minerals

Review

Knowledge Structure and Frontier Evolution of Research on Chromitite: A Scientometric Review

Pengjie Cai [1,*], Jingsui Yang [1,2], Dongyang Lian [1,*], Weiwei Wu [1], Yu Yang [1] and Huichao Rui [3]

[1] State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210093, China
[2] Center for Advanced Research on Mantle (CARMA), Key Laboratory of Deep-Earth Dynamics of Ministry of Natural Resources, Institute of Geology, Chinese Academy of Geological Sciences (CAGS), Beijing 100037, China
[3] Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Guangzhou 510640, China
* Correspondence: caipengjie@nju.edu.cn (P.C.); ldy199008@163.com (D.L.)

Abstract: Big data analysis can reveal the relevance, hidden patterns, and bursts of activity in data. Therefore, big data analysis has recently aroused great interest and curiosity among scientists in various fields. The powerful data organization and visualization capabilities of CiteSpace software is an effective way to achieve this goal. Chromitite is a strategic mineral resource of global importance with several industrial applications, including steel manufacturing. Research on chromitite has not only had high economic significance, but also has important scientific value. An understanding of chromitite can be used to obtain insight into the processes operating deep within the crust and mantle. However, no big-data analysis has been performed on chromitite-related publications; hence, the evolution of various views over time is unclear. The purpose of this study was to rapidly assess and summarize the development of research in the field, and to identify and briefly describe current research developments. The CiteSpace software was used to reveal research hotspots and predict future trends. The results of the co-occurrence network analysis indicate an active collaboration among current chromitite researchers, and the countries and institutions in which they are based. Hot research topics include a focus on podiform chromitite, the origin of chromitites, and the co-occurrence of platinum group elements (PGE). The main subject of current research is podiform chromitite containing ultrahigh-pressure minerals, which will help to elucidate the relationship between chromitite and the deep processes within the earth.

Keywords: chromitite; co-occurrence network; CiteSpace; hot topics; research frontier; knowledge map

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1. Introduction

Scientific research has entered an era of big data [1–3]. There has been an explosive increase in the number of scientific research papers, leading to a body of knowledge that is now large, multisource, heterogeneous, and loosely organized, making it more difficult for people to obtain key information [2,4,5]. This presents significant challenges for scientists and researchers, especially when carrying out a literature review on a topic of interest, due to the voluminous number of publications [6]. A potential solution is developing a language that both people and machines can understand and establishing a practical, effective, and systematic method to extract useful information from references [7]. With the increasing development of modern information technology and statistics, the drawing of knowledge domain maps has become a new research topic [2,4]. These maps can be used to summarize and intuitively represent the structural relationships and mode(s) of scientific knowledge development. Visualization software programs such as CiteSpace (5.8 R3, Chaomei Chen, Tianjin, China) [2], VOSviewer (version 1.6.18, Leiden University's Centre for Science and Technology Studies, Leiden, Netherlands) [8], and BibExcel (version 2011-10-12, Olle Persson, Umeå, Sweden) [9] have been developed and used to produce scientific knowledge maps. CiteSpace is a Java-based information visualization software program [2], that uses co-citation analysis theory and a pathfinder algorithm to explore the key paths and knowledge inflection points for the evolution of ideas in a field of interest [2,10,11]. Visual maps generated using CiteSpace can be used to rapidly assess and summarize the development of research in a field, and identify research hotspots and key researchers and institutions, intuitively showing the relationship between knowledge structure and the evolution of ideas and revealing the development frontier of this research [2,4]. At present, this method has been applied in economics [12], environmental science [13], medicine [14], and other disciplines, whereas limited research has been performed in the field of geology, especially in relation to a single ore or mineral.

Chromitite, a strategic resource of global importance, is widely used in fields such as metallurgy, for the development of fire-resistant materials, and in the chemical industry [15]. In fact, chromitite is a rock chiefly composed of the mineral chromite, which is an oxide mineral belonging to the spinel group [16]. The main components of chromite are magnesium, iron, aluminum, and chromium [17]. According to their occurrence, shape, and texture, chromite deposits can be roughly divided into either stratiform or podiform deposits [18]. Stratiform chromite deposits originate from layered mafic–ultramafic complexes in ancient Precambrian cratons with stable layered ore body morphology [19,20]. They usually form a group of rhythmic layers with upper peridotite and pyroxenite [21,22]. Podiform chromite deposits are characterized by irregular lenticular or podiform morphology, which occurs in the ophiolite upper mantle sequence and the crust mantle transition zone [23–31]. Geological research on chromitite has focused on aspects such as its geochemistry, isotopes, petrogenesis, and the geological settings in which it is found [32–39]. In addition, the geological information contained in chromitite deposits has been used to understand the composition of the crust and mantle, as well as the processes taking place deep within the crust and mantle [40–50]. In particular, the discovery of high-pressure minerals in chromitites are a matter of intense discussion [44–52]. An increasing number of genetic models for chromitite have been proposed, such as melt–rock interaction, magma mixing, mantle plume, and fluid immiscibility models [29,30,44–50]. By using chromitite as the subject keyword, we identified 1124 related research papers on 24 November 2021 using the Clarivate™ Web of Science Core Collection (WoSCC) database. Although reviews of chromitite have been published before, they all focus on a single topic, such as geochemistry, mineralogy, or metallogenic models. As such, few or even no scientometric studies have been conducted to analyze the similarities and differences of chromitite-related geological studies.

