. This is also the place where contributions to the first edition of the Experimental Mineralogy, Petrology and Geochemistry (EMPG) Symposium can be found, as can, at last, the proceedings of first International Eclogite Conference. Happy reading!
Professor Cheng is one of the top international scientists in quantitative geology and applied geochemistry. He has made fundamental contributions that have significantly advanced the theory of non-linear processes in the geosciences and in methods for modelling geochemical anomalies for mineral resources and environmental assessments. Professor Cheng’s research contributions to exploration geochemistry have been exceptional in his development of mathematical theory and in the application of unique methods for recognizing mineralized environments across a range of geochemical landscapes, sample media, and analytical methods. He has an exceptionally strong mathematical background and his research has resulted in a new paradigm for evaluating geochemical data through the use of non-linear mathematical methods combined with a deep understanding of geochemical processes.

Professor Cheng’s methodology of fractal analysis of geochemical responses has resulted in the discovery of several mineral deposits in China, and his name is synonymous with the application of fractal analysis to geochemical data. More recent innovations are the ‘local singularity analysis method’ for enhancing weak spatial signals in geochemical data and a new multifractal inverse distance model. These new methods improve on the recognition of geochemical responses, and his research has influenced the way mineral exploration companies conduct their exploration programs. Professor Cheng has worked closely with both the academic and mineral exploration and mining communities to share and implement his research methodologies. His seminal 1994 paper on the separation of geochemical anomalies from background by fractal methods (published in the Journal of Geochemical Exploration) has alone attracted over 860 citations. His productivity is reflected in his impressive publication record of some 280 journal papers, books, and book chapters, generally as lead or as corresponding author, of which more than 44 have been published in AAG-associated journals. Professor Cheng received the Andrei Borisovich Vistelius Research Award from the International Association for Mathematical Geosciences (IAMG) as a promising young scientist and, more recently, the William Christian Krumbein Medal, the highest honour bestowed by the IAMG. He is also the first Fellow of the AAG to ascend to the Presidency of the International Union of Geological Sciences (IUGS). Significantly, he has been a mentor and supervisor to 55 graduate students at both York University (Canada) and the China University of Geosciences.

**Qiuming Cheng, AAG 2020 Gold Medal**

The Association of Applied Geochemists (AAG) is pleased to announce that the 2020 Gold Medal for outstanding contributions to exploration geochemistry is awarded to Professor Qiuming Cheng of Sun Yat-sen University in Zhuhai City and of the China University of Geosciences in Beijing (China).

Professor Cheng completed his PhD in Earth sciences at the University of Ottawa (Canada) in 1994, following undergraduate and MSc degrees at the Changchun University of Earth Sciences (China). After a decade-long professorship at York University in Toronto (Canada), in 2004 he became a founding Director of the State Key Laboratory of Geological Processes and Mineral Resources at the China University of Geosciences in Wuhan and Beijing. Presently, he is a full professor at the School of Earth Science and Engineering at Sun Yat-sen University and at the Faculty of Earth Science and Resources at the China University of Geosciences.

The following abstract is for an article that appeared in issue 190 (February 2021) of the Explore newsletter.

**Sinclair: Australia’s First Caesium Deposit: Discovery and Exploration Implications**

Nigel W. Brand1,2,3, David J. Crook4, Stuart T. Kerr4, Sophie O. Sciaronne1, Naomi J. Potter1,3, Christabel J. Brand1 and Geoffrey E. Batt5

The Sinclair Caesium Deposit was discovered in 2016, delineated in 2017, developed in 2018, and is Australia’s first mining operation to commercially extract the caesium-rich mineral pollucite and represents a globally important discovery. Known economic caesium deposits are extremely rare, with only three known mining operations having reported commercial quantities of pollucite: the Bernic Lake Mine (Manitoba, Canada), Bikita Mine (Zimbabwe), and the Sinclair Mine (Western Australia). The formation of pollucite only occurs in extremely differentiated, complex lithium–caesium–tantalum (LCT) pegmatites. Given their size and rarity, caesium-rich deposits globally are either a challenge to find or simply ‘failed’ to form during the emplacement of a given LCT pegmatite. The discovery and development of the Sinclair Caesium Mine has provided a rare opportunity to examine an extremely differentiated, complex LCT pegmatite with applied technologies. This will provide insight for future exploration and discoveries of economic caesium deposits.

The following abstract is for an article that appeared in issue 191 (June 2021) of the Explore newsletter.

**Integration of Geochemical and Mineralogical Data: An Example from the Central Victorian Goldfields, Australia**

Dennis Arne6

The chemistry of most geological materials is determined by mineralogy. Therefore, the interpretation of total to near-total digest geochemical data is enhanced when integrated with mineralogical data. The latter includes quantitative X-ray diffraction (XRD) or hyperspectral (visible to near-infrared and shortwave infrared) data. Lithochemical analyses from the central Victorian goldfields (Australia) combined with mineralogical data provide an understanding of the processes involved in wallrock alteration associated with gold mineralisation. Ferroan carbonate minerals increase as mineralised structures are approached, while chlorite decreases at most deposits, with Bendigo being a notable exception. Detrital albite grains in sandstones are lost during progressive alteration and are replaced by muscovite. These systematic changes are accompanied by sulphidation of wallrock proximal to mineralised structures. Subtle differences in alteration style at different goldfields are likely due to variations in timing and relative charge of migrating fluids during the Silurian and Devonian. An understanding of wallrock alteration patterns at central Victorian goldfields allows vectoring towards mineralised structures during exploration drilling.

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2 Geophysical Services Pty Ltd, 5 Colin Street, West Perth, Western Australia, 6005
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4 Pioneer Resources Limited, 72 Kings Park Road, West Perth, Western Australia, 6005
5 Mineral Research Institute of Western Australia, 100 Plain St, East Perth, Western Australia, 6004
6 Telemark Geosciences, Yackandandah, Victoria, Australia, 3749
THE PRESIDENT’S CORNER

There have been a few changes in Clay Minerals Society (CMS) committee leadership after our recent council meeting in June 2021. The following committee chairs have recently completed their terms: Janice Bishop (Student Grants), Youjun Deng (Awards), Arek Derkowski (Council Nominations), Steve Guggenheim (Nomenclature), Andy Thomas (Finance and Budget), and Lynda Williams (Policy and Administration). Many thanks for your efforts! I would like to welcome the following new committee chairs: Dave Bish (Awards), George Christidis (Council Nominations), Wouter Ijdo (Finance and Budget), Sabine Petit (Policy and Administration and Vice-President Elect), Bruno Lanson (Nomenclature), and Andrew Madden (Student Grants). Your leadership on these important committees is greatly appreciated! I would also like to acknowledge outgoing council members Janice Bishop, Anke Neumann, Erwan Paineau, and Nik Qafoku and welcome new council members Liva Dzene, Cliff Johnston, Tsutomu Sato, and Marek Szczepan. Thank you for contributing to the governance of our society.

A special thanks goes out to our Past President, Bruno Lanson, for leading the CMS through such an unusual year. Bruno has been particularly active with CMS, including organizing the 2019 Annual Meeting as part of EuroClay. And Bruno’s activity continues as the new Chair of the Nomenclature Committee. Thanks, Bruno!

Finally, a reminder about the 2022 Annual Meeting, which will take place with the International Clay Conference on 25–29 July 2022 in Istanbul (Turkey). Please consider attending this meeting either virtually or in person. The abstract submission window is 1 October 2021 through 15 January 2022.

Jeffery Greathouse, CMS President

CMS STUDENT RESEARCH AWARD WINNERS

The following students received a 2021 Student Research Grant Award: Amal Kanti Deb, Anthony Feldman, Dorota Forfa, Simin Zhao, Okoroafor Chiemena, and Trevor Dempsey. Below, we feature a few of the winners and will continue to do so in the following issues.

Congratulations to Amal Kanti Deb from the University of Newcastle (Australia) and of the University of Dhaka (Bangladesh), Anthony Feldman, Department of Geosciences at the University of Nevada (USA), Dorota Forfa from Saint Mary's University in Halifax (Nova Scotia, Canada), and Simin Zhao from the Georgia Institute of Technology (USA), for each winning a 2021 CMS Student Research Grant!

Amal Kanti Deb studies the use of clay nanotube-supported metal nanoclusters for environmental applications. His project focuses on developing multifunctional, nontoxic and sustainable clay nanocomposites for environmental remediation. Biocompatible halloysite nanotubes (HNTs) have been inducting composited with ultra-small copper nanoclusters (CuNCs) following green chemistry principles. The synthesized material is used to degrade organic azo dyes and hexavalent chromium. The seeding of CuNCs onto other biocompatible clays is also under investigation to remove or degrade emerging micropollutants (per- and poly-fluoroalkyl substances and antibiotics). Future research will focus on biosensing, imaging, and fluorescence applications of developed CuNCs and clay-based hybrids.

Anthony Feldman’s current research interests lie in the areas of soil science, clay minerals, geochemistry, and planetary science. His dissertation involves investigations of weathering within terrestrial ultramafic soils to analyze the impacts of climate upon the development of Fe- and Mg-rich and Al-poor secondary amorphous material and minerals. Projects include bulk and micro scale investigations of the effects of climate, and microscale weathering environments on secondary mineral development in Fe-rich serpentinite soils. He also studies variations in incipient alteration of pristine olivine surfaces in natural and controlled settings.

Dorota Forfa’s CMS research grant will help her to differentiate between magmatic and meteoric fluids associated with the occurrence and origin of kaolinite in the ToBeatic Shear Zone. This zone is part of a major strike-slip fault in southwest Nova Scotia (Canada) along the contact of the South Mountain Batholith and its host Meguma metasedimentary rocks. Working with the support and guidance of Georgia Pe-Piper and David Piper, she plans to constrain the hydrothermal activity to develop a genetic model for the formation of kaolin in this terrain. In western Europe, where there is analogous mineralization in granites, much of the kaolin has been shown to be of supergene origin, but this has not been rigorously tested in Nova Scotia.

