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# The Current Status and Hot Issues of Tourmaline Research Based on CiteSpace—A Comparison Between China and Abroad from the Perspective of Tourmaline

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***Abstract:*** *Based on literature from the WOS and CNKI databases and using CiteSpace software, this study conducts a quantitative analysis of tourmaline research from 2000 to 2025 in China and abroad. Through publication volume statistics, keyword co-occurrence, and burst detection mapping, the study reveals the similarities, differences, and evolution of the research. The findings are as follows: (1) International research focuses on fundamental theory and technological innovation, emphasizing geochemical processes, fluid inclusions, and crystal structure analysis, creating an interdisciplinary framework, (2) Research in China is more application-oriented, focusing on mineral resource development, regional metallogenic models, and rare metal exploration, with significant achievements in pegmatite-type deposits and new energy minerals, (3) There are significant differences in technical approaches: international research relies on high-precision technologies (e.g., X-ray morphology and isotope analysis) to enhance theory, while China relies on traditional geological frameworks, with basic theories and technological innovation lagging behind. It is recommended to strengthen interdisciplinary integration and technological application, promoting collaboration between regional achievements and global metallogenic theories. Future research could explore the potential applications of tourmaline in environmental science and deep exploration, leveraging big data and AI technologies for intelligent exploration.*

***Keywords:*** *Tourmaline, Research Hotspots, Geochemistry, Resource Exploration*

## 1. Introduction

Tourmaline, an important boron-containing mineral, holds unique research value in Earth sciences. Since its systematic study began in the early 19th century, its crystal structure, physical properties, and role in geological processes have become research hotspots [1,2]. Tourmaline has a complex chemical composition, typically containing elements such as boron, silicon, aluminum, iron, and magnesium, with its diverse crystal structures making it widely applicable in fields like geology, mineralogy, and geochemistry [3-5]. In recent years, with increasing attention to the physical and chemical properties of minerals, the role of tourmaline in rock genesis, plate tectonics, and geodynamic processes has gained more focus. For example, studies show that the formation of tourmaline is closely linked to fluid activities in subduction zones, and its chemical composition can reflect the evolution of mantle fluids [6]. Moreover, its magnetic and electrical properties are used to study rock formation environments and geophysical properties [7].

Although substantial progress has been made in tourmaline research, existing literature mainly focuses on mineralogy and petrology, with few comprehensive summaries of its research progress [8-10]. Furthermore, while recent advances in experimental petrology and geochemical techniques have provided new tools for tourmaline research, significant differences remain in the application of these methods in domestic and international literature [11]. Therefore, a comprehensive review of the progress in tourmaline research in Earth sciences is needed to reveal its hotspots and future development directions. This paper, based on relevant literature on tourmaline from the WOS (Web of Science) and CNKI (China National Knowledge Infrastructure) databases from 2000 to 2025, combined with the CiteSpace bibliometric visualization tool, analyzes keyword co-occurrence, burst detection, and time trend mapping to systematically review and classify the research progress and hotspots over the past 26 years. On this

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basis, the paper critiques the gaps in domestic research compared to international methods and offers suggestions and prospects for addressing challenges in tourmaline research, aiming to provide a comprehensive overview of its current status in Earth sciences and serve as a reference for further studies.

## 2. Research Methods and Data Processing

This study employs bibliometric analysis through CiteSpace (v6.3) to systematically map global tourmaline research trends in Earth sciences. Using both CNKI (Chinese) and Web of Science (international) databases, we collected 608 Chinese and 1,916 English publications (2000-2025) filtered by geological relevance. The methodology involves three key steps: (1) data preprocessing with deduplication and manual screening, (2) network analysis using keyword co-occurrence and clustering to identify research nodes, and (3) knowledge visualization with time-sliced (1-year intervals) mapping techniques including "Pruning Sliced Networks" and "Minimum Spanning Tree" algorithms. This approach enables tracking of citation networks and thematic evolution, revealing disciplinary hotspots and developmental trajectories.