As far as we know, there has been limited research on chromitite using knowledge domain maps. In this paper, CiteSpace was used to analyze statistical data for chromitite-related publications and systematically review the geological research on chromitites, providing a useful means to identify new research directions for future research on chromitites.

2. Data and Analytical Methods

2.1. Data Sources

The data used for this study were obtained from the WoSCC database, which is the premier research platform for information in the hard sciences, social sciences, art, and humanities. To increase the representativeness and accessibility of the data, we collected the data on 24 November 2021. We used "TS = Chromitite" (with TS = topic search) as the search statement to perform the literature search and obtained 1124 records, which we used as the basic data for our study. A complete list of the final selected publications is presented in Supplementary Material Table S1.

2.2. Analytical Methods

The time threshold in CiteSpace was set to cover the period from 1966 to 2021, with five years selected as the time slice, the interval duration used for the analysis and discussion of results. The strength of the connection between the studies was calculated by filtering the data of the 25 most frequently occurring nodes in each period using the cosine distance (as shown in Equation (1)), to remove redundant information and ensure the clarity of the knowledge map. After completing the threshold configuration, information on institutions, keywords, categories, and countries in the object analysis function panel were selected as the clustering library, whereas the automatic clustering function of CiteSpace was used to draw a scientific knowledge map. A detailed description of the equation used by the CiteSpace software can be found in Chen et al. [2,4]. The equation is as follows:

$$\cos\left(C_{ij}, S_i \times S_j\right) x, y = \frac{XY}{XY} = \frac{C_{ij}}{\sqrt{S_i \times S_j}} \tag{1}$$

where the normalized values obtained are between 0 and 1; S_i is the frequency of i; S_j is the frequency of j; and C_{ij} is the co-occurrence of i and j.

In the co-occurring maps of institutions, keywords, categories, and countries, the size of a node is proportional to the number of times the item is used. The thickness and color of the lines between the nodes indicate the relevance and timing of the nodes. The "years" in the results indicate the date of items with the strongest co-occurrences. Centrality indicates how important the target keyword is in all results.

3. Results

3.1. Annual Publishing Trends

The number of publications in a field of interest can be used as a measure of research activity, to analyze trends in the development of a field of interest, and to predict future directions for research development. Figure 1 shows the annual trends in the number of papers with a research focus on chromitite between 1966 and 2021. The number of chromitite-related studies was initially low, but soon started increasing rapidly during this period. In greater detail, the trend in the number of publications can be divided into three stages: an early slow-growth phase (1966–1990); an early growth phase (1991–2012); and the current phase (since 2013). During the early slow-growth phase (1966–1990), chromitite research was just starting and the number of published papers was relatively low, with an average of approximately one paper per year. During the early growth phase (1991–2012), more than 500 papers were published (n = 517), with an annual average of 22 papers with a chromitite focus, as several new directions for research emerged during this phase. In the current phase (2013–present), the number of chromitite-related research publications has continued to increase, with more than 500 papers being published during this stage as well (n = 570), with an annual average exceeding 60 papers. The results show that an increasing number of researchers are studying chromitite.

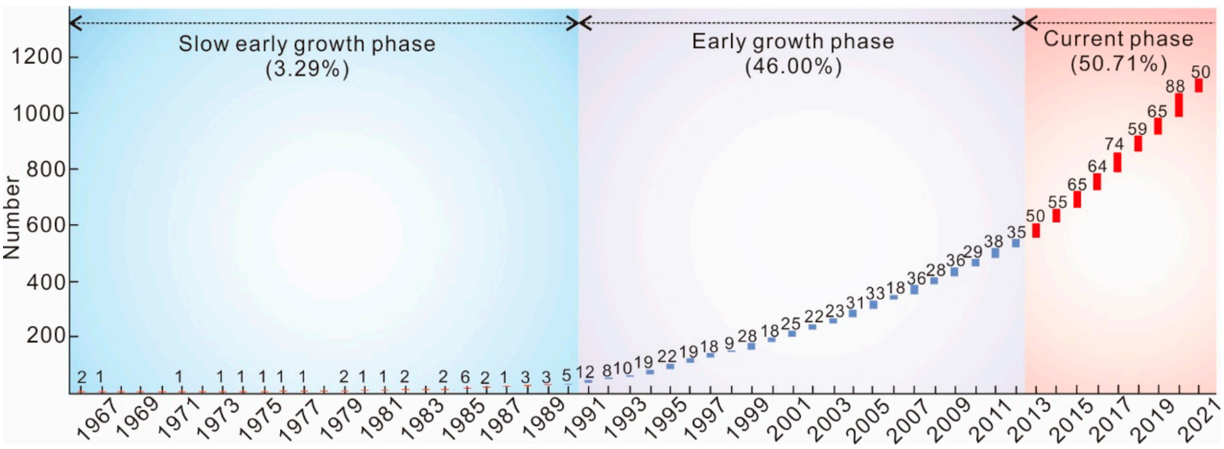

Figure 1. Annual number of articles on chromitite, based on data extracted from the WoSCC.

3.2. Author Co-Occurrence Network Analysis

The number of publications and of cooperative networks can effectively demonstrate the relative contribution of researchers in a field of research. When the core-author nonlinear network analysis was carried out, the time interval was set at five years and pruned to pathfinder. The number and size of nodes represented the co-occurrence frequency of the core author group, whereas the number and magnitude of lines reflected the cooperative relationship and intensity between authors. A total of 450 nodes and 1077 links were identified, while the network density was 0.0107. The colors employed indicate the date when the scholar published their first paper with a focus on chromitite, with darker colors indicating earlier publication dates.