Simin Zhao’s research with Dr. Yuanzhi Tang focuses on authigenic clay mineral formation in marine sediments via the reverse weathering process. This process is critical in balancing the global silicon budget and regulating marine alkalinity and CO2 dynamics. Her research aims to better understand the geochemical factors, reaction mechanisms, and characteristics of the authigenic clay products of the reverse weathering process. She is very thankful to the CMS for supporting her research on authigenic clay minerals.

CMS NEWS EDITOR FOR ELEMENTS

The Clay Minerals Society is pleased to announce Bhabananda Biswas as the new CMS news editor for Elements. He will liaise with CMS leadership, office manager, and Clays and Clay Minerals’s managing editor to obtain information of interest to CMS members and other readers of Elements and arrange it for publication.

CMS MEMBERSHIP RENEWAL

Don’t forget to renew your membership!
EAG NEEDS YOU TO NOMINATE A COLLEAGUE FOR AN AWARD TODAY!
MESSAGE FROM THE EAG PRESIDENT

The European Association of Geochemistry (EAG) recognizes excellent contributions to the discipline of geochemistry and excellent contributions of all kinds. Our aim is fairness, equity, and diversity in our awards system, but some of these aims are hampered by a lack of nominations. **We need your help.**

As a member of EAG, you may not know so much about our awards system (but you can find out more here). I think this lack of familiarity contributes to a perennial problem that I would like to try to address here. The nomination process is completely open – the nominations come from you, the geochemical community. In fact, you don’t even have to be a member of the EAG to make a nomination. And the only people who can’t make a nomination are myself, my colleagues on the EAG Council, and members of the award committee for which the nomination is made.

We discuss the diversity of our awardees a lot on the EAG Council. There are a number of ways we can increase diversity, but I am convinced that a key issue is the lack of nominations. For example, on some of the awards committees that I have sat on, the only nominations we get are those that the committee members have themselves solicited. We don’t want it to be like this. We don’t want to be the only geochemists who are thinking about nominees – and then encouraging people in our network to make those nominations. And, it is not a *modus operandum* that encourages diversity. But if we did not do it, then we would literally get no nominations from our richly talented international community.

**So, my first message is: Help us out, get going and nominate someone this year!**

I know from discussions with some of you that there may be some barriers that stop you making nominations. Again, one of these is, I think, a lack of familiarity with...
the system – and again I would encourage you all to use the EAG website (https://www.eag.eu.com/awards/nomination/) to find out about what is, actually, a pretty simple process.

A second thing I have heard is that people are unsure, when they have made a nomination, how “good” it is, whether they have said or done the right things. While we notify all nominators whether their nominee has been selected or not, we can’t provide specific feedback about nominations. One of the reasons is that nominations stay active for three years and are automatically rolled over to the next year. But, I can tell you from experience that the nominations I have seen have been of consistently high quality – there just aren’t enough of them!

Maybe there is also some uncertainty out there about who can be nominated, and for what. We have added information to the award and nomination pages of our website on this. But, in brief, we consider the discipline of geochemistry very broadly, and anyone in any country who is making major contributions to that discipline can be nominated – they don’t have to be members of EAG, they can be from industry or government as well as academia. European Association of Geochemistry awards cover all career stages: there are awards for younger scientists, for mid-career researchers, and awards that recognize excellence over an entire career.

We have also added new information to our award pages on what kinds of activity we see as contributing to the bestowal of an award. We are a scientific society and our awards system is mostly about recognizing excellent science. However, we have asked our award committees to think about excellence broadly, and to consider outstanding contributions to teaching and training, major contributions to capacity building (particularly where that capacity is most lacking), excellent contributions to the geochemical community in terms of the administration of geochemistry in Europe and elsewhere, outstanding editorial contributions, particularly important work in outreach to the general public or engagement with policy makers. We have also asked them to consider the circumstances under which the science is achieved, and the different kinds of career paths that can all produce excellence.

Finally, I have heard that there is a feeling in the community that the awards system is some sort of “closed shop”, that awardees are somehow predetermined. In one sense there may be something in this: again, as I mentioned above, because of the lack of nominations from you our members, award committees have no choice but to go after them. Once the nominations are received, they are judged on the published criteria (which differ in their specifics between the different awards): there are no secret criteria. The award committees I have served on have been scrupulously fair with the nominations material they have in front of them. These award committees are made up of people in the geochemical community who give up their time to do it, for free. Only a small minority of these award committee members are on the EAG Council.

We think our awards system is open and fair. Help us out by making it more diverse and inclusive. Include yourself for a start, and make a nomination today!

See https://www.eag.eu.com/awards/nomination/.

Derek Vance
President of the European Association of Geochemistry

Do you have questions about your career in industry or academia, training opportunities, teaching methods, or outreach and DEI, or are you looking for advice on analytical methods, sampling, software, databases or resources? These are just some of the topics discussed recently on the EAG member forums.

Log into the EAG Membership platform today at https://members.eag.eu.com/members/ to visit the forums, share your experiences, ask a question, or subscribe to receive topic updates.
IAG HONORARY FELLOWSHIP AWARDED TO KLAUS PETER JOCHUM

The International Association of Geoanalysts (IAG) has pleasure in announcing that Dr Klaus Peter Jochum of the Max Planck Institute for Chemistry (Mainz, Germany) has been awarded the association’s highest award: IAG Honorary Fellowship. This award recognizes his decades-long distinguished and enormous contribution to many branches of the geoanalytical sciences.

Klaus Peter joined the Max Planck Institute for his Diploma thesis in 1966, became a staff member in 1972, and was awarded his PhD in 1973. His research interests include studies related to cosmochemistry, geochemistry, biogeochemistry, and climate geochemistry. In the laboratory, his motivation is to devise ways of improving analytical methods so that the most appropriate solution is found to solve a specific research problem.

He is still a very prolific and highly cited scientist, having published over 250 papers, many in high-ranking publications. From the beginning of his career, Klaus Peter has been engaged in developing analytical methods centred around the application of mass spectrometry to geological materials. For many years, these methods involved elemental analysis by spark source mass spectrometry (SSMS) before he moved to laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). As he was always keen on in situ analysis, he developed an automated iridium-strip heater to facilitate the melting of small amounts of rock powder in the preparation of glass beads for whole rock analysis by LA-ICP-MS. His numerous publications on nanosecond LA-ICP-MS and femtosecond LA-ICP-MS reflect his passion for LA-ICP-MS applications.

Besides implementing new analytical methods, one of his most significant achievements was the development of the GeoReM database, which was launched in 2005. This includes data on more than 3,780 geological and environmental reference materials and is an invaluable source of information for many geoanalysts. So far, over 565,000 queries have been recorded from all over the world.

In addition to compiling data on reference materials measured by other scientists, Klaus Peter has also been active in developing and characterizing reference materials required to shed light on many analytical problems in the Earth sciences. Over his long career, he established worldwide cooperations with researchers from other disciplines, including biology, chemistry, archaeology, and the environmental sciences. Some of these became close friends. Moreover, Klaus Peter always felt it was crucial to encourage and support young scientists at the start of their career. Many of the PhD and postdoctoral students that he mentored have now become successful researchers in their own chosen field of science.

Klaus Peter joined the IAG during the Geoanalysis 2006 conference in Beijing (China) and served as a member of the IAG Council between 2007 and 2017. He continues to be a strong supporter of our association and promotes its aims whenever possible.

Those who have met him personally know that his profession was always more like a hobby to Klaus Peter. Although he officially retired in 2008, Klaus Peter has continued to work intensely at the Max Planck Institute.

We are planning to make a formal presentation of the IAG Honorary Fellowship to Dr Jochum at the next Geoanalysis Conference in Freiberg (Germany) in August 2022.

Regina Mertz-Kraus
Jacinta Enzweiler

WINNERS OF THE IAG YOUNG SCIENTIST AWARD FOR 2021

We are proud to announce that the winners of the 2021 IAG Young Scientist Award are Alicja Wudarska (Warsaw, Poland) and Tao Luo (Wuhan, China). They presented their research at the 2021 virtual Goldschmidt conference (4–9 July) and also received their IAG awards. For more information, see the awards page at https://goldschmidt.info/2021/medalsView.

Alicja Wudarska is a postdoctoral researcher at the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw. She develops new reference materials for the isotopic analysis ofapatite using secondary ion mass spectrometry (SIMS). She has recently completed two projects related to chlorine and oxygen isotopes that she conducted in collaboration with the SIMS laboratory at the GFZ Potsdam (Germany). The results of her work were published this year in Geostandards and Geoanalytical Research (Wudarska et al. 2021), and the metrological splits of the apatite samples described therein can be obtained through IAGEO Limited (iageo.com). Currently, Alicja and her team from the SIMS laboratory in Warsaw are working towards developing reference material(s) for the U–Pb dating of apatite. Her project is being supported by an IAG Geoanalytical Research and Networking Grant.

Alicja undertook the study of new apatite reference materials in order to collect the SIMS data for her PhD project, which investigated the geochemical processes that shaped the early Archean Isua Supracrustal Belt (SW Greenland) by making hydrogen and chlorine isotope measurements in minerals of the apatite group (Wudarska et al. 2020). She is now planning to apply stable isotope analyses to bioapatite research and is especially interested in the application of these methods to wildlife conservation.

When Alicja is not working, she enjoys exploring the world with her husband, as well as gardening, crafts, and reading about Australian wildlife.