The analytical framework combines quantitative bibliometrics with qualitative interpretation, where CiteSpace's capabilities in information visualization help decode complex research patterns. By comparing Chinese (CNKI) and international (WoS) corpora through standardized search parameters ("Tourmaline" as subject keyword/AK field), the study ensures cross-database comparability while maintaining geological focus. The resulting knowledge maps provide structured insights into tourmaline research dynamics, serving as both a retrospective analysis tool and a predictive framework for emerging trends in mineralogy and applied geosciences.

## 3. Evolution of Publication Patterns of Tourmaline Research in China and Abroad

Tourmaline, an important mineral in Earth sciences, shows significant differences and dynamic evolution in research intensity between China and international literature. Based on literature statistics from the WOS and CNKI databases (2000-2024, see Figure 1), this paper systematically analyzes the publication status and academic trends of tourmaline research in China and abroad from three dimensions: publication volume, growth trends, and phased characteristics.

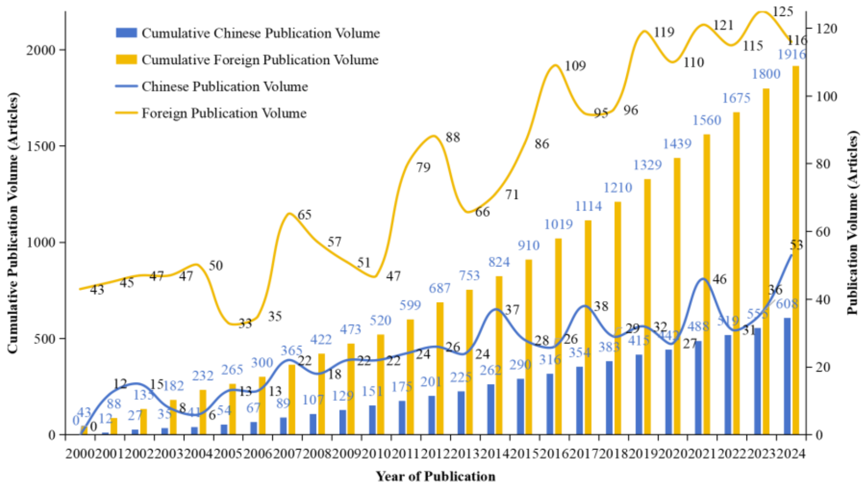


*Figure 1: Publication Volume and Trends of Tourmaline Research in China and Abroad.*

In terms of China's research publication volume, tourmaline studies show distinct phased growth. Starting in 2000, research in China was slow, with zero publications in the early years. By 2010, the cumulative number of publications reached 151, averaging about 15 articles per year. After 2011, research growth accelerated, with annual publications surpassing 20. By 2015, cumulative publications reached 290, with an annual growth rate close to 50%. From 2016 onward, Chinese research on tourmaline entered an explosive growth phase, with annual publications exceeding 30, reaching 53 articles by 2024, and cumulative publications surpassing 600, reflecting a significant expansion of research scale. Despite a slight slowdown in growth after 2020, annual publications remain at a high level, reflecting the impact of policy support and technological investments on research outcomes.

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In contrast to the explosive growth in China, international research on tourmaline shows a "steady linear growth." Since 2000, international research had a higher base, with 43 publications per year, steadily increasing. By 2010, cumulative publications reached 520, with an annual growth rate of 8.6%. From 2011 to 2020, international research entered a scaling phase, with annual publications exceeding 80. By 2020, cumulative publications reached 1,439, with an annual growth rate of 7.2%. After 2021, the growth rate slightly increased to 9.1%, and by 2024, cumulative publications reached 1,916, maintaining a global leadership position. Despite not experiencing explosive growth like in China, international research, with long-term accumulation, shows a cumulative increase of 1,873 articles, 3.1 times higher than China's (608 articles), demonstrating a strong research foundation and lasting academic influence.