As shown in Figure 2 and Table 1, there was relatively little cooperation among scholars in the early years of the investigated period. Since 1991, the level of collaboration between researchers began to increase, which coincided with the rapid increase in the number of articles on chromitite being published after 1991. The nodes and connections shown in Figure 2 indicate that research on chromitite is not yet characterized by a large scientific research team, with most of the research being produced by individuals or small groups. The independent core authors of early research on chromitite include S.J. Barnes, R.G. Cawthorn, S. Arai, M.F. Zhou, and F. Gervilla. The independent core authors for the current phase include B.X. Su, R. Latypov, B. O'Driscoll, G. Grieco, and W.L. Griffin. Large co-authorship networks first appeared during this stage. The members of one network include F. Zaccarini and G. Garuti, and those of a second research team include T. Aiglsperger, J. A. Proenza, and J.M. González-Jiménez. A third group include J.S. Yang, P.T. Robinson, X.Z. Xu, F.H. Xiong, and D.Y. Lian.

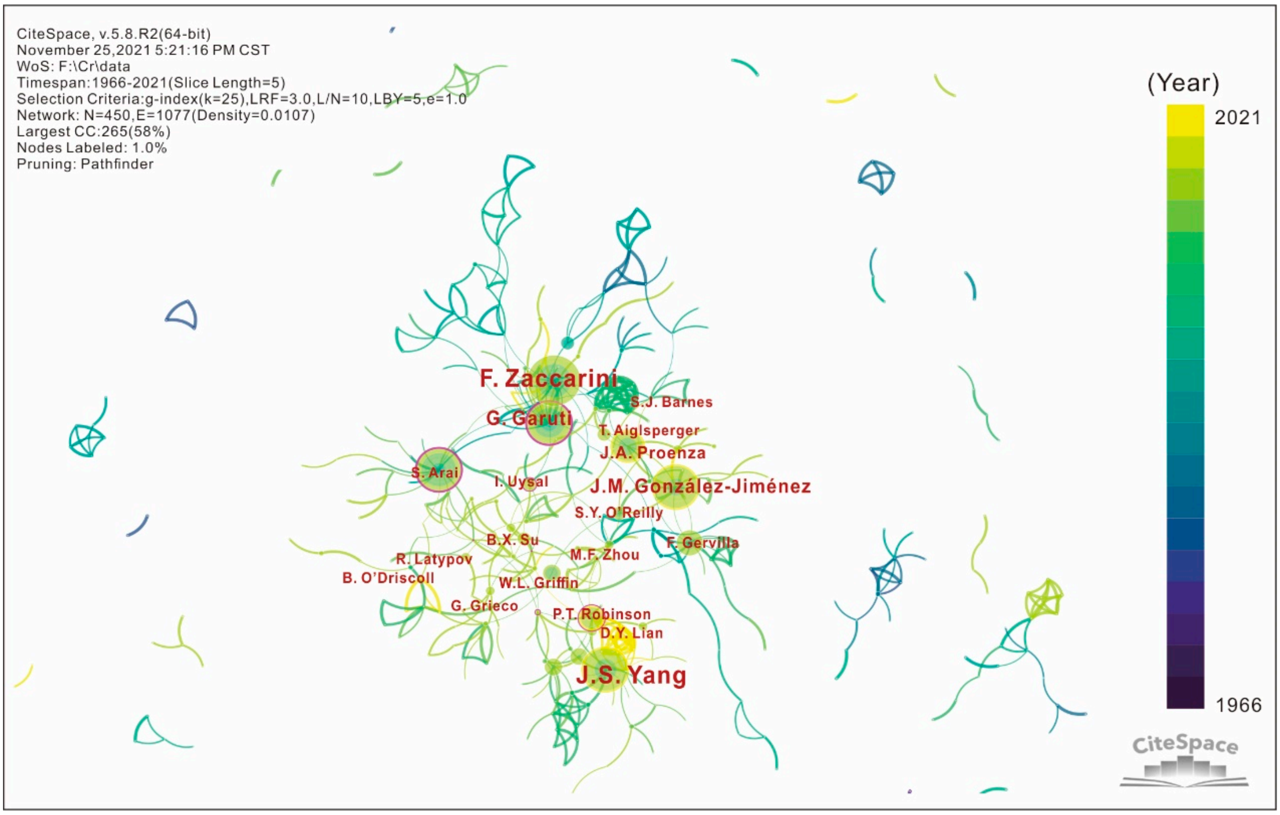

Figure 2. Co-occurring authors map.

Table 1. Top 20 authors ranked by the number of publications with a focus on chromitite.

Rank	Count	Centrality	Year	Authors
1	61	0.05	2006	J.S. Yang
2	61	0.10	1997	F. Zaccarini
3	61	0.21	1980	S. Arai
4	57	0.26	1997	G. Garuti
5	45	0.07	2009	J.M. González-Jiménez
6	42	0.10	2007	J.A. Proenza
7	39	0.06	1999	F. Gervilla
8	30	0.10	2011	P.T. Robinson
9	25	0.12	2007	I. Uysal
10	24	0.02	2011	W.L. Griffin
11	23	0.00	2013	F.H. Xiong
12	23	0.10	1996	M.F. Zhou
13	21	0.06	2011	S.Y. O'Reilly
14	21	0.05	2008	X.Z. Xu
15	18	0.05	2014	B.X. Su
16	16	0.07	1996	S.J. Barnes
17	16	0.04	1991	R.G. Cawthorn
20	15	0.00	2015	T. Aiglsperger
20	14	0.03	2017	D.Y. Lian
20	14	0.03	2012	R. Latypov
20	14	0.03	2009	G. Grieco
20	14	0.04	2009	B. O'Driscoll