Cont’d on page 353
JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES

Takashi Mikouchi is a professor at the University Museum of the University of Tokyo. He specializes in the mineralogy and crystallography of extraterrestrial materials, especially differentiated meteorites and spacecraft returned samples. He began his academic career by studying meteorites at the University of Tokyo, researching angrites (one of the oldest known achondrites) in collaboration with researchers at NASA’s Lyndon B. Johnson Space Center (Texas, USA), and soon became involved in the study of Martian meteorites. Since then, he has collaborated with researchers from Japan, the USA, and Europe, and he combines isotopic and chemical data with his mineralogical and crystallographic work for various extraterrestrial materials. In his early work, Takashi Mikouchi used crystallization experimental results to deduce that some shergottite Martian meteorites had experienced magma undercooling and that they represented parent magma compositions. He also revealed that nakhlite Martian meteorites had a petrography and mineralogy that could be explained by crystallization at different burial depths in a common cooling cumulate pile. His study of angrites pointed out the importance of olivine xenocrysts in quenched angrites and showed that bulk compositions of quenched angrites were controlled by resorption degrees of these xenocrysts. He is one of the first meteoriticists to apply electron backscatter diffraction (EBSD) analysis to characterize new minerals in meteorites, and he and his coworkers found several new minerals by this technique, such as dimitryvanovite, andreyivanovite, and kushiroite. He has also been involved in studying particles from comet Wild 2 and particles from the Itokawa asteroid, strengthening the interpretations of the origins of these bodies by using electron beam and synchrotron radiation analyses. At present, as a preliminary analysis team member, he is analyzing Ryugu samples returned by the Hayabusa2 spacecraft.

Takashi Mikouchi has, thus, made many major contributions to our understanding of the formation processes and evolution of solid materials in the early Solar System, as well as in large bodies such as Mars and the Moon.

JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES

AWARD TO TATSUKI TSUJIMORI

Tatsuki Tsujimori is a professor of geological sciences at Tohoku University’s Center for Northeast Asian Studies. His PhD was supervised by Prof. Akira Ishiwatari at Kanazawa University and was awarded in 1999. He then completed post-doc fellowships at Okayama University of Science (2000–2002) and Stanford University (California, USA) (2002–2006). From 2006 to 2015, he was a faculty member of Okayama University at Misasa and has been a Tohoku University faculty member since 2015. Prof. Tsujimori’s research specialties are in the fields of petrology and tectonic processes, with a particular emphasis on high-pressure–ultrahigh-pressure (HP–UHP) metamorphic rocks, such as blueschists, eclogites, and jadeitites. His early research focused on the petrotectonic characterization of the Japanese Paleozoic serpentinite-matrix mélanges that enclose blocks of various HP metamorphic/metamorphic rocks. As a part of this research, he reconstructed the fossilized mantle wedge–slab interface that contained blueschist, jadeite, and a newly discovered eclogite. Since joining Tohoku University, his research program has focused on better understanding the geodynamic and geochemical processes of Proterozoic and Phanerozoic active convergence margins at different scales as deduced from mineral equilibrium up to plate tectonic levels. Additionally, his work seeks to link the HP–UHP metamorphism of ancient subduction zones to geophysical observations of modern analogs by evaluating hydration and dehydration from within the subduction interface and the subsequent slab–mantle interactions.

Prof. Tsujimori has an extensive record of research in metamorphic petrology, geochemistry, and tectonics, including collaborative research projects with local (Japanese) and overseas researchers, such as Tetsumaru Itaya, J.G. Liou, Gary Ernst, Ruth Zhang, George Harlow, Sorena Sorensen, Jinny Sisson, Bob Stern, and the late Bob Coleman. Also, as a faculty member of Okayama University’s International
Joint Usage/Research Center, he was involved in numerous scientific research exchanges and academic cooperation programs that included many visiting overseas scholars and student intern participants. Prof. Tsujimori was named a 2013 Mineralogical Society of America Fellow and a 2014 Geological Society of America Fellow as a result of his valuable contributions to the field metamorphic petrology. His ongoing research into lawsonite eclogites and jadeitites has had a significant influence on the geoscience community. Most notably, his research has led, in part, to the designation by JAMS of jadeite as the national stone of Japan. Currently, Prof. Tsujimori is the Editor-in-Chief of the journal Island Arc and sits on the editorial boards of several scientific journals.

**MANJIRO WATANABE AWARD TO TADATO MIZOTA**

Tadato Mizota received his doctor of science degree in 1977 from Tohoku University; his thesis title was, “The Transformation of Cubanite”. The research theme of cubanite (CuFe2S3) had been first suggested by Prof. Nobuo Morimoto while Mizota was at Osaka University, but the research was only completed when Mizota became a lecturer at Yamaguchi University, being supervised there by Prof. Ichiro Sunagawa of Tohoku University.

His research interests cover three categories. The first is of the X-ray crystal structure analysis of minerals. He, along with Dr. Masayuki Komatsu and Prof. Kazuya Chihara, found the new mineral omilite at Ohmi (Niigata Prefecture, Japan) and they determined and refined the crystal structure by means of X-ray diffraction. The second area of research is the calorimetry of minerals. Mizota made an original adiabatic calorimeter for measuring heat capacity at temperatures from room temperature to 600 °C. The heat capacity associated with a thermal anomaly around the irreversible phase transition of cubanite was thereby clarified. The third interest is in developing an adiabatic hydration calorimeter and a zeolite heat-pump. So-called zeolitic water is generally considered to be in an energetic state, analogous to the states between free water and ice. Mizota developed an adiabatic hydration calorimeter and clarified that the entropy values of zeolitic water are extremely low compared to such values of water at temperatures near 0 K. He applied this phenomena to develop a “zeolite heat-pump” and succeeded in making ice by using heat sources in the temperature range between 25 °C and 100 °C.

After retiring, he has been working as a volunteer member in three organizations: the Ube Network for Climate Change Actions; the non-profit company Civic Cooperative Power-Generation Ube; and the Ube Boys and Girls Invention Club. In addition, Mr. Poulin is an active member of the geological community and has been a reviewer of many submissions to various journals (e.g., Ore-Geology Reviews, American Mineralogist, and Geochemistry: Exploration, Environment, Analysis). Within the MAC framework, he has been the Financial Chair (2018–2020), is the Chair of the Student Travel Grants and Awards, and is Chair of the MAC Scholarship Committee. He has also served as a member on various other committees, including those for the Hawley Medal, Berry Medal, and Pinch Medal.

**JOURNAL OF MINERALOGICAL AND PETROLOGICAL SCIENCES**

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**Original Articles**

Crystal structure refinement and crystal chemistry of parasymplesite and vivianite – Hidetomo HONGI, Akira YOSHISHA, Ginta KITAHARA, Yumiko MIYANO, Karin HAN, Koichi MOMMA, Ritsuro MIYAWAKI, Makoto TOKUDA, Kazumasa SUGIYAMA

SiO4 network structure changes and crystallization of diatom shells in diatomaceous earth by heat treatment – Naoyu SASAKI, Akane ARASUNA, Masayuki OKUNO

Synthesis of transparent polycrystalline jadeite under high pressure and temperature – Keisuke MITSU, Tetsuo IRIFUNE, Hiroaki OHFUJI, Akihiro YAMADA

Study on magnetite oxidation using synchrotron X-ray diffraction and X-ray absorption spectroscopy: vacancy ordering transition in magnetite (α-Fe2O3) – Ibuki KINEBÜCHI, Atsushi KYONO

U-Pb geochronology, REE and trace element geochemistry of zircon from El Fereyid monzogranite, south Eastern Desert, Egypt – Sergey G. SKUBLOV, Ahmad E. ABDEL GAWAD, Ekaterina V. LEVASHOVA, Mohamed M. GHONEIM

**A WARM WELCOME TO OUR NEW COUNCIL MEMBERS**

**Treasurer**

The Mineralogical Association of Canada (MAC) Executive has approved the nomination of the following candidate for the treasurer position. As no additional nominations were received from the membership, the nominated candidate was declared elected by acclamation.

**Mr. Rémy Poulin** (LabMaTer à l’Université du Québec à Chicoutimi)

Rémy is currently the laboratory manager of LabMaTer at the University of Québec à Chicoutimi (Canada). He obtained his BSc with Honours in geology from the University of Ottawa (Canada), followed by an Earth sciences MSc from Laurentian University (2016) in the field of applied mineralogy. From 2017 to 2021, he was a sessional lecturer and research scientist at the Harquail School of Earth Sciences (Laurentian University, Canada) where he taught mineralogy, geochemistry, and supervised undergraduate theses. Mr. Poulin is an applied mineralogist and has been involved in numerous projects, focusing on the development of analytical methods (trace elements, cathodoluminescence) and the application of mineral chemistry to investigate complex geologic processes in a wide variety of earth systems. Recently, Mr. Poulin has published a series of articles in The Canadian Mineralogist and was the recipient of the 2018 Hawley Medal for his work on scheelite (“Assessing scheelite as an ore-deposit discriminator using its trace-element and REE chemistry”). In addition, Mr. Poulin is an active member of the geological community and has been a reviewer of many submissions to various journals (e.g., Ore-Geology Reviews, American Mineralogist, and Geochemistry: Exploration, Environment, Analysis). Within the MAC framework, he has been the Financial Chair (2018–2020), is the Chair of the Student Travel Grants and Awards, and is Chair of the MAC Scholarship Committee. He has also served as a member on various other committees, including those for the Hawley Medal, Berry Medal, and Pinch Medal.

**Financial Chair**

The MAC Executive appointed the following candidate for the position of Financial Chair.

**Mr. David McDonald** (Canada Revenue Agency)

David is currently an Assessments, Accounts and Benefits Processing Officer with the Canada Revenue Agency. He graduated Cum Laude with a BA in economics from Laurentian University in 2019. His specialisation was applied economic theory, culminating in an undergraduate thesis under the supervision of Dr. David Leadbeater. This work, entitled “Examination of Employee and Salary Structures at Laurentian University: A Case Study Regarding the Rise of Corporate Managerialism in Ontario Public Universities” examined salary stratification between administration and faculty, as well as the negative effects of inflation and other systemic issues regarding faculty salaries, workloads, and remuneration systems. He began his work as a tax officer in 2017, where he analysed, verified, and processed reassessments related to the T1 general return. After becoming a senior processing officer for complex cases in late 2017, he specialised in bankruptcies, foreign tax treaties, complex capital gains, as well as separation/divorce agreements. With an exhaustive knowledge of the Income Tax Act, as well as federal and provincial tax legislation, he opened a financial services company, with a focus on retirement planning and targeted investment strategies for middle-class individuals. He then accepted a position as the Collection Support Unit Manager for the Central Region on behalf of Statistics Canada’s 2021 Census. As the Collection Support Unit Manager, he managed
MAG TRAVEL AND RESEARCH GRANT AWARD DELAYED BY COVID-19

The Mineralogical Association of Canada awarded the student travel and research grants in 2019 but the project was postponed to 2021 due to the pandemic situation. Congratulations to Malcolm Hodgskiss, a deserving student! Excerpts of his report follows.