When comparing the publication volume of tourmaline research in China and abroad, two main differences are evident. First, there is a significant gap in publication volume: China's total number of publications is only 31.7% of the international total, and in 2010, international publications (520) were already close to China's 2024 total (608). This indicates that although China's growth rate in recent years has far surpassed international research, its overall publication volume remains relatively low due to a later start. Second, the growth rate difference is notable: from 2016 to 2024, China's average annual growth rate (15.8%) was significantly higher than international research (7.3%). However, the absolute gap in increments continues to widen: China's average annual increase is 40 articles, while international research has 115 articles per year, further expanding the gap.

## 4. Analysis of Tourmaline Research Hotspots in China and Abroad

### *4.1 Keyword Co-occurrence and Comparison Between China and Abroad*

Keyword co-occurrence analysis of tourmaline research in China and abroad reveals notable differences in research focus, academic structure, and methodology, shedding light on the evolution of knowledge and research trends in the field. This study analyzes keyword frequency from literature published between 2000 and 2025, highlighting distinct academic priorities in China and internationally.

Chinese research focuses more on mineral resources and applications, with a different keyword distribution (Table 1, Fig. 2a). The term “Tourmaline” (136 occurrences) is central, highlighting its role in mineral deposit exploration and resource assessment. Keywords like “Heavy mineral” (51 occurrences)and “Source analysis” (36 occurrences) focus on specific deposits or geological contexts. “Pegmatite” (25 occurrences), “Rare metals” (16 occurrences), and “Himalayas” (16 occurrences) show a preference for regional studies, examining ore-forming patterns in certain areas. Terms like “Mineralization” (11 occurrences) and “Mineralization regularities” (6 occurrences) indicate an applied focus on ore exploration and metallogenic mechanisms.

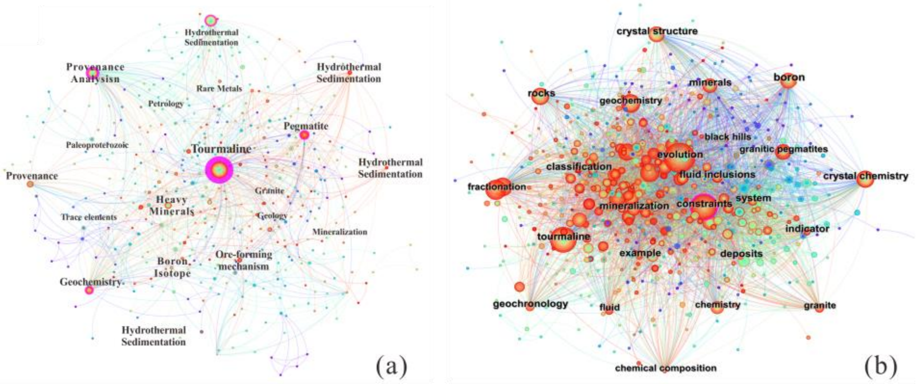


*Figure 2: Co-occurrence keyword maps of tourmaline research in China (a) and abroad (b)*

In contrast, international research prioritizes fundamental theories and geochemical processes, with strong emphasis on theoretical and technical aspects (Table 1, Fig.2b). High-frequency keywords like “Evolution” (318 occurrences) and “Boron isotope” (149 occurrences) highlight attention to the evolutionary processes of tourmaline in geodynamics and its boron isotope geochemistry. The keyword “Fluid inclusion” (142 occurrences) reflects a focus on geological fluid evolution, especially in mineralogy. The term “Trace element” (195 occurrences) emphasizes the role of trace elements in geochemical processes, while other geochemical terms like “Geochemistry” (174 occurrences), “Rock” (169 occurrences), and “Crystal chemistry” (140 occurrences) underscore the integration of mineralogy

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and geochemistry. This compact keyword network reflects the interdisciplinary nature of international research, using advanced techniques to explore tourmaline's role in Earth's evolution.

Thus, international research emphasizes theoretical exploration and geochemical analysis, while Chinese research focuses on mineral resource evaluation and regional metallogenic studies, with a more applied approach. These differences reflect variations in research systems, resources, academic traditions, and policy support. International research integrates geochemistry, mineralogy, and fluid dynamics, using modern techniques like isotope and trace element analysis. Chinese research, relying more on traditional geological frameworks, has made notable advances in mineral deposit exploration, particularly in rare metal resources, recognizing tourmaline's role in deposit genesis.

