

Editorial

Editorial for the Special Issue “Multi-Method (Geo-) Thermochronology and Trace Elements Tracing Magmatism, Mineralization and Tectonic Evolution”

Fan Yang ^{1,*} , Cun Zhang ²  and Jian Chang ³ 

¹ Key Laboratory of Mineral Resources in Western China (Gansu Province), School of Earth Sciences, Lanzhou University, Lanzhou 730000, China

² School of Materials Science and Engineering, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250353, China; gemzhangc@qlu.edu.cn

³ National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing 102249, China; changjian@cup.edu.cn

* Correspondence: fanyang@lzu.edu.cn

With the rapid development of analytical techniques, especially the in situ Lu-Hf, Rb-Sr, U-Pb, fission-track and (U-Th)/He dating of garnet, zircon, apatite and other accessory minerals, several important geological issues have been successfully resolved or re-determined in the past decade [1–4]. Additionally, machine learning approaches help us determine the genetic types of different mineral deposits [5]. Among these, precise temporal evolution and duration of magmatism and mineralized processes, as well as uplift and exhumation history of mineral deposits and basins within orogenic belts and cratons, can assist the exploration of mineral and petroleum resources [6–9]. Further, in situ mineral-scale trace element concentrations could also be simultaneously determined using LA-ICP-MS in situ accessory mineral dating; this would provide new perspectives on the formation and evolution of major geological objects via integration with corresponding ages [1,2]. Although early studies focused on most scientific issues in magmatism, mineralization and tectonic evolution within different geological objects, several aspects of these investigations have not shown agreement.

Thus, this Special Issue, “Multi-Method (Geo-) Thermochronology and Trace Elements Tracing Magmatism, Mineralization and Tectonic Evolution”, highlights state-of-the-art analytical techniques for exploring accurate formation and tectonic mechanisms, as well as new scientific issues related to geological objects (e.g., intrusions, mineral deposits, basins). In total, seventeen manuscripts were submitted for consideration for the Special Issue, and all of them were subject to the rigorous peer review process of *Minerals*. Eventually, ten articles with high qualities contributed by 62 different researchers from about 37 different institutions were accepted for publication and inclusion in this Special Issue.

The contributions are listed in Table 1; most (1, 2, 3, 4, 6, 7, 8, 10) relate to the field of petrology, mineralogy and mineral deposits. Contribution 5 focuses on sedimentology and tectonics, and contribution 9 involves regional tectonics. All submitted articles strictly adhere to the requirement and scope of the Special Issue. The authors employ advanced methodologies including in situ trace element geochemistry, stable isotope geochemistry (e.g., He, Ar, S), multi-technique and high-precision geochronology (e.g., zircon U-Pb, Rb-Sr dating) and thermochronology (e.g., apatite fission-track, (U-Th)/He), as well as simulation and machine learning methods, to conduct comprehensive studies on different rocks, minerals and regional terranes.



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Table 1. Detailed analysis of the ten contributions published in this Special Issue.

Contribution N#	Title	Research Area	Author
1	Petrogenesis of the Laoshan Suite in the Jiaodong Peninsula (Eastern China): An Oxidized Low Ba–Sr A1-Type Granite	Petrology; mineral deposits	Li et al.
2	Genesis of the Daliuhang Gold Deposit, Jiaodong Peninsula, Eastern China: Constraints from H–O–S–Pb–He–Ar Isotopes, and Geochronology	Mineral deposits	Tian et al.
3	Mineralogy and Geochemical Characteristics of Scheelite Deposit at Xuebaoding in Pingwu, Sichuan Province	Mineralogy	Cao et al.
4	Mineralogical Characteristics and Genetic Types of Pyrite with Different Occurrence: Constraints from Spectroscopy, Geochemistry and $\delta^{34}\text{S}$ Stable Isotopes	Mineralogy	Ma et al.
5	Present-Day Geothermal Regime and Thermal Evolution of the Fukang Sag in the Junggar Basin, Northwest China	Sedimentology; Tectonics	Guo et al.
6	Occurrence of State of Gold in Crude Oil and Its Economic Significance	Mineral deposits; Petroleum geology	Ni et al.
7	In Situ Geochemical and Rb–Sr Dating Analysis of Sulfides from a Gold Deposit Offshore of Northern Sanshandao, Jiaodong Peninsula, North China: Implications for Gold Mineralization	Mineralogy; Mineral deposits	Tian et al.
8	Interpretable Machine Learning for Geochemical Anomaly Delineation in the Yuanbo Nang District, Gansu Province, China	Mineral deposits	Zhang et al.
9	Thermochronological Constraints on the Tectonic History of the Arabian–Nubian Shield’s Northern Tip, Sinai, Egypt	Tectonics	Mansour et al.
10	Detrital Zircon Dating, Deformation Stages, and Tectonics of the Pane Chaung Formation and Surrounding Units in the Western Indo-Burma Range, Southeast Asia	Petrology; Tectonics	Zhang et al.