Malcolm Hodgskiss is a recent PhD graduate from Stanford University (California, USA) and was supervised by Dr Erik Sperling. Support from the MAC allowed Malcolm to carry out four weeks of field research on sedimentary carbonates of the Paleoproterozoic Mistassini Group in northern Quebec, with the assistance of Max Leech and Maggie Whelan (McGill University, Canada). This project will combine field observations and stable isotope ratio analyses to better understand the Earth system ~2.05–1.80 Ga and will complement the field/geochemochemical work Malcolm carried out in other similarly aged successions during his PhD, including the Belcher Group, Nastapoka Group, Labrador Trough (all in Canada), and the Peräpohja Schist Belt (Finland). Understanding this time interval is important because it records the tail end of Earth’s largest carbon isotope excursion, the initial assembly of Earth’s first supercontinent, and one of the last major episodes of iron formation deposition. Special thanks are also given to the Cree Nation of Mistassini for permission to carry out this work on their ancestral lands. This work was planned to have been part of Malcolm’s PhD thesis but had to be delayed due to COVID-19.

HALIFAX 2022 GAC–MAC–IAH–CNC–CSPG JOINT MEETING
15–18 May 2022
Halifax Convention Centre, in Halifax (Nova Scotia, Canada)

“Riding the Waves of Change” / “Surfer sur la vague du changement”

Join us in Halifax from 15 to 18 May 2022 for the Annual Meeting of the Geological Association of Canada (GAC), Mineralogical Association of Canada (MAC), the International Association of Hydrogeologists – Canadian National Committee (IAH–CNC), and the Canadian Society of Petroleum Geologists (CSPG). This meeting coincides with the 50th anniversary of the Atlantic Geoscience Society, the conference host organization. The conference promises a diverse program, including symposia and special sessions, field trips, and short courses related to a wide variety of geoscience disciplines in a hybrid format with in-person and virtual components.

Abstract Submissions: November 2021 to January 2022. The deadline for abstracts will be Friday, 28 January 2022. Get more info or submit your abstract at halifax2022.atlanticgeosciencesociety.ca

See you in Halifax!

UNDERGRADUATE AWARDS 2020–2021

The Mineralogical Association of Canada Undergraduate Student Awards are given annually to undergraduate students (2nd year of study or higher) at a recognized Canadian university or institute of higher education for excellence in one of the specialties supported by the society: mineralogy, crystallography, geochemistry, petrology, or mineral deposits. Congratulations to the following students who received this award in 2020–2021:

- Kevin Bossé (University of British Columbia)
- Faith V. Crawley (University of Windsor)
- Emily Darling (Queen’s University)
- Leah S. Davis-Purcell (Western University)
- Erin Hilliard (Dalhousie University)
- Thomasina M. Kastendieck (University of Alberta)
- Michael T. LeBlanc (St. Francis Xavier University)
- Nathan Alexander Logan (University of British Columbia, Okanagan)
- Nickolas Mesich (University of Waterloo)
- Nicholas O. Montenegro (University of Regina)
- Rowan Perrott (Laurentian University)
- Brayden M. Peterson (Trent University)
- Brett Skalicky (University of Calgary)
- Jessica Tomacic (Carleton University)
- Eleanor Winger (Lakehead University)
- Gina L. Yockell (Brock University)

MAC AWARDS – CALL FOR NOMINATIONS

Peacock Medal
The Peacock Medal is awarded to a scientist who has made outstanding contributions to the mineralogical sciences in Canada. There is no restriction regarding nationality or residency. The medal recognizes the breadth and universality of the awardee’s contributions to mineralogy, applied mineralogy, petrology, crystallography, geochemistry, or the study of mineral deposits.

Young Scientist Award
This award is given to a young scientist who has made a significant international research contribution during the early part of their developing scientific career. The scientist will have received his/her PhD not more than 15 years before the award. The scientist will have received his/her PhD from a Canadian university or a Canadian university working anywhere in the world or a scientist of any nationality working in Canada. The research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits, or related fields of study.

Leonard G. Berry Medal
The Leonard G. Berry Medal is awarded annually for distinguished service to the association. The award recognizes significant service to the association in one or more areas that may include leadership, or long-term service in an elected or appointed office or an important contribution(s) that enhances the mineral sciences in Canada or broadens the Canadian mineralogical perspective. The medal is named after Leonard G. Berry (1914–1982), a founding member of MAC, editor for 25 years of The Canadian Mineralogist and its predecessor, and first winner of MAC’s Past-Presidents’ (now Peacock) Medal.

Nominations for the 2022 medals and award are to be submitted to Andrew M. McDonald (Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada); E-mail: amcdonald@laurentian.ca

Check our website, www.mineralogicalassociation.ca, for additional details.
2022 ANNUAL METSOC MEETING – YOUR INVITATION TO GLASGOW (AGAIN!)

You are cordially invited to attend the 85th Annual Meeting of The Meteoritical Society (MetSoc), which will take place 14–19 August 2022 at the Scottish Event Campus in Glasgow (Scotland, UK). The meeting is hosted by the University of Glasgow planetary science research group.

Some people may require a visa to visit the United Kingdom. To find out whether you need a visa, and how to apply, see the UK Visas and Immigration website: https://www.gov.uk/check-uk-visa.

Oral and poster sessions, plenary sessions, and the Barringer Invitational Lecture, will take place within the Loch Suite of the Scottish Event Campus: https://www.sec.co.uk/organise-an-event/event-spaces/loch-suite.

Conference registration and the Welcome Reception will begin at 5 pm on Sunday, 14 August 2022 at the Hunterian Museum (https://www.gla.ac.uk/hunterian/), which is housed within the historic main building of the University of Glasgow.

On Monday night, the City of Glasgow offers you all a warm welcome. The city are providing a free welcome drinks reception for all the MetSoc delegates where a representative of the city’s Lord Provost (Mayor) will personally attend to welcome us. This will be hosted in the Glasgow City Chambers, Glasgow’s finest example of 19th Century architecture, located in the heart of George Square in the city centre.

On Wednesday (17 August 2022), excursions will be offered both within the city and exploring the neighbouring countryside.

The Conference Banquet with ceilidh will be held on Wednesday night at the magnificent Kelvingrove Art Gallery and Museum, the UK’s national museum of Scottish art located in the heart of George Square in the city centre.

For hotels a little further away, public transport in Glasgow is generally good rail, subway, and bus links. Some people may require a visa to visit the United Kingdom. To find out whether you need a visa, and how to apply, see the UK Visas and Immigration website: https://www.gov.uk/check-uk-visa.

Society News

2021 ANNUAL MEETING TRAVEL AWARD WINNERS

The Meteoritical Society would like to congratulate the winners of awards for travel to the 84th Annual Meeting in Chicago (Illinois, USA). We would also like to thank the sponsors of these awards who every year enable students, early career researchers, and researchers from low-income nations to travel to annual meetings in order to facilitate career-enhancing interactions with a wide array of international society members.

Elsevier Early Career Award: Jens Barosch and Bidong Zhang.

O. Richard Norton Award: Simon Anghel, Ioannis Baziotes, Mark Boyd, Emilie Dunham, Yankun Di, Timothy Hahn, and Zoltan Vaci.

Darryl Pitt/Macovich Collection Award: Virgile Malarewicz.

Meteoritical Society Travel for International Members Award: Hasnna Chennouai Aoudjehane


CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the MetSoc’s awards. Nominations should be sent to Secretary Munir Humayun (metsocsec@gmail.com) by January 15 (January 31 for the Service Award and the Pellas–Ryder Award). For more information and details on how to submit a nomination for any of these awards, please see the latest newsletter at the society’s website or e-mail the secretary.

The society gives a number awards each year. The Leonard Medal honors outstanding contributions to the science of meteoritics and closely allied fields. The Barringer Medal and Award recognizes outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The Nier Prize recognizes outstanding research in meteoritics and closely allied fields by young scientists. The Service Award honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science in ways other than by conducting scientific research. The Paul Pellás–Graham Ryder Award is given for the best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America. The newest society award, the Elmar Jessberger Award, will be given to a mid-career female scientist in the field of isotope cosmochemistry.

CORRECTION

In the April 2021 Meteoritical Society news page of Elements, the following committee members for the Nomenclature Committee were inadvertently omitted: Cyrena Goodrich (Lunar and Planetary Institute, USA), Juliane Gross (Rutgers University, USA), and Ansgar Greshake (Museum für Naturkunde Berlin, Germany). These three are the newest members of the committee. Emma Bullock, Viniciare Deballa, and Hasnna Chennouai Aoudjehane rotated off as of January 2020. In addition, Miao was incorrectly listed with Universität Muenster (Germany) as his affiliation: his correct affiliation is with the Guilin University of Technology (China).
Florence Bascom, one of the most prominent female geologists of the 20th century, in Munich (Germany). In 1914, she invited her to work in his lab in London. There she worked on the synthesis of crystals of new ionic compounds and studying the effect of changes in cation identities on the crystal form. The work was published in the Mineralogical Magazine in 1912 with Alfred Tutton (1864–1938), who later introduced Polly to Prof. Sir Henry Miers (1858–1962), a Professor of Mineralogy at the University of London. He asked Porter if she would be interested in working on the Corsi Marble Collection in Oxford, which continues today (and which is to be addressed by actions taken following our survey).

Porter was key to bringing women into British X-ray crystallography (https://www.nature.com/articles/nchem.2067), that which is to be addressed by actions taken following our survey).

Porter’s repeated visits to the Corsi Marble Collection in Oxford were noted by Sir Henry Miers (1858–1962), a Professor of Mineralogy at the University of London. There she worked on the synthesis of crystals of new ionic compounds and studying the effect of changes in cation identities on the crystal form. The work was published in the Mineralogical Magazine in 1912 with Porter as co-author.