*Table 1: The Top 20 Keywords in Tourmaline Research Literature in China and Abroad.*

| Chinese Literature | | | Foreign Literature | | |
|---|---|---|---|---|---|
| Keywords | Frequency | First Appearance Year | Keywords | Frequency | First Appearance Year |
| Tourmaline | 136 | 2000 | Evolution | 318 | 2000 |
| Heavy minerals | 51 | 2002 | Tourmaline | 241 | 2000 |
| Geochemistry | 36 | 2002 | Trace element | 195 | 2000 |
| Provenance analysis | 36 | 2003 | Constraint | 181 | 2000 |
| Pegmatite | 25 | 2004 | Geochemistry | 174 | 2001 |
| Himalayas | 16 | 2015 | Rock | 169 | 2000 |
| Rare metals | 16 | 2019 | Boron isotope | 149 | 2001 |
| Boron isotope | 15 | 2000 | Mineral | 148 | 2000 |
| Provenance | 15 | 2005 | Granitic pegmatite | 143 | 2000 |
| Geological features | 12 | 2002 | Fluid inclusion | 142 | 2000 |
| Ore-forming processes | 11 | 2006 | Crystal chemistry | 140 | 2000 |
| Geology | 11 | 2004 | Crystal structure | 130 | 2000 |
| Petrology | 10 | 2009 | Fractionation | 127 | 2003 |
| Granite | 9 | 2002 | Boron | 123 | 2000 |
| Adsorption | 9 | 2007 | Chemistry | 123 | 2000 |
| Ore-forming mechanism | 8 | 2008 | Mineralization | 120 | 2000 |
| Hydrothermal deposition | 7 | 2001 | Origin | 119 | 2001 |
| Eastern Qinling | 6 | 2019 | Deposit | 116 | 2000 |
| Kuqa Depression | 6 | 2005 | Heavy mineral | 107 | 2004 |
| Mineral chemistry | 6 | 2018 | U-pb | 106 | 2009 |

### *4.2 Keyword Clustering and Comparison*

Keyword clustering analysis is a key bibliometric tool to reveal differences in research focus, directions, and technological applications in tourmaline studies. Using CiteSpace, this study compares keyword clusters in Chinese and international tourmaline research, highlighting contrasts in academic focus and methods. Clustering analysis helps identify research hotspots and provides insights into future interdisciplinary development.

International research clusters cover diverse disciplines such as geochemistry, mineralogy, and mineral physics. CiteSpace analysis reveals seven major research directions, with "#0 Boron isotopes" and "#1 Fluid inclusions" as core clusters. The "#0 Boron isotopes" cluster emphasizes boron isotopes' key role in mineral genesis and geochemical processes, aiding in understanding mineralization environments. The "#1 Fluid inclusions" cluster highlights tourmaline's role in geological fluid evolution, offering insights into fluid conditions and mineralization processes. The "#3 Crystal structure" and "#6 X-ray topography" clusters reflect the use of X-ray technology to study tourmaline's crystal structure, physical properties, and mineralization processes, showcasing both theoretical depth and advanced technologies.

In contrast, Chinese research focuses more on application-oriented studies and regional genesis analysis. Chinese research clusters into nine directions, with "#0 Tourmaline" as the core cluster, emphasizing its role in mineral deposit studies and resource evaluation. The "#1 Source analysis" cluster highlights the analysis of ore-forming rocks and their connection to tourmaline, aiding mineral exploration. The "#2 Geological features" and "#3 Geochemistry" clusters show China's focus on regional geological contexts, particularly in areas like the Himalayas, Eastern Qinling, and Tibet, addressing practical application issues. Although China's research is application-focused, there is limited exploration of basic theories and modern technological applications. While the "#8 Borates" cluster addresses specific substances, there is less in-depth study of crystal structures and geochemical fractionation, likely due to reliance on traditional geological frameworks. In contrast, international research emphasizes advanced technologies, such as X-ray morphology and isotope analysis, to explore

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crystallography, geochemical fractionation, and ore formation.