3.3. Institutions and Countries/Regions Co-Occurrence Network Analysis

The number of articles published by country, region, and scientific research institution can be used to identify the centers of excellence for particular fields of interest. The top 20 co-institutions with the highest number of publications with a focus on chromitite are shown in Figure 3 and Table 2. The map of network co-institutions revealed 339 nodes and 445 lines. The top 20 institutions basically have a cooperative relationship with each other. According to the data analysis, the Chinese Academy of Geological Sciences (CAGS; 70 papers, centrality value = 0.13) produced the largest number of papers. The most prolific institutions after the CAGS were (from second to fourth) the Russian Academy of Sciences (Moscow, Russia), Kanazawa University (Kanazawa, Japan), University of Barcelona (Barcelona, Spain), and University of Witwatersrand (Braamfontein, South Africa). Although the China University of Geosciences (CUG) ranked fifth in terms of the number of publications (n = 58), it had the greatest value for centrality (centrality value = 0.18), which indicated that its cooperation with other institutions was the most extensive. The institutions ranking from 6th to 20th were as follows: University of Granada (Granada, Spain); University of Leoben (Leoben, Austria); Chinese Academy of Sciences; Macquarie University (Sydney, Australia); Cardiff University (Wales, United Kingdom); Karadeniz Technical University (Trabzon, Turkey); University of Milan (Milan, Italy); University of Hong Kong (Hong Kong, China); University of the Chinese Academy of Sciences; University of Patras (Patras, Greece); University Nacional Autónoma de México (Ciudad de México, Mexico); University of Pretoria (Pretoria, South Africa); Peking University (Beijing, China); University of Québec at Chicoutimi (Saguenay, Canada); and Jadavpur University (South Calcutta, India).

The map of network co-countries with the highest number of publications on chromitite is shown in Figure 4. Table 3 details the top 20 partner countries with the highest number of publications with a focus on chromitite. Researchers based in China published the highest number of papers per country, followed by South Africa, the USA, Canada, and Germany. The countries/regions ranking from 6th to 20th were as follows: Russia, Japan, Australia, Spain, Italy, Austria, India, England, France, Turkey, Egypt, Greece, Wales, Iran, and Brazil.

Figure 3. Co-occurring institutions map.

3.4. References Analysis

The map of the network references for chromitite is displayed in Figure 5. It is worth noting that only articles that have been cited at least once appear in the figure; accordingly, the number of citations was then calculated. As shown in Figure 5, a total of 921 articles were cited one or more times. Most of the articles cited more than 25 times were published after 2011. The details of the top 20 references on chromitite with the highest number of citations have been listed in Table 4. Seven articles published in "Gondwana Research" were cited more than 27 times: Zhou et al. (2014) [44], who proposed a possible model for podiform chromitite deposits in ophiolites (60 citations); Robinson et al. (2015) [45], who studied crustal minerals in ophiolitic chromitites and peridotites (41 citations); Yang et al. (2015) [46], who proposed a model to explain the formation of diamonds and highly reducing minerals in podiform chromitite (41 citations); Rollinson and Adetunji (2015) [47], who reviewed the geochemistry and oxidation state of podiform chromitites from the mantle section of the Oman ophiolite (33 citations); Xiong et al. (2015) [48], who suggested that the formation of podiform chromitite from the Luobusa ophiolite (Tibet) was a multistage process (32 citations); Xu et al. (2015) [49], who found ultrahigh pressure and highly reducing minerals in the chromite and olivine from the Luobusa chromitite in Tibet (27 citations); and González-Jiménez et al. (2015) [50], who studied the genesis and tectonic significance of the Dobromirtsi chromitite in Bulgaria (27 citations). Four studies published in "Lithos" were cited more than 27 times, namely: González-Jiménez et al. (2014) [53], a review of the crystallization of ophiolitic chromitites (68 citations); a review by Arai and Miura (2016) [54] on the formation and modification of chromitites in the mantle (59 citations); a review by González-Jiménez et al. (2011) [55] on the origin of high-Cr and high-Al chromitites from the Sagua de Tanamo District (Cuba); and a review by González-Jiménez et al. (2014) [56] on the origin of platinum-group minerals from ophiolitic chromitites (31 citations). Two articles were published in "Mineralium Deposita", namely Maier et al. (2013) [57], who reviewed PGE deposits in layered intrusions (38 citations), and Naldrett et al. (2012) [58], who focused on chromitites in the Bushveld Complex in South Africa (36 citations). One article was published in the "Journal of Petrology", namely Griffin et al. (2016) [59], who described the peridotites and chromitites associated with the transition zone metamorphism of Tibet (38 citations). In addition, Yang et al. (2014) [43] introduced the concept of ophiolite-type diamonds (35 citations, published in "Elements"); McGowan et al. (2015) [60] demonstrated that the Luobusa chromitite was formed in the upper mantle transition zone (35 citations, published in "Geology"); Arai (2013) [61] described how low-pressure chromitites may change to ultrahigh-pressure chromitites by deep recycling from crust to mantle (31 citations, published in "Earth and Planetary Science Letters"); O'Driscoll and González-Jiménez (2016) [62] reviewed the origin of platinum group minerals (PGM; 31 citations, published in "Reviews in Mineralogy and Geochemistry"); Junge et al. (2014) [63] discussed magmatic differentiation in relation to chromitites and PGE in the Upper Group 2 (UG2) chromitite of the Bushveld Complex (29 citations, published in "Economic Geology); Miura et al. (2012) [64] compared the characteristics of discordant and concordant chromitite pods in the Wadi Hilti ophiolite in northern Oman (29 citations, published in "Economic Geology"); and Zaccarini et al. (2011) [65] studied the geodynamic implications of chromitite and platinum group element mineralization in the Santa Elena Ultramafic Nappe in Costa Rica (27 citations, published in "Geologica Acta").