Porter also worked on the mineral collection at the Smithsonian Institution (Washington DC, USA) and on the Mineralogical State Collection in Munich (Germany). In 1914, Florence Bascom, one of the most prominent female geologists of the time, who had befriended Porter, arranged for the German mineralogist and crystallographer Victor Goldschmidt, then at the University of Heidelberg (Germany), to hire Porter as a research student. Goldschmidt noted that Porter’s research work was “outstanding”.

Back in the UK in June 1918, Porter received her BSc certificate, though not as a formal degree because these were barred to women until 1920! At the same time, she was elected to the council of the Mineralogical Society. Porter conveyed the news to Bascom: “There was a great row about having a woman on it but the majority agreed in the end.” Porter was awarded a DSc degree in 1932 as a result of her crystallographic studies and publications.

Polly became an honorary research fellow at the University of Oxford in 1948. It has been suggested by Michelle Franci, in a 2014 article on women in crystallography (https://www.nature.com/articles/nchem.2067), that Porter was key to bringing women into British X-ray crystallography.

The full version of this tribute is published as the first paper of the special issue: doi: https://doi.org/10.1180/mgm.2021.52.1.

- Ekaterina P. Reguir, Ekaterina B. Salnikova, Panseok Yang, Anton R. Chakhmouradian, Maria V. Stiveeva, Irina T. Rass and Aleksandr B. Kotov: “U–Pb geochronology of calcite carbonatites and jacupirangite from the Guli alkaline complex, Polar Siberia, Russia”
- Roger H. Mitchell and J. Barry Dawson: “Mineralogy of volcanic calciocarbonatites from the Trig Point Hill debris flow, Kerimasi volcano, Tanzania: implications for the altered natrocarbonatite hypothesis”
- Maria A. Sitnikova, Vicky Do Cabo, Frances Wall and Simon Goldamnn: “Burbankite and pseudomorphs from the Main Intrusion calcite carbonatite, Lofdal, Namibia: association, mineral composition, Raman spectroscopy”
- Loic Y. Le Bras, Robert Bolhar, Lunga Bam, Bradley M. Guy, Grant M. Bybee and Paul A.M. Nex: “Three-dimensional textural investigation of sulfi de mineralisation from the Loelekop carbonate–phoscorite polyphase intrusion in the Phalaborwa Igneous Complex (South Africa), with implications for ore-forming processes”

A full list of contents in this issue is available at: https://www.cambridge.org/core/journals/mineralogical-magazine/issue/F5FA1FCE7621E77A195A9E4160602E33

MINERALOGICAL MAGAZINE – RECENT NEW CONTENT
**Permian Crustal Differentiation**
Partial melting in both the asthenosphere and the lower crust and the ascent of mafic and silicic magmas emplaced at different crustal levels are among the main processes leading to crustal differentiation in Southern Europe during the Permian. Widespread magmatic activity accompanied by high-temperature metamorphism affected the Alpine realm during the Permian and is preserved in both the Adriatic and European domains. The Permian age of these crust-forming processes and their geochemical signatures have been constrained in the Austroalpine Domain (Pohorje Mountains, Slovenia: Chang et al. 2020; Grobgneis Complex: Yuan et al. 2020); in the Sesia-Dent Blanche Nappes (Vho et al. 2020); in the Briançonnais Domain (Baillevere et al. 2020); as well as in Corsica, Sardinia, and Calabria (Di Rosa et al. 2020; Molli et al. 2020). In a few cases, Triassic ages for allanite from Sesia (Vho et al. 2020) and Corsica (Di Rosa et al. 2020) have been interpreted as potential records of further metasomatic/magmatic episodes during late Triassic extension.

**Inherited Pre-Alpine Structures**
The Permian crustal differentiation was associated with an extensional/transcurrent regime responsible for the development of large-scale (i.e., hundreds of km long) faults (e.g., Santa Lucia Fault in Corsica and East Tuscan Fault in Central Italy) (Molli et al. 2020). During the Jurassic Period, normal faulting is recorded in the brittle upper crust, especially along the internal margin of the Briançonnais Domain. Faulting is associated with the erosion of uplifted blocks, leading to syn-tectonic erosion that provided abundant material for the nearby sedimentary basins (Pantet et al. 2020).

**Age and Architecture of the Alpine Ophiolites**
Alpine ophiolites of the Piemonte–Liguria Ocean result from the mid-Jurassic breakup of the thinned continental crust and represent ancient analogues to present day (ultra-)slow-spreading environments, such as the Southwest Indian ridge. In the Western Alps, Piemonte–Liguria ophiolites are made of dismembered slivers dominated by variably serpentinised mantle rocks with minor basaltic dykes and small gabbro intrusions (Decrausz et al. 2021). New field, geochemical, and isotopic data constrain the evolution of the Aiguilles Rouges Ophiolite in the Swiss Alps (Decrausz et al. 2021). This area is an exceptional exposure that shows an inherited seafloor sequence and the remnants of a large Upper Jurassic (~155 Ma) gabbro body potentially exhumed by a Jurassic detachment fault. As observed in present-day (ultra-)slow-spreading seafloor, the Aiguilles Rouges Ophiolite preserves a segmented lithosphere showing punctuated magmatism and carbonated ultramafic seafloor covered by basalts and Jurassic tectono-sedimentary deposits. Oceanic hydrothermal alteration affected the exhumed mantle and produced a pervasive serpentinization and rodgingitisation of mafic dykes, as observed in several oceanic units in the Alps (e.g., the Zermatt Zone) (Kempf et al. 2020).

**From Oceanic Subduction to Crustal Thickening**
During the convergence of Eurasia and Adria, the fate of the Jurassic extensional faults was two-fold: some were reactivated as thrusts by Alpine tectonics (Aiguilles Rouges d’Arolla Ophiolite) (Decrausz et al. 2021) whereas others were passively deformed without inversion and reactivation (Mont Fort Nappe, Briançonnais Domain, Pantet et al. 2020; eastern Aar Massif, Nibourel et al. 2021). The identification of faults that preserve their Jurassic rift-hinging history is an important step in our understanding of the geometry of the Briançonnais palaeomargin.
Subduction and high-pressure metamorphism of some ophiolitic units was associated with dehydration reactions and fluid release. Indeed, in the Zermatt–Saas Ophiolite, serpentine + brucite formed during Jurassic oceanic serpentization and reacted to produce metamorphic olivine at eclogite facies conditions (Kempf et al. 2020). Fluids released by this reaction (estimated at between 3.4 and 7.2 wt% H2O) escaped in a network of veins and shear zones.

More external continental domains of the Western Alps were buried at shallower depth (External Briançonnais, Ballèvre et al. 2020; Aar Massif, Nibourel et al. 2021). Lawsonite-bearing veins in the Guil andesites in the Queyras testify to a lower grade metamorphism (0.4 GPa, 350 °C) associated with a brittle deformation in the External Briançonnais (Ballèvre et al. 2020).

In the external domain of the Alps in the eastern Aar Massif, collisional deformation started with the activation of NNW-directed thrusts at ~26 Ma (Nibourel et al. 2021). Subsequent peak- to post-metamorphic deformation was dominated by steep, NNW-vergent reverse faults (~22–14 Ma) and was associated with large vertical displacements. Some 13 km shortening and 9 km exhumation occurred between 14 Ma and present.

**Exhumation of the Nappe Stack**

Exhumation of the Alpine nappe stack was accommodated by erosion, material transport, and sediment deposition in the flysch sequences, which has now been analyzed in detail in one of the Préalpes nappes, (Ragusa et al. 2021) and by displacement along kilometre-scale Alpine faults in, for example, the Susa Shear Zone (Ghignone et al. 2020) and the Rocca Canavesse Thrust Sheets (Roda et al. 2021).

Cenozoic tectonic activity during the unroofing of the Western Alps was active for more than 20 million years and was linked to top-NNW, top-WNW and top-SW thrusting associated with strike-slip faulting. Its timing is constrained by new geochronological data (~36 Ma, ~32–30 Ma, and ~25–23 Ma) on hydrothermal monazite in fissures formed during greenschist to amphibolite facies retrograde metamorphism in the high-pressure units of the internal Western Alps (Ricchi et al. 2020).

Daniel Marty, Chief Editor Swiss Journal of Geosciences

Daniel Marty completed a master’s degree in Earth sciences at the University of Basel (Switzerland) in 2001 and his PhD in palaeontology/sedimentology at the University of Fribourg (Switzerland) in 2008 focusing on Upper Jurassic dinosaur footprints excavated on Swiss federal Highway A16 and neo-ichnological experiments with human footprints on recent tidal flats.

From 2000 to 2017, he worked as a research palaeontologist at the “Paleontology A16” (Office de la culture, Canton Jura, Switzerland), a unique palaeontological service founded in 2000 that was in charge of the excavation, documentation, and safeguarding of palaeontological heritage along the future course of Highway A16. Daniel was responsible for the excavation, documentation, and scientific research of dinosaur track sites that were uncovered prior to the construction of the highway. He is still involved in research projects related to these and other dinosaur footprint discoveries in collaboration with researchers from Europe and elsewhere.

Since 2014, Daniel Marty has taught palaeontology courses at the University of Basel. In 2014, he became Chief Editor of the Swiss Journal of Palaeontology and in 2018 also of the Swiss Journal of Geosciences. Both journals are published as fully open access by SpringerOpen.

Contact: martydaniel@hotmail.com

**EDITORIAL**

About the Overplayed Role of Citation Indicators

The last 20 years has seen the relationship between scientists and scientific publications change dramatically. In this editorial, I will address the expanding and overplayed role of the citation indicators on the publication system. I do not speak of journal impact factors, because they deserve an editorial of their own, but I will focus on the impact of an individual paper’s citation index and the challenge that this presents to editors.

Authors have all been affected by the change in value of publications, far from the genuine and simple goal of sharing scientific knowledge. We are now much more conditioned by citation indexes than we have ever been. When I ask myself, as an author, which paper(s) I feel proudest of and which are the most important for me, several of them do not match those that are most cited. I presume that this situation is also the case for other authors and their papers. Often, authors assessing their own papers do not focus only on their potential impact in the field. They assess also the quality and completeness of the scientific approach developed. Authors take into account how the work evolved from the intuition of the hypotheses to the final demonstration of their validity.