These investigations elucidate magmatic activities, mineralization processes and tectonic evolution within and around orogenic belts and cratons. Contributions 1, 2, 6, 7 and 8 investigate gold enrichments and mineralization. Through extensive experimental research on the affinity of gold with rock bodies including granite and associated Au-hosting minerals such as pyrite and crude oil, these articles offer unique insights into the tectonic environments of gold mineralization and precipitation. Other articles, such as contributions 3 and 4, focus on the mineralogy and formation process of scheelite and pyrite. The remaining two studies (9, 10) focus on a specific area to reveal the issues of tectonic evolution for different geological objects. The details of all contributions are provided below.

Contribution 1 conducts comprehensive analyses of whole-rock major and trace elements, along with LA–ICP–MS zircon U–Pb geochronology and geochemistry, to explore the genetic link between gold mineralization and Mesozoic granites in the Jiaodong Peninsula, Eastern China. The study concludes that oxidized adakitic magmas likely played a significant role in gold enrichment and mineralization. In contrast, the Laoshan A-type granite, characterized by high oxygen fugacity, appears to inhibit gold formation, primarily due to its distal location from the ore-controlling fault zones.

Contribution 2 systematically investigates the genesis of the Daliuhang gold deposit (Jiaodong Peninsula, Eastern China) through multi-isotopic (H–O–S–Pb–He–Ar) geochemistry and geochronology. The results demonstrate that mantle-derived gold-bearing fluids enriched in volatiles migrated along tectonic weak zones. Fluid phase separation at

granite-hosted fault sites facilitated gold extraction from granodiorite, ultimately forming economically significant mineralization.

Contribution 3 characterizes gem-grade scheelite mineralization in the Xuebaoding deposit (Pingwu, Western China) through mineralogical and geochemical analyses. The study establishes a genetic association with A-type granites, constraining scheelite formation to the Early Jurassic under low-sodium conditions.

Contribution 4 employs advanced analytical methods to differentiate sedimentary versus hydrothermal pyrite based on crystallinity, trace element signatures and sulfur isotopes. Sedimentary pyrite exhibits sulfur sourced from granite–sedimentary interactions, while hydrothermal varieties show mixed mantle-derived sulfur with seawater sulfate contributions.

Contribution 5 reconstructs the thermal evolution of the Fukang Sag (Junggar Basin, NW China) using thermochronology (apatite (U-Th)/He, fission-track) and thermal modeling. Findings indicate Late Triassic maturation of Carboniferous–Permian source rocks in the eastern sag, highlighting implications for hydrocarbon generation.

Contribution 6 investigates gold occurrence mechanisms in crude oil from the Linnan Depression (Bohai Bay Basin, Eastern China). Gold enrichment is attributed to complexation with organic acids/thiols, establishing crude oil as a potential transport medium for precious metals under specific geological conditions.

Contribution 7 (by the same team as Contribution 2) employs in situ sulfide geochemistry and Rb-Sr dating to constrain gold mineralization processes in the Jiaodong Peninsula, Eastern China. The results propose a mixing model between deep magmatic–hydrothermal fluids and seawater as the critical precipitation mechanisms.

Contribution 8 pioneers interpretable machine learning applications for geochemical anomaly detection in the Yuanbo Nang District, NW China, with an aim to extract richer insights from the ML modeling of a geochemical exploration dataset. The work elucidates the impact of different trace elements (e.g., As, Sb) on gold mineralization. The findings hold substantial guiding value for future mineral exploration and geological surveys.

Contribution 9 reconstructs the tectonic history of the Arabian–Nubian Shield’s northern margin (Sinai, Egypt) through thermochronology, identifying four cooling phases linked to (1) Neoproterozoic post-accretion erosion, (2) Devonian–Carboniferous Variscan tectonism, (3) Cretaceous Gondwana breakup and (4) Oligocene–Miocene Gulf of Suez rifting.

Contribution 10 utilizes detrital zircon geochronology to decipher deformation stages in the Indo-Burma Range’s Pane Chaung Formation. The results reveal dual subduction dynamics during Gondwana–microcontinent interactions in SE Asia, and the characteristic of orogenic doublet subduction systems in the Indo-Myanmar orogenic belts.

In the Special Issue, most researchers employed traditional approaches to conduct investigations into the genetic mechanisms and tectonic evolution of certain minerals, rocks and other geological objects. However, all the contributions ultimately failed to contemplate establishing tectonic model diagrams to clearly interpret the fluid migration, source characteristics and enrichment processes of different elements. Quantitative evaluation in this area is required in the future. In the Special Issue, five contributions, accounting for 50% of total articles, focus on gold deposits, highlighting that formation mechanisms and tectonic evolution models of gold deposits remain significant research hotspots and challenges in contemporary academia. Despite extensive studies investigating the precipitation mechanisms of gold, most research explores its pre-mineralization, formation processes and age information from associated Au-hosting minerals. In addition, studies demonstrating temporal evolution, tectonic exhumation and preservation potential are still lacking in research on the post-mineralization assessment of gold deposits [10].

In summary, the Special Issue confirms that a growing number of researchers are working on various fields of mineralogy, petrology, mineral deposits and tectonics and sedimentology. Certainly, future research directions ought to be further pursued in terms of new production areas, new methods and interdisciplinary intersections. Hopefully, this series of articles will contribute to a better understanding of scientific issues of magmatism, mineralization and tectonic evolution in different geological objects.

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