In conclusion, international research tends to be more theoretical and refined, focusing on geochemistry, mineral physics, and advanced technologies. Chinese research, while strong in resource exploration and regional studies, lacks deep exploration of basic theories and modern technologies.

### *4.3 Keyword Burst Analysis*

Spatiotemporal evolution analysis of burst keywords in tourmaline research reveals differences in academic focus, technological applications, and research paradigms between China and international research. These differences are linked to each region's research environment, policy background, and technological development.

In China, keyword burst analysis shows a strong regional and resource development focus (Fig. 3a). From 2003 to 2008, keywords like “purification,” “Kuqa Depression,” and “South Tianshan” dominated, reflecting resource exploration and basic geological studies in western China, aligned with the "Western Development" strategy. Research focused on purification processes and deposit distribution, particularly in the western regions. From 2009 to 2018, keywords like “Guangxi,” “heavy minerals,” and “adsorption” signified a shift to ore-forming mechanisms and refined resource utilization. The focus on “heavy minerals” indicated deeper exploration into ore genesis, while “adsorption” highlighted resource development and environmental concerns. After 2015, keywords like “Pegmatite” and “Rare metals” pointed to strategic resources like lithium and beryllium, aligning with modern industrial needs. By 2020, keywords such as “East Qinling,” “granite,” and “mineralization” reflected a transition to a “tectonic-magmatic-mineralization” approach, advancing mineralization prediction technologies.

International research, in contrast, shows a clear technology-driven focus (Fig. 3b). Early keywords (2000-2010) like “Crystal structure” and “Tourmaline” emphasized basic mineralogy and composition analysis. After 2010, the emergence of keywords like “Mas NMR” and “Raman spectroscopy” highlighted the shift to micro-scale mineral characterization, driven by technological advancements. These innovations allowed a deeper exploration of tourmaline’s role in geochemistry and ore formation. After 2018, international research adopted a dual approach: keywords like “Petrogenetic indicator” and “Major element” continued geochemical tracing, while regional terms like “Tethyan Himalaya” and “Nw China,” combined with U-Pb dating methods, reflected the integration of global tectonics and high-precision chronostratigraphy.

In summary, Chinese research is largely policy-driven, with hotspots aligned to national resource development strategies, particularly for new energy and rare metal resources. International research, in contrast, is more technology-driven, progressing from static structural analysis to dynamic ore formation and tectonic evolution. While both regions show some overlap, Chinese research focuses on resource utilization and ore-forming processes, while international research emphasizes magmatic processes and geochemical analysis. These differences highlight potential areas for future international collaboration, especially in deep mineralization prediction and green mining, where merging both regions' expertise could foster new disciplinary growth.

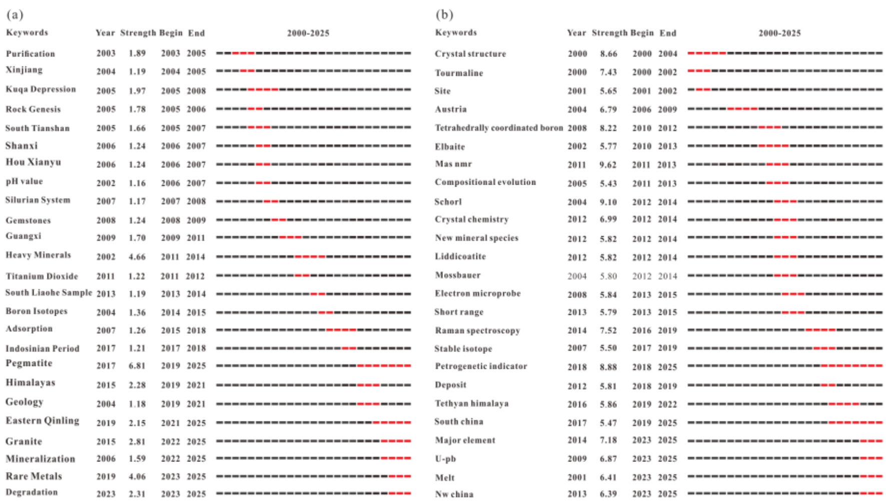


*Figure 3: Keyword burst maps of tourmaline research in China (a) and abroad (b).*

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### *4.4 Keyword Evolution Analysis*

Analyzing the evolution of keywords in tourmaline research in China and abroad, along with spatiotemporal trends, reveals changes in academic focuses and emerging research hotspots in different regions. These trends reflect distinct academic demands, technological innovations, and significant differences in research directions.