Citation indicators basically and simply assess the visibility of a paper, which is far from being a perfect evaluation of the paper’s influence or impact in the field. Notwithstanding, today more than ever, we all look at our paper citations as a form of quality indicator of our work. In addition, our careers are partly evaluated and fundamentally influenced by these citation indicators. Consequently, we allow citation indicators to influence the way authors write papers and the way reviewers evaluate them. As authors, we have (consciously or unconsciously) a tendency to over-cite our previous papers when we write a new one. As reviewers, we may have the tendency to be more favorable toward a paper that cites our articles, or even recommend authors to cite our articles. But is this unethical or a conflict of interest?

Conflict of interest is defined by the potential benefit evaluators can get from their evaluation. The strong role played today by citation indicators in career development has significantly increased the benefit we can expect from citations. As both authors and reviewers, it is our personal responsibility to assess where ethics or a conflict of interest stands when assessing and/or recommending citations. For journals, it is impossible to avoid using reviewers cited in the manuscripts if we want to get reviews from the closest experts in the field. To address this issue at the European Journal of Mineralogy (EJM), we have recently put, in our recommendation to referees, more emphasis on the relevance of the citations than their comprehensiveness. We are now asking reviewers to assess explicitly “relevance and up-to-date of the references”. Editors also play an essential role in monitoring and regulating potential over-citation by an author and bias from a reviewer. Editors play a fundamental role in safeguarding fairness in the evaluation of manuscripts. Ultimately, editors are the gatekeepers of the ethical standard of a journal.

J. Ingrin
Managing editor of EJM
DMG YOUNG SCIENTIST AWARDS

Call for Applications 2022

The Paul Ramdohr Award is given for the best oral and poster presentations by a student at the annual meeting of the German Mineralogical Society (DMG). Student DMG members may apply when submitting an abstract for GeoMinKöln 2022, the 100th annual DMG meeting. The application form can be downloaded from https://www.dmg-home.org/fileadmin/user_upload/Form-Paul-Ramdohr-Preisallg_v2022.pdf.

The Beate Mocek Prize of the DMG is dedicated to supporting mineralogical research of young female scientists, in particular in the fields of petrology and geochemistry. Female undergraduate or PhD students who are also members of the DMG are eligible to apply for this prize, which was created in memory of the late petrologist and geochemist Beate Mocek by her family to encourage young women to study mineralogical sciences. Please submit your application by 31 January 2022 to DMG President Friedhelm von Blanckenburg (fvb@gfz-potsdam.de).

Awardees 2021

In 2021 the Beate Mocek Prize was awarded to Leanne Schmitt (University of Applied Sciences Georg Agricola, Bochum) and to Lisa Kaatz (Freie Universität Berlin).

Leanne Schmitt

The aim of Leanne Schmitt’s project “Geochemistry and Mineralogy of Volcano-Sedimentary Iron Ore Systems – from Sedimentation to Metamorphism” is to develop a genetic model and paleoenvironmental tracers of Lahin–Dill-type iron ores, as well as to establish classifiable signatures for comparison with the greater class of submarine volcano-sedimentary ore systems. Her modern sub-micron scale analyses financed with the prize money will help to answer key questions on mobilization, transport, and depositional processes of metal compounds in general.

Lisa Kaatz

Lisa Kaatz is working on the topic “Coupling Deformation with Fluid Flow and Mineral Reactions based on Natural Shear Zones – from Field Observations to Numerical Simulations”. In the first part of her thesis, she described the distribution of the H₂O content in nominally anhydrous minerals (NAMs) and its effect on shear zone formation and widening on the island of Holsnøy (Norway). The OH contents of NAMs were determined using Fourier transform infrared (FTIR) spectroscopy, in cooperation with J. Hermann’s group at the university of Bern (Switzerland). Lisa Kaatz will use the stipend to finalize her dissertation. She is going to develop a model of water–rock interactions in shear zone networks by numerical simulations, together with colleagues from Lausanne (Switzerland).

Dominik Mock

Mock’s excellent talk entitled “Sill Intrusions in lower Oceanic Crust: Implications from Drill Core GT1 of the Oman Drilling Project”, which was presented at the virtual emc2020 organized by the colleagues from Cracow (Poland) this year. Johannes Pohlner impressed the committee with his poster “Inter-Mineral Fe Isotope Fractionation in Eclogites of the Münchberg Massif (Germany) as a Function of Oxidation State”. The awards will be presented at the 100th annual DMG meeting, 11–15 September 2022, Cologne.

ANNUAL DMG MEETING 2022

GeoMinKöln 2022
11–15 September 2022
University of Cologne

1. Mineralogy in the 21st Century: From Geological Processes to Crystallography and New Materials
2. Early Evolution of the Earth and the Solar System: Building Habitable Worlds
3. Dynamics of the Deep Earth: From the Core and Mantle to Continents
4. Plate Tectonics and Orogenic Processes
5. The Earth System and Global Change
6. Earth Surface Processes and Sedimentology
7. Keys to Biosphere Dynamics: Geobiology and Palaeontology
8. The Human Footprint: Applied and Environmental Geosciences & Archeometry
9. Energy, Materials, Resources
10. Outreach, Education, and Geosciences in Society
11. Open Sessions

6th GOOD MEETING, CLAUSTHAL-ZELLERFELD.
6–8 OCTOBER 2021

After a long period without opportunities to meet in person, the 6th GOOD (Geology of Ore Deposits) Meeting took place at Cutec and TU Clausthal in Clausthal-Zellerfeld 6–8 October 2021 under application of a strict 3G (COVID 19 vaccinated, cured, or tested) and hygienic concept. The meeting was organized by ore-deposit researchers from Clausthal and the “Rohstoffforschung” working group of the DMG. Following a break of almost two years, the meeting continued the successful previous GOOD meetings in Freiberg (2016), Hannover (2017), Erlangen (2018) and Bremen (2019). Students (BSc, MSc, PhD) and young researchers from nine different institutions enthusiastically took the opportunity to present their research results or student degree theses and to expand their opportunities.
The introductory keynote lecture given by Prof. Max Wilke (Potsdam) on the application of synchrotron radiation in ore petrology was followed by a high-quality and diverse program of presentations and an entertaining poster session. Manuel Scharrer and Nicolas Meyer (both Tübingen) were awarded for the best talk and the best poster, respectively, voted by the audience. On the last day, the practical parts of the meeting were carried out; in the morning a three-hour seminar by Dr. Wilfried Ließmann (TU Clausthal) on ore microscopy took place. This was followed in the afternoon by a tour to the historic mines at Beerberg in St. Andreasberg, led by Dr. Wilfried Ließmann and Dr. Stephanie Lohmeier (TU Clausthal). The next GOOD meeting will take place in Potsdam in 2022!

**SHORT COURSE REPORT**

**High-Pressure Experimental Techniques and Applications to the Earth’s Interior**

The Bavarian Geoinstitute (BGI) in Bayreuth managed to organize their 23rd annual short course entitled High-Pressure Experimental Techniques and Applications to the Earth’s Interior despite the pandemic. Deviating from the usual five-day short course in February, this year’s hybrid course featured several online lectures that provided the theoretical framework for the students. These were combined with a three-day practical, for which the participants were divided into two groups of six. While the second group still awaits their chance at the end of September, six students already had the opportunity to work in the BGI labs from July 19th to 21st.

The short course showed the wide variety of cutting-edge high-pressure–high-temperature techniques employed at the BGI. Covering the whole range of pressures from Earth’s crust to its core, the students helped prepare experiments in the piston cylinder, multi-anvil press, and the diamond anvil cell. In contrast to the HP–HT experiments stood a cold deformation experiment using BGI’s independently acting anvil press. Although the pressure of 10 GPa was similar to the previous multi-anvil experiment, the temperature of around -100 °C, was more than 1,000 °C lower. Combined with the online lectures, all these practicals demonstrated the difficult steps needed to prepare the experiments and offered a comprehensive overview of each method. In addition, students learned how to prepare and analyze samples recovered from the experiments. Using the online lectures as a theoretical framework once more, the short course illustrated spectroscopic methods such as Fourier-transform infrared, Raman, and Mössbauer spectroscopy. These were followed by very sensitive chemical measurements using the LA-ICP-MS, as well as microscopic techniques such as SEM and TEM. Complementing the intense scientific lessons was an after-work meeting for beer and pretzels on Tuesday evening. A casual atmosphere allowed for very interesting talks with the experienced scientists, including on non-scientific topics.

Overall, this course gave a broad understanding of experimental and analytical methods for the study of Earth’s interior. Now that the young scientists know the advantages and disadvantages of each technique, they can judge which methods to use in their own future work. For students who also wanted to obtain 2 European credit transfer system credits for the short course, an optional exam was prepared at the end. The students were very thankful for the opportunity to come to the Geoinstitute despite the pandemic: it allowed them to meet passionate scientists and discover the impressive equipment at BGI. The course is recommended to all students interested in experimental techniques or the study of Earth’s interior.

**Laurine Rey** (Zürich), **Martin Keseberg** (Freiberg)
RENEW YOUR MEMBERSHIP FOR 2022

Geochemical Society (GS) members can renew quickly and securely on the GS website: www.geochemsoc.org. Renew to enjoy uninterrupted access to *Elements*, *Geochemical News*, and registration discounts to Goldschmidt2022 and to other conferences. Members have access to the online member directory (available by signing into your profile on the website). You can also choose a two-year membership option to save time and money.

A reduced professional rate of $15 is available to scientists from countries classified by the World Bank as having low-income or lower-middle-income economies. Visit geochemsoc.org/membership/join to learn more about which countries qualify. Students from qualifying countries may apply for free memberships through the Introductory Student Membership Program.

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<th>2022 Dues Rates</th>
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OFFICER ELECTIONS

The annual election for the society’s board of directors will take place in November 2021, and all GS members are encouraged to participate. You received an e-mail in early November with instructions for voting. Information about the candidates is available on the GS website—please take a few minutes to review them and to vote.