Table 2. Top 20 institutions ranked by the number of publications with a focus on chromitite.

Rank	Count	Centrality	Year	Institution
1	70	0.13	1999	Chinese Academy of Geological Sciences
2	65	0.09	1997	Russian Academy of Sciences
3	63	0.15	1998	Kanazawa University
4	59	0.13	1999	University of Barcelona
5	59	0.05	1998	University of Witwatersrand
6	58	0.18	2001	China University of Geosciences
7	51	0.09	1999	University of Granada
8	46	0.11	1997	University of Leoben
9	45	0.11	2006	Chinese Academy of Sciences
10	36	0.04	2011	Macquarie University
11	30	0.11	1997	Cardiff University
12	26	0.07	2007	Karadeniz Technical University
13	24	0.06	2001	University of Milan
14	22	0.09	1998	University of Hong Kong
15	19	0.04	2014	University of Chinese Academy of Sciences
15	17	0.07	2007	University of Patras
17	17	0.02	2004	University Nacional Autónoma de México
17	17	0.06	1979	University of Pretoria
19	16	0.08	2003	Peking University
20	15	0.03	2001	Université du Québec à Chicoutimi
20	15	0.07	1997	Jadavpur University

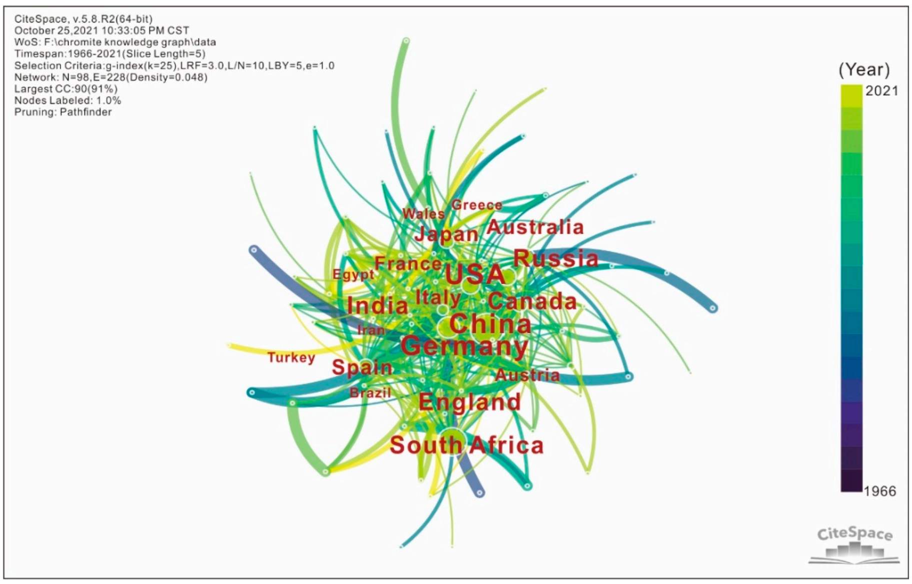

Figure 4. Co-occurring countries map.

Table 3. Top 20 countries ranked by the number of publications with a focus on chromitite.

Rank	Count	Centrality	Year	Country
1	179	0.22	1988	China
2	159	0.06	1979	South Africa
3	124	0.21	1973	USA
4	115	0.20	1984	Canada
5	106	0.12	1995	Germany
6	106	0.01	1995	Russia
7	100	0.14	1994	Japan
8	95	0.33	1990	Australia
9	89	0.21	1995	Spain
10	77	0.14	1995	Italy
11	72	0.16	1995	Austria
12	69	0.08	1997	India
13	67	0.18	1984	England
14	49	0.12	1991	France
15	43	0.10	2005	Turkey
16	40	0.11	2000	Egypt
17	39	0.04	1991	Greece
18	34	0.03	1997	Wales
19	32	0.07	2010	Iran
20	28	0.05	1995	Brazil