China’s keyword evolution is closely linked to national policies, resource needs, and application-focused research (Fig. 4). From 2000 to 2025, Chinese research evolved through several phases, with each phase marked by keyword bursts reflecting shifts in mineral resources, ore-forming mechanisms, and regional geology. In the early period (2000-2008), keywords like “tourmaline,” “heavy minerals,” and “geochemistry” dominated, indicating a focus on mineral characteristics and composition. At the same time, terms like “purification” and “Xinjiang” reflected research on resource exploration in western China, especially Xinjiang's mineral deposits. In the middle period (2009-2018), keywords like “source analysis,” “pegmatite,” and “rare metals” emerged, signaling a shift to ore-forming mechanisms and regional genesis studies. “Rare metals” highlighted China’s growing focus on new energy minerals like lithium and beryllium, driven by policies supporting green mining. From 2019 onward, keywords like “East Qinling,” “granite,” and “mineralization” signified a shift towards integrating deep mineralization and tectonic evolution studies into a systematic “tectonic-magmatic-mineralization” framework, combining traditional geology with modern techniques.

In contrast, international research has evolved with a stronger focus on technology and interdisciplinarity (Fig. 5). Since 2000, international research has emphasized high-precision mineral characterization and geochemical methods, especially in crystal structure and composition analysis. In the early period (2000-2010), keywords like “Crystal structure” and “Tourmaline” were central, reflecting basic properties and structure analysis. Keywords like “Boron isotope” and “Fluid inclusion” emerged, signifying a deeper exploration of tourmaline’s role in geochemical processes, particularly in fluid inclusion studies. After 2010, advanced characterization techniques like “Mas NMR” and “Raman spectroscopy” highlighted international research’s focus on micro-scale analysis, enhancing the study of tourmaline’s role in geochemistry and ore formation. Keywords like “Petrogenetic indicator” and “Major element” continued geochemical tracing, emphasizing ore-forming mechanisms and tectonic dynamics. From 2018 onward, international research adopted a “dual-track” approach: one focused on regional keywords like “Tethyan Himalaya” and “Nw China,” using high-precision U-Pb dating to explore global tectonics and ore-forming timelines, while the other continued to apply advanced mineral characterization techniques like “X-ray topography” and “Raman spectroscopy.”