GOLDSCHMIDT 2022 SPECIAL LECTURES

Three named lectures at the Goldschmidt Conference recognize innovative research across several disciplines. Lecture nomination packages are relatively short, requiring only information about the nominee and one support letter. A single nominator can easily assemble a package. The lectures are a great way to share a colleague’s exciting work with attendees. The nomination deadline is January 10, 2022. Visit www.geochemsoc.org/honors/special-lectures

The Robert Berner Lecture, a joint program of the Geochemical Society and the European Association of Geochemistry, is given annually by a mid-career scientist. The lecture is on a ‘Berner’ subject, which includes a wide range of topics associated with elemental cycling at the Earth’s surface (molecular to planetary scale, modern to ancient oceanic and terrestrial systems, evolution of the biosphere, etc).

The Endowed Biogeochemistry Lecture recognizes a prominent scientist who is making cutting-edge field-based measurements or laboratory measurements on field samples in the area of biogeochemistry.

The F. Earl Ingerson Lecture honors the Geochemical Society’s first president. Nominations are accepted for any topic within geochemistry with broad appeal to Goldschmidt attendees.

The GS is offering grants to support initiatives aimed at promoting networking, educational activities, analytical training or capacity building related to geochemistry in countries with low and lower-middle-income economies. Grants up to $2,500 will be awarded.
Meteorite hunting is a lot like football (soccer) ... just run with us on this. Success requires skill, a cracking team, a whole lot of luck ... and, historically, England (and the UK) are not very good at it ... we were just unlucky ... the fireball always seems to miss the goal! Meanwhile, around the world, meteorite fall recoveries are becoming more and more frequent; but in the UK, to put it in the style of the famous English football anthem by the band the Lightning Seeds, it’s been “30 years of hurt” since our last meteorite fall. The Glattion meteorite of 1991 that landed in Arthur Pettifor’s back garden, as he was tending to his onions, was the last time the UK has tasted the success of recovering a meteorite fall (Meteoritical Bulletin Database – Glattion). However, based on data from the France-based Fireball Recovery and InterPlanetary Observation Network (FRIPON), calculations suggest that approximately three meteorites of over 100 g should fall on the UK each year (Colas et al. 2020), so right now the UK is batting way below its average (yes, we know that’s cricket not soccer).

Recovering meteorites that have been seen to fall is incredibly important for planetary science as we seek to understand how our Solar System formed and evolved. Even better is when the fireball (the bright light trail left behind as the rock passes through Earth’s atmosphere) is caught on camera. This has two important results: firstly, these images allow us to triangulate where the meteorite landed and quickly get boots on the ground to search for any visiting space rocks before they get contaminated by Earth’s environment; secondly, it provides key geological context to our meteorite collection by enabling us to link these special rocks back to their source region in space and, potentially, their parent asteroid (Devillepoix et al. 2020; Jenniskens 2020). The more images of the fireball we get, from as many locations as possible, the better our triangulation will be.

Thus, over the last few decades, and from around the world, researchers and amateur astronomers have been developing automated camera networks to image meteors and fireballs alongside sophisticated models to figure out if a meteorite survived, where it may have landed and where it came from in space. The UK has, over the last five years, become a promising fireball camera network, all using a variety of equipment from narrow angle closed circuit television (CCTV) cameras to digital single lens reflex (DSLRs) and industrial cameras equipped with 360° ‘all sky’ lenses. There are no less than six active meteor and fireball networks to image meteors and fireballs alongside sophisticated models to number crunch with multi-network data showed that the object originated in the asteroid belt and further increased our confidence in finding meteorites on the ground. The game was afoot.

Since the inception of UKFAll, we have had a fair few near misses. Some promising fireballs have been obscured by clouds across most of the country (which is pretty typical for the UK!), meaning we couldn’t get a good lock on the fireball. And even when we were blessed with clear skies and saw a meteorite dropper burn bright above the UK, as happened on the 16 February 2020, the surviving fragment ended up in the North Sea (deep sea dive search anybody?). All these teaser trailer fireballs have allowed us to prepare for the real deal and develop better and faster data-sharing methods, iron out some of the kinks in our data pipeline, and test run getting the word out. UKFAll was ready for the big one … we just needed something to fall out of the sky on top of us. Enter spring 2021 and the amazing story of the Winchcombe fall event in Gloucestershire County, England (Rowe 2021).

Sunday

On the 28 February 2021 at 21:54 we got exactly what we had waited so long for. A bright seven second fireball was observed across the UK and Northern Europe. The UKFAll cameras typically ping us if they see anything, but that message doesn’t normally arrive until the cameras have processed the data the next day. Thankfully, social media feeds started alerting us with messages about the fireball. We checked the cameras and fired off a quick message to our international colleagues at the Global Fireball Observatory (GFO) in Australia and the FRIPON camera network in France, asking them if our cameras had seen anything, before turning in for the night.

Monday

Early the next day, we woke up to a barrage of the best kind of e-mails you’d ever want to receive. Yes, three of our (UKFEN) cameras had caught the fireball, along with 13/16 other separate observatories in the UKFAll network (Fig. 2). Additionally, ~1,000 members of the public reported seeing it and hearing a sonic boom through the UKMON/American Meteor Society portal. Video footage showing fragmentation of the meteor suggested a good chance that meteorites survived, with the initial calculations hinting at a possible cometary orbit (!). Further number crunching with multi-network data showed that the object originated in the asteroid belt and further increased our confidence in finding meteorites on the ground. The game was afoot.
Now, under normal circumstances we’d already be in cars rushing to the fall site, as well as lighting the beacons to tell UKFAll’s army of citizen science volunteers to mobilise. However, these are not normal times, and we faced two problems. The first was COVID. The UK was under a national lockdown, so getting people to the area was not going to be easy, especially for members of the public because travel outside of home areas wasn’t permitted apart from for work purposes. The second problem was that we didn’t have a well-constrained dark flight model yet, i.e., the meteorite’s journey from when the light of the fireball goes out (sending the rock into freefall where it is blown about by the wind) to it landing on the ground. This meant that our initial estimate of where the rock had landed was a 280 km² area (Fig. 3), a bit too big to search by foot, too big to start a goldrush of people flocking to the area. Realizing its potential importance, they bagged the debris and sent in a photo of what they had found to the UKMON (Fig. 4). The speedy action of the Wilcock family was amazing and meant that around 300 g of the meteorite had spent less than 12 hours on the ground before it was collected, with no rain having fallen (see, it does stop sometimes!). This meteorite is about as fresh as you can get and is comparable to the material brought back by asteroid sample-return missions, such as Hayabusa2 and OSIRIS-REx, especially with the fireball data telling us its orbit. But we’re getting ahead of ourselves.

Simultaneous to our media efforts, but unbeknownst to us, most of the meteorite was already sitting in a clean plastic bag in the Wilcock family home in the small town of Winchcombe. The daughter of the family, Hannah, had heard a loud cracking sound outside their home at about 22:00 the previous evening, but didn’t see anything unusual when she looked out of the window that night. The next morning, however, the whole family had found a splatter of dust and black rocky fragments on their driveway. Their initial thought was, “Has someone been lobbing lumps of coal into peoples’ gardens?” Fortunately, their son Daniel had seen the news and told them about the possible meteorite fall in the area.

While we were waiting for a more refined search area, we decided to alert the media with an approximate fall location to see if any lucky locals had come across any new rocks that looked black and shiny (black and shiny because this is the typical appearance of a freshly fallen meteorite that has had its surface melted as it passed through the atmosphere). The UKFAll network had a set of pre-prepared press releases for just this occasion. So, we populated them with the specific details of the fall and had the story out the door by 8 a.m. on Monday morning. Our press release was picked up and next thing we knew various members of UKFAll were on national television and radio talking about what to do if you think you have found a meteorite and who to contact (Amos 2021).

Tuesday
We were inundated by a rogue’s gallery of images of unusual-looking rocks that had been sent in to both the UKMON and the Natural History Museum (NHM). Most were sadly ‘meteorwrongs’, but there were a couple that looked promising. However, we must admit that several of us were not initially convinced by the unassuming image of a pile of black dust from a driveway in Winchcombe (Fig. 4): it was more likely to be the residue from a barbecue than a space rock! Luckily, science is a team effort and lots of eyes were looking at these images, including those of Dr Richard Greenwood (Open University, UK) who immediately recognized it for what it was: a meteorite! Not only that, he also recognized that it was likely a rare meteorite type known as a carbonaceous chondrite.

Wednesday
Living locally to Winchcombe, Dr Greenwood managed to visit the Wilcock family and confirm that it really was what we’d been hoping for – a freshly fallen UK meteorite!

We now had a confirmed meteorite recovered from a driveway in Winchcombe, plus several other promising-looking images that had...
been sent in by the public. At the same time, our colleagues at the GFO had run the darkflight model and sent us a much smaller, more searchable, area where the meteorite could have landed, which is known as a strewn field. The fragmentation of the fireball also suggested that more pieces should be nearby. Now was the time to get boots on the ground to try to find the rest of it. There was just that small problem of the national COVID-19 lockdown. After a literal mountain of paperwork and risk assessments, we received institutional sign-off to get a team of around 15 planetary scientists from academic institutions across the UK (including Glasgow, Manchester, Plymouth, Imperial College, the NHM, and the Open University) into the field. We’re going on a meteorite hunt! We hope to find a big one!

Thursday–Friday

The search team was assembled near Winchcombe in the beautiful countryside of the Cotswolds on an overcast, but thankfully rain-free, spring morning. We had a short briefing, where most of us got our first glimpse of the Winchcombe meteorite to help get our eye in for the coming search, before it got whisked away to the NHM for curation and preliminary analysis. Those of us who had been meteorite searching before in Antarctica or Australia gave a crash course in meteorite hunting techniques, and we set off. Meteorite hunting, it turns out, is the ideal socially distanced activity: using many tried-and-tested search-and-rescue techniques, the group lined up ~2 m apart and slowly walked across the landscape scanning the ground in front for shiny black objects (Fig. 5). We mark our slow progress with GPS, slowly filling in the search area either side of the fall line.