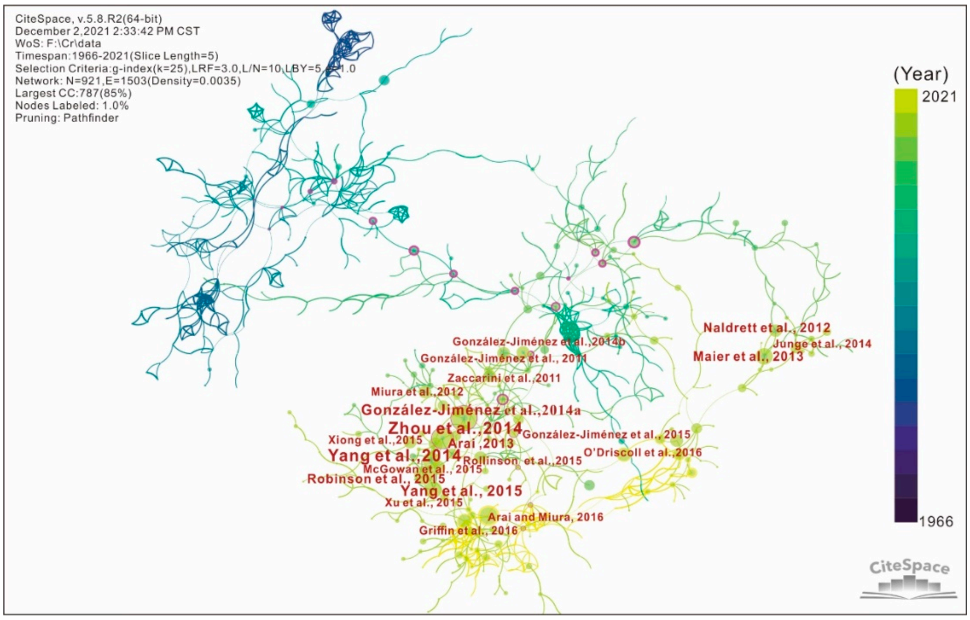

Figure 5. Co-occurring references map.

Table 4. Top 20 co-citation references related to chromitite.

Rank	Count	Centrality	Year	Cited Reference
1	68	0.12	2014	González-Jiménez et al., 2014a, LITHOS [53]
2	60	0.13	2014	Zhou et al., 2014, GONDWANA RESEARCH [44]
3	59	0.01	2016	Arai and Miura, 2016, LITHOS [54]
4	41	0.03	2015	Robinson et al., 2015, GONDWANA RESEARCH [45]
5	41	0.06	2015	Yang et al., 2015, GONDWANA RESEARCH [46]
6	38	0.04	2013	Maier et al., 2013, MINERALIUM DEPOSITA [57]
7	38	0.08	2016	Griffin et al., 2016, JOURNAL OF PETROLOGY [59]
8	38	0.07	2011	González-Jiménez et al., 2011, LITHOS [55]
9	36	0.04	2012	Naldrett et al., 2012, MINERALIUM DEPOSITA [58]
10	35	0.08	2014	Yang et al., 2014, ELEMENTS [43]

Table 4. *Cont.*

Rank	Count	Centrality	Year	Cited Reference
11	35	0.00	2015	McGowan et al., 2015, GEOLOGY [60]
12	33	0.01	2015	Rollinson et al., 2015, GONDWANA RESEARCH [47]
13	32	0.03	2015	Xiong et al., 2015, GONDWANA RESEARCH [48]
14	31	0.03	2013	Arai, 2013, EARH AND PLANETARY SCIENCE LETTERS [61]
15	31	0.02	2016	O'Driscoll and González-Jiménez, 2016, REVIEWS IN MINERALOGY AND GEOCHEMISTRY [62]
16	31	0.00	2014	González-Jiménez et al., 2014b, LITOHOS [56]
17	29	0.03	2014	Junge et al., 2014, ECONOMIC GEOLOGY [63]
18	29	0.01	2012	Miura et al. 2012, JOURNAL ASIAN EARTH SCI [64]
19	27	0.00	2015	Xu et al., 2015, GONDWANA RESEARCH [49]
20	27	0.03	2011	Zaccarini et al., 2011, GEOLOGICA ACTA [65]
20	27	0.07	2015	González-Jiménez et al., 2015, GONDWANA RESEARCH [50]

3.5. Keywords

Burst analysis can reveal research hotspots and future research trends [66]. The keywords represent the key topics addressed by the article and can be used as a source of data to assess the core content of research in a particular field of study [6]. The accurate representation of the distribution and collinear relationship between keywords can be used to identify research hotspots for a field of study [6]. Therefore, a knowledge map of keyword co-occurrence and appearance of keywords can be used to identify hot research fields and cutting-edge research topics. The results of the co-occurrence network analyses for the keywords are shown in Figure 6. The recent popular research topics with a focus on chromitite include: podiform chromitite (229 counts), origin (188 counts), PGE (130 counts), platinum group mineral (115 counts), Merensky Reef (101 counts), geochemistry (100 counts), deposit (99 counts), Bushveld Complex (98 counts), complex (97 counts), Luobusa ophiolite (88 counts), and upper mantle (87 counts).

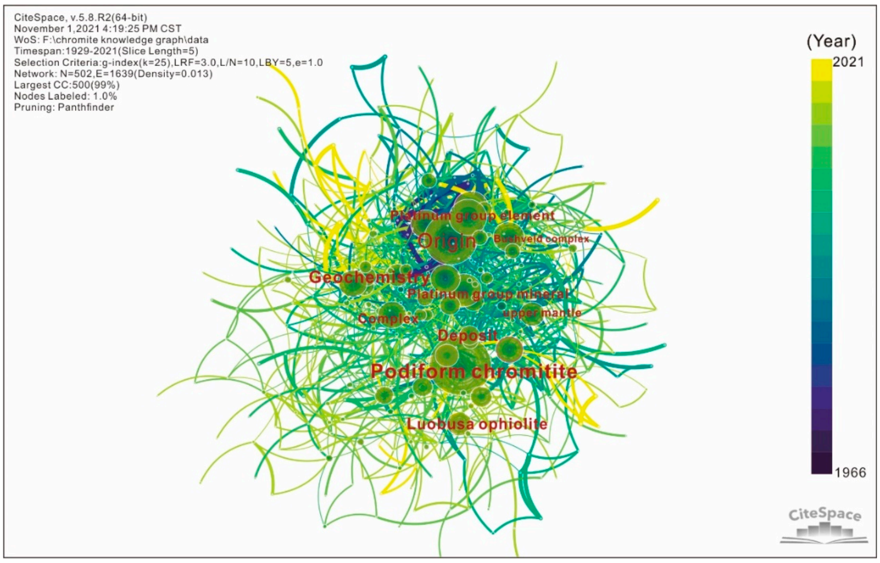

Figure 6. Co-occurring keywords map.