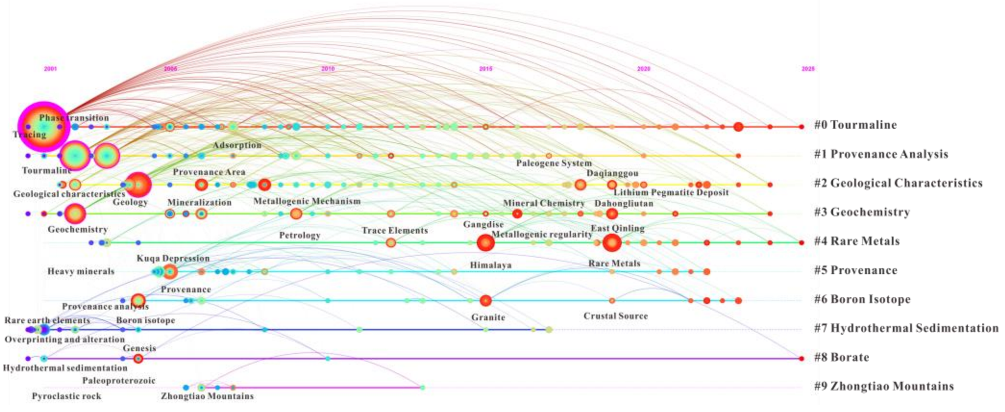


*Figure 4: Timeline of tourmaline research keywords in China.*

In summary, the evolution of Chinese research keywords reflects national priorities related to resource security, energy development, and mineral exploration. China has increasingly focused on rare metal exploration, aligning with green mining and new energy policies. The research paradigm has shifted from mineralogy to a more integrated approach involving “tectonic-magmatic-mineralization.” In contrast, international research, driven by technological advances, has developed into a multidisciplinary approach centered around crystallography, geochemistry, and ore-forming systems. These differences reflect contrasting academic drivers and methodologies: Chinese research emphasizes resource application, while international research focuses on technological innovation and cross-disciplinary approaches. As Chinese research deepens, future studies could benefit from adopting advanced international technologies, merging theory and technology to strengthen tourmaline's role in geochemistry, mineralogy,and resource development.

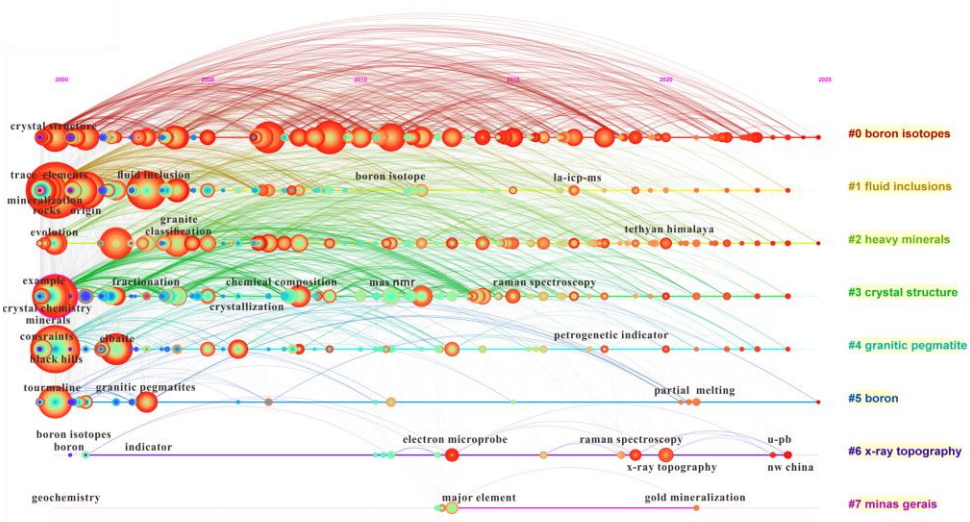


*Figure 5: Timeline of tourmaline research keywords in abroad.*

## 5. Discussion and Recommendations

Tourmaline research exhibits distinct trends between China and the international community. Globally, studies emphasize fundamental mineralogical and geochemical investigations, employing advanced techniques like fluid inclusion analysis and isotope geochemistry to unravel tourmaline's role in ore-forming processes and environmental systems. In contrast, China's research prioritizes applied aspects, particularly in mineral resource exploration and new energy material development, though with relatively less focus on underlying theoretical frameworks. Moving forward, both research communities should synergize their strengths: international efforts should continue pioneering high-precision characterization methods and interdisciplinary applications (e.g., environmental remediation and smart mining through AI integration), while Chinese research would benefit from enhanced foundational studies and technological adoption to bridge current gaps. This convergence of global theoretical innovation with regional application expertise promises to advance tourmaline's scientific understanding and practical utilization in Earth sciences.

The future of tourmaline research lies in three key directions. First, deepening geochemical and metallogenic mechanism studies using cutting-edge analytical techniques will refine its role as a geological indicator. Second, cross-disciplinary integration with crystallography, environmental science, and data analytics will unlock novel applications in sustainable resource development. Third, international collaboration should be strengthened to combine China's resource-focused approach with global theoretical advancements, fostering comprehensive solutions for both scientific challenges and industrial needs in mineral exploration and utilization.

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