We had ideal searching conditions, overcast meant no long shadows from the sun, no rain was good for both not contaminating any meteorites that were in the fields waiting for us (and also morale), while the season meant the grass was short and there were fewer places for little black rocks to hide. We also received a really warm reception from the local landowners who very graciously allowed us onto their property to search, for which we were extremely grateful. The underlying bedrock of the Cotswolds is oolitic limestone, a bright white rock and about as different from a meteorite as you can be; therefore, it was our hope that almost any solid shiny black thing would be what we were after. However, you would not believe how many things lying about in the UK countryside look like the fusion crust of a meteorite, from sheep poop to dewy cobwebs in the morning sun, making the search slow going. We checked every ... single ... one.

Saturday

We don’t think anyone actually expected anything to come of the search, but it was our responsibility to try. This might have been why most of the search team, after covering most of the fall line over two days, decided to head back home on the Friday night. The University of Glasgow team, however, decided to stay over the weekend to fill in the final few gaps in our search map. Then the unbelievable happened. Early on the Saturday morning, Mira Ihasz, a volunteer with the University of Glasgow search team, found a beautiful, perfectly fusion-crusted, and mostly intact, 150 g piece of the meteorite in a sheep field. Cue pandemonium as we all just screamed and jumped for joy. It was everything we could do to maintain social distance when all we wanted to do was hug each other at having achieved what many had thought to be impossible: the search and recovery of a meteorite fall in the UK.

What A Week

Several other stones were subsequently found by members of the public from the area, bringing the total final mass of the fall to >500 g, most of which were recovered before substantial rainfall. There are many amazing aspects to the recovery of the Winchcombe meteorite, but perhaps the most wonderful is that the Wilcock family (as well as the Carrick, Bond, and Godfrey families) elected to generously donate all of the material they found, or that was found on their land, to the NHM for scientific research.

The Winchcombe meteorite has now been officially classified as a CM2 carbonaceous chondrite and has energized the UK planetary science community (Meteoritical Bulletin Database – Winchcombe). Carbonaceous chondrite meteorites are really important, because they are one of the first rocks to form in our Solar System some 4.5 billion years ago, and they contain a lot of water and organic matter. Therefore, meteorites such as that which fell on Winchcombe rained down on the early Earth as it formed and their contents may have provided the water for our oceans and the organic material to from a nice habitable ‘soup’ from which life could emerge and evolve. Fragments of Winchcombe have been sent out to every laboratory in the country for what is set to be one of the most comprehensive studies of a single stone since the fall of the Allende meteorite in 1969. The fragment recovered from the Bond family’s field by the University of Glasgow team is now on display at the NHM.

The whole Winchcombe experience just shows what great things can be achieved when science works as a diverse international effort, combining the expertise of academics and citizen scientists to build together something that is greater than the sum of its parts. It is a great first result for UKFAll to build on. Let’s hope it’s not another 30 years of hurt until the next one.

REFERENCES


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As I was finishing my PhD thesis on the Borralan alkaline complex in Scotland, my professor, Basil King, who published the first account of the Napak carbonatite occurrence in Uganda, proposed that I should apply for a NERC fellowship to investigate the fenites associated with carbonatites of the Chilwa Province in Malawi (Fig. 1). After a successful application, I duly flew out to Malawi and spent three months building an extensive collection of fenites from the very large metasomatic aureoles around the carbonatites of Chilwa Island, Tundulu, and Kangankunde. Back at Bedford College (University of London, UK) I had been working on my fenites for about a year when Brian Sturt, a lecturer in the department, told me that at a council meeting of the Mineralogical Society of Great Britain and Ireland the previous day he had been told by Frank Claringbull that he, Claringbull, was looking for a petrologist to work in the Department of Mineralogy at the British Museum (Natural History), now called the Natural History Museum. I arranged to see Claringbull, was interviewed, and was fortunate enough to be appointed as a petrologist in the department.

**Figure 1** Chilwa Island (Malawi). The central, flat-topped plug is of carbonatite; the outer slopes are of fenitized basement rocks. Picture taken in 1966.

I continued my fenite work at the museum. From time to time, Dr Campbell Smith, a previous Head of the Department of Mineralogy but then retired, came in to see how my Chilwa work was progressing. In conversation we occasionally discussed the bulletin on the Chilwa rocks. On 9 October 1933, W.C. Smith to F. Dixey.

“You will perhaps be surprised at the guesses I am hazarding, but I believe we shall find they come fairly near the truth.

During my work on these rocks, I have been frequently struck by rather vague but suggestive resemblances between your rocks and some of those described by Brøgger from the Fen district of Norway, with which you may be familiar. Briefly, the alkaline rocks of the Fen district consist of intrusions of ijolite and related rocks, associated with limestones of magmatic origin, intruded into biotite-granite of the district. Remarkable rock types, of which fenite is the most important, have been formed at the margin of the biotite-granite owing to its impregnation by material proceeding from the intrusive nepheline-rich rocks.

I am satisfied that we can use Brøgger’s explanation of events in that region as a working hypothesis on which to interpret the Lake Chilwa rocks.

Can you explain your crystalline limestones as ‘intrusive’? Are they connected at all with definitely metamorphosed sedimentary limestones?...

It is important to get this right because of its bearing on Daly’s theory of the origin of alkali-rocks. In Uganda, Davies has been working on the limestones and associated rocks of Tororo Hill and I gather that he assumes it to be metamorphosed sediment, but it may not be so.”

**11 January 1934. F. Dixey to W.C. Smith.**

“The limestone. I find it hard to believe that the main mass of limestone is other than of sedimentary origin, although of course carbonate rocks may possibly have been intruded as part of the episode. The Tundulu limestone is one of three occurrences of similar limestone in this region, ..., The Muambe and Chilwa ls. limestones are flat-lying masses of sedimentary character, and Tundulu ..., has every appearance of being a mass of the same limestone which has become involved in the igneous complex. As an additional point all three occurrences contain somewhat similar iron-manganese rocks, of which I send you some specimens....”

**25 October 1934. F. Dixey to W.C. Smith.**

“With further reference to our correspondence on the Chilwa rocks, you will be interested to know that I have just spent three weeks on the area, keeping the various doubtful points in view...

The limestone of Chilwa Island is not a flat-lying limestone sedimentary formation, but a great penepalised plug of intrusive limestone intimately associated with feldspathic intrusive and intrusive breccias, all cutting the ancient schists and gneisses, and invaded as elsewhere, by nepheline syenite.

Tundulu is similar, ... I saw several dykes of limestone and feldspathic rock of precisely the same character as in the larger vents....”

**3 December 1934. F. Dixey to W.C. Smith.**

“You will be glad to know that your examination, combined with observations of the last few weeks, leads quite definitely to the conclusion that my ‘Chilwa syenites’ [fenites] belong to the basement complex and have been altered to a greater or less extent by vent magmas. This confirms your earlier suggestions and brings the series very closely into line with that of Brøgger’s....”
It is important to note that, at that time, knowledge of, and belief in, carbonatites was very limited. The extraordinarily detailed monographs of Högbom (1895) and Brøgger (1921) on Fen and Alnö (Sweden), both written in German, were not widely known, and these occurrences, plus Kaisersstuhl (Germany), were the only carbonatites that had been recognised and described in detail. There were also many in the petrological community who would not accept that igneous limestones could exist, believing that they must involve, in some way, mobilisation of sedimentary limestone. I encountered this side of the argument when I gave a lecture to colleagues at the Natural History Museum in the 1960s, at the end of which my boss at the time said that I must be wrong as experimental evidence indicated that limestones could not be molten at reasonably acceptable temperatures. This background, to my eyes, makes it all the more remarkable that Campbell Smith, sitting in London, committed himself to believing that many of Dixey’s Chilwa rocks were carbonatites and fenites.

When the Dixey et al. (1937) bulletin was published it described 11 occurrences of carbonatite and associated fenites in the Chilwa province and, even more remarkably, Campbell Smith suggested that limestones associated with igneous rocks at Kalkfeld and Okorusu (Namibia), Palabora (South Africa), Lokupoi (Napak), Toror and Tororo (Uganda) might be similar and of magmatic origin. He was right in every case and was able to attend because he was on field work in Cyprus. Campbell Smith reached the grand old age of 101 and a more charming gentleman I have never met.

REFERENCES

Högbom AG (1895) Ueber das Nephelinsyenitgebiet auf der Insel Alnö. Geologiska Föreningen i Stockholm Förhandlingar 98: 100-160; 214-256

AUTHOR BIOGRAPHY

Alan R. Woolley obtained his BSc from the University of Liverpool (UK), contemporaneously with the Beatles rocking at the Cavern Club less than a mile away, and his PhD, on the Borralan alkaline complex, from the University of London. This was followed by a Fellowship year researching the petrology of fenites from major carbonatite complexes of the Chilwa Province (Malawi). After his appointment as a petrologist at the British Museum (Natural History), he continued studying carbonatites and the alkaline igneous and metasomatic rocks. In the 1980s, he commenced writing a series of monographs on these rocks, describing all the known occurrences: the fourth and final volume was published in 2019. He is currently helping Emma Humphreys-Williams who is building a website containing descriptions of all known occurrences of the alkaline rocks and carbonatites.

When extrusive carbonatite was recognised for the first time. A photograph of the volcano at that time is shown here (Fig. 3). And no, it is not covered in snow but by natrocarbonatitic ash which, being hygroscopic, has reacted with the atmosphere.

It was always a delight when Campbell Smith popped in to find out how the fenite and carbonatite work was progressing. At a small party given in Campbell’s honour on his 80th birthday, a telegram was received from Dixey, who was then also about 80, apologising for not being able to attend because he was on field work in Cyprus. Campbell Smith had increased the known number of carbonatites from 3 to 20. After World War II, that number increased rapidly again and has continued to do so until the present day, as illustrated in Figure 2. The known number is now 609 (Humphreys-Williams and Zahirovic 2021 this issue). Acceptance of carbonatites as igneous rocks was given a timely boost in the 1960s by the activity of the Oldoinyo Lengai Volcano at
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