4. The Research Frontier for Chromitite

The burst rate of an article refers to the number of citations quoted in a field over a period of time [67]. The length of time can be selected by the researcher. A high burst rate indicates a high level of interest in a certain field of research frontier [2]. A significant increase in interest in chromitite as a research topic in geological journals has been highlighted by publications with citation bursts. The top 25 references with the strongest citation bursts for the period 1966–2021 are presented in Figure 7. This period was divided into five intervals (or stages) to show how research foci have changed over time. The main research foci for each stage are listed and summarized below.

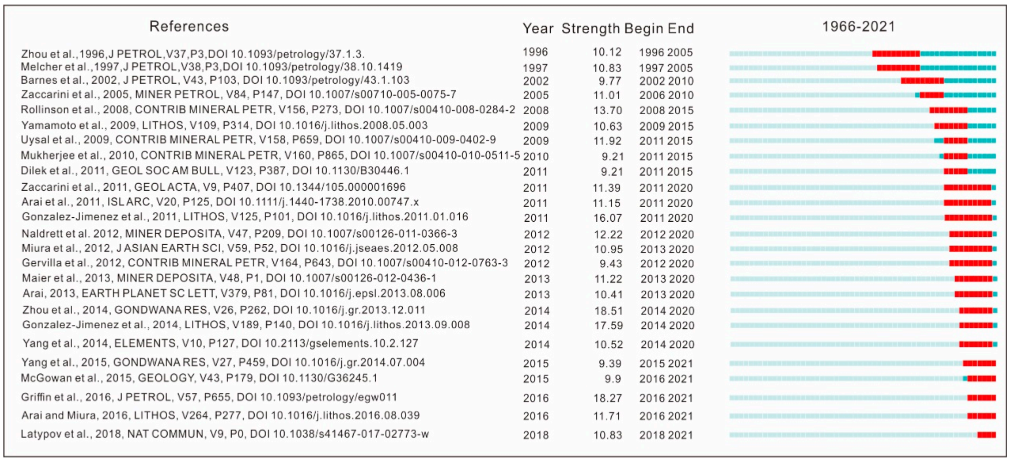

Figure 7. Top 25 references with the strongest citation bursts.

The first stage of burst references occurred from 1996 to 2005. Two articles on the origin of chromitite were burst references during this interval. Melt-rock interaction, chromitite differentiation, and magma mixing should lead to changes in the composition of the melt, resulting in the formation of massive and disseminated chromitite in the Luobusa podiform chromitite [68]. The Kempirsai Massif chromitite (Kazakhstan) contains a large number of inclusions, such as silicates, sulfides, alloys, arsenides, and fluids [69]. This indicates that the formation of chromitite is a multistage process involving mantle fluids.

The second stage of burst references occurred from 2002 to 2010. Two articles on the genesis of PGE and PGM in chromitite were burst references in this interval. The first discussed the genesis of PGE in chromitite [70], and the second discussed the changes to the nature of PGM in chromitite due to metamorphism, without changes to the concentration of PGE in the whole rock [71].

The third stage of burst references occurred from 2008 to 2015. Five articles discussing chromitite in ophiolites were burst references during this interval. The first article discussed melt-rock reactions that formed chromitites in the northern part of the Oman ophiolite [72]. The second article focused on the exsolution lamellae of diopsidic clinopyroxene and coesite in the Luobusa chromitite, which indicate that the mantle peridotite under the mid-ocean ridge of Tibet migrated upward from the deep mantle (at least 100 km, possibly more than 380 km), driven by mantle convection, implying that the source of mantle upwelling was much deeper than previously thought [73]. The third article investigated the genesis of high-Cr and low-Cr chromitites [36]. The fourth article discussed the use of chromitite composition to trace the source of the parent magma [74]. Finally, the geochemical and tectonic fingerprints of Phanerozoic ophiolites were reviewed by Dilek et al. (2011) [75], who pointed out that fingerprints could be used as an effective tool to characterize the geodynamic environment of ocean crust formation during Earth's history.

The fourth stage of burst references occurred from 2015 to 2020. Two of these articles discussed the Bushveld Complex, whereas eight articles focused on podiform chromitite. Some of the focus points and/or findings presented in these papers are summarized as follows: the chemical and mineralogical characteristics of chromitite can be used to determine the tectonic setting during formation [65,76]; the genesis of high-Cr and high-Al chromitites [55]; the origin of chromitite and related PGE mineralization in the Bushveld Complex [57,58]; changes in the composition of chromitite were affected by ultrahigh pressure (UHP) metamorphism and the subsequent exhumation process [77]; the discovery of ultrahigh-pressure minerals in podiform chromitite may support the two-layer convection model, in which low-pressure chromitites change to ultrahigh-pressure chromitites in response to deep recycling [62]; the ultrahigh-pressure minerals in chromitite originate during deep subduction, slab break-off, and the effects of the asthenosphere on the subducting slab [44]; the continuous injection of new mafic melt leads to melt flow in the crystallization and mixing channel system, which reacts with it in the melt to produce more chromitite [53]; the discovery of diamonds in peridotite and podiform chromitite in ophiolites, which formed in the oceanic lithosphere, indicates that diamond-bearing chromitite may form near the transition zone of the mantle, and then be carried to the shallow layer of the upper mantle [43].

The fifth stage of burst references occurred from 2015 to 2021. Four articles in this interval discussed podiform chromitite containing ultrahigh-pressure minerals, whereas on other article considered the layer of chromitite. Some of the focal points and/or findings presented in these papers have been summarized as follows: diamonds recovered from ophiolite chromitite were completely different from most kimberlites and diamonds from other UHP metamorphic rocks, representing a new source for diamonds on earth [46]; the exsolution of diopside and coesite in the Luobusa chromitite indicates that it was formed in the upper mantle transition zone, with the chromitite rising rapidly from a depth of 400 km in the early Tertiary and/or Late Cretaceous, in accordance with a proposed thermomechanical model [60]; Griffin et al. (2016) [59] suggested that the Luobusa-Kanjingla-Zedang Peridotite block (“ophiolite”) was an ancient sub-continental lithospheric mantle fragment that has been modified in the supra-subduction zone environment, suggesting that chromitite initially formed at a relatively shallow depth, was subducted to a great depth, and then rose rapidly in response to upwelling; Aira and Miura (2016) [54] conducted a comprehensive review of the genesis of podiform chromitite, confirming the importance of the peridotite–magma reaction and magma mixing, and discussing the characteristics of hydrothermal chromitite; during the ascent and decompression of magma, a large amount of chromitite-only saturated melts supplement the magma chamber, thus forming a single mineral layer of chromitite with associated PGE [78].

The results of the keyword cluster analysis in relation to time are presented in Figure 8. Six research directions could be used to classify research on chromitites, namely: #0 podiform chromitite; #1 South Africa; #2 PGM; #3 Merensky Reef; #4 Arabian Shield; and #5 Cr-spinel. Early research focused on topics related to layered chromitite, whereas most recent research has focused on podiform chromitite. The focus of current research is the origin of podiform chromitite, which is consistent with our results for the burst references. Moreover, the discovery of ultrahigh-pressure minerals and new minerals in podiform chromitite has generated a new window to study the deep mantle cycle of subduction materials [45,46,59,79,80]. This explains why podiform chromitite is the first research frontier.

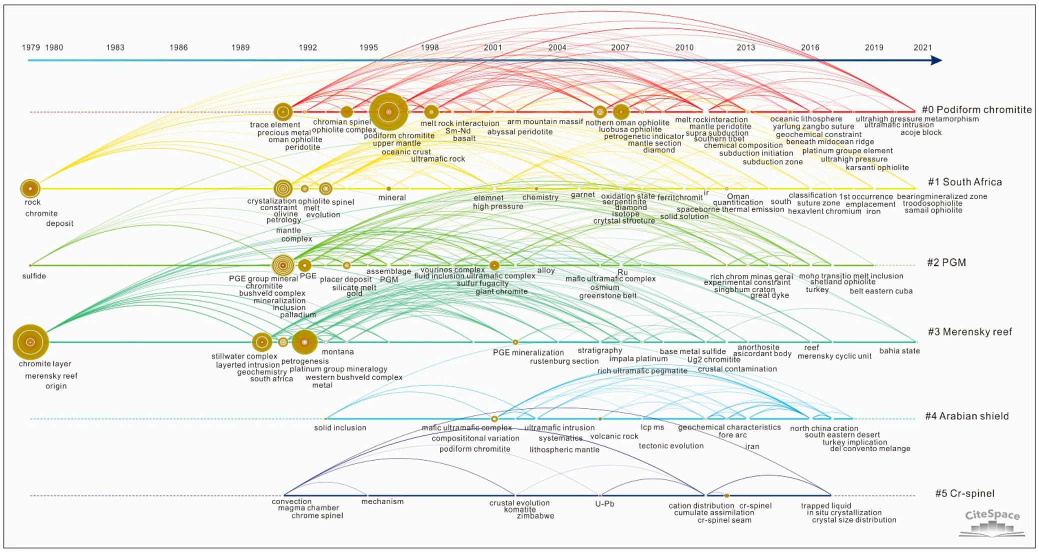

Figure 8. Timeline of co-citation clusters for keywords.

5. Conclusions

The changes in the quantity and growth rate of articles with a focus on chromitite can be divided into three stages: an early slow-growth phase (1966–1990); an early growth phase (1991–2012); and the current phase (since 2013). The top three countries with the highest number of research articles on chromitite are China, South Africa, and the USA. The top three institutions that have contributed the most to chromitite research are the Chinese Academy of Geological Sciences, the Russian Academy of Sciences, and Kanazawa University in Japan. Professors Jingsui Yang, Federica Zaccarini, and Shoji Arai are the top three contributors to the cooperative networks of chromitite research. The top three most-cited articles on chromitite are González-Jiménez et al. (2014a) [53], Zhou et al. (2014) [44], and Aira and Miura (2016) [55]. The results of the co-occurrence network analysis indicate an active collaboration among current chromitite research authors, countries, and institutions. The most popular research topics were podiform chromitite, the origin of chromitite, and the co-occurrence of chromitite with PGE. Frontier scientific issues have always focused on the genesis of podiform chromitite containing ultrahigh-pressure minerals.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/min12101211/s1, Table S1: 1124 records from WoSCC (topic search is Chromitite, Nov 2021).

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