

Revisiting the IOCG Sin Quyen Deposit, Lao Cai Province: A New Perspective on Fluid Evolution and Ore Genesis

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Abstract: *The Sin Quyen deposit in northern Vietnam is a representative Fe–Cu–REE (iron–copper–rare earth element) system genetically linked to prolonged magmatism and structurally controlled fluid flow. This study integrates fluid inclusion, isotopic, and mineral chemical data to define a three-stage hydrothermal evolution: (1) an early high-temperature REE stage (~880 Ma), (2) a main-stage Fe–Cu stage (~840 Ma), and (3) a late Cu–Au overprint (~35 Ma). The early REE stage involved high-temperature, moderate-salinity fluids of crustal origin. The main Fe–Cu stage was driven by moderate-temperature fluids with a significant mantle component, as indicated by Nd–S isotopes. The late epithermal Cu–Au stage was facilitated by low-temperature meteoric fluids during Paleogene tectonic reactivation. The entire system developed in an active continental margin, where episodic subduction-related magmatism and crust–mantle interaction were critical for metal endowment. This model underscores the importance of targeting areas with long-lived, composite magmatic-hydrothermal history for regional IOCG and REE exploration in Southeast Asia. Our findings provide a robust framework for identifying similar polyphase mineralization systems in analogous tectonic settings, particularly along reactivated structures in ancient continental margins.*

Keywords: *Copper ore; Sin Quyen deposit; Lao Cai; IOCG*

1. Introduction

Iron Oxide Copper Gold (IOCG) deposits are a economically significant class of mineralization defined by abundant low-Ti iron oxides and Cu-sulfides, commonly enriched in Au, Ag, REEs, and U (Hitzman et al. 1992). They form in extensional tectonic settings, often along major crustal structures in continental margins, and are broadly associated with magmatic activity and high heat flow (Hitzman et al., 1992; Sillitoe, 2003; Williams et al., 2005). A central debate in their genesis concerns the source of the ore-forming fluids, with models ranging from purely magmatic (e.g., Pollard, 2000; Sillitoe, 2003) to non-magmatic brines (e.g., Barton & Johnson, 1996), though a hybrid fluid-mixing origin is increasingly favored (e.g., Haynes et al., 1995; Baker et al., 2008). These systems are characterized by high-temperature (200–500°C), saline fluids that drive extensive sodic-calcic and iron-rich alteration, culminating in diverse ore bodies controlled by faults and lithological contacts (Williams et al., 2005; Corriveau & Mumin, 2008).

The Sin Quyen deposit in northern Vietnam is a premier example of an IOCG system with significant REE enrichment. It hosts substantial reserves of Cu, Au, Fe, and REEs, the latter contained primarily in allanite rather than the more common REE-fluorocarbonates (Li et al., 2017a). This distinctive mineralogy points to a unique genetic process. Previous studies have proposed conflicting models for its formation, attributing it to either Cenozoic alkaline magmatism (Ishihara et al., 2011) or a Neoproterozoic (~840 Ma) magmatic-hydrothermal event (Li et al., 2017a). However, recent field evidence revealing complex mineral textures and paragenesis suggests the deposit may be the product of multiple mineralization episodes, a possibility that existing geochronological and geochemical data have not fully resolved.

This persistent ambiguity highlights a critical research gap: a lack of robust, multi-method constraints on the timing, fluid sources, and evolutionary history of the Sin Quyen deposit. To address this, we present an integrated study combining U–Pb geochronology of hydrothermal allanite, Nd isotope analysis of titanite, and detailed fluid inclusion microthermometry. Our results delineate three distinct mineralization stages and identify the evolving crustal and mantle contributions to the ore-forming system. This study not only clarifies the complex polygenetic history of the Sin Quyen deposit but also provides a refined genetic model that enhances the exploration criteria for IOCG-REE systems in Southeast Asia and analogous tectonic settings.

2. Geological setting

Northwestern Vietnam belongs to the South China and Indochina blocks (Figs. 1a, b). These blocks are integral components in the Paleogeographic reconstruction of the Rodinia supercontinent (Metcalf, 2002; 2006; Golonka et al., 2006; Hung, 2010). Several copper deposits, including the Iron Oxide Copper-Gold (IOCG) deposits of Sin Quyen, and copper Suoi Thau, Ta Phoi, are distributed in Northwestern Vietnam (Fig. 1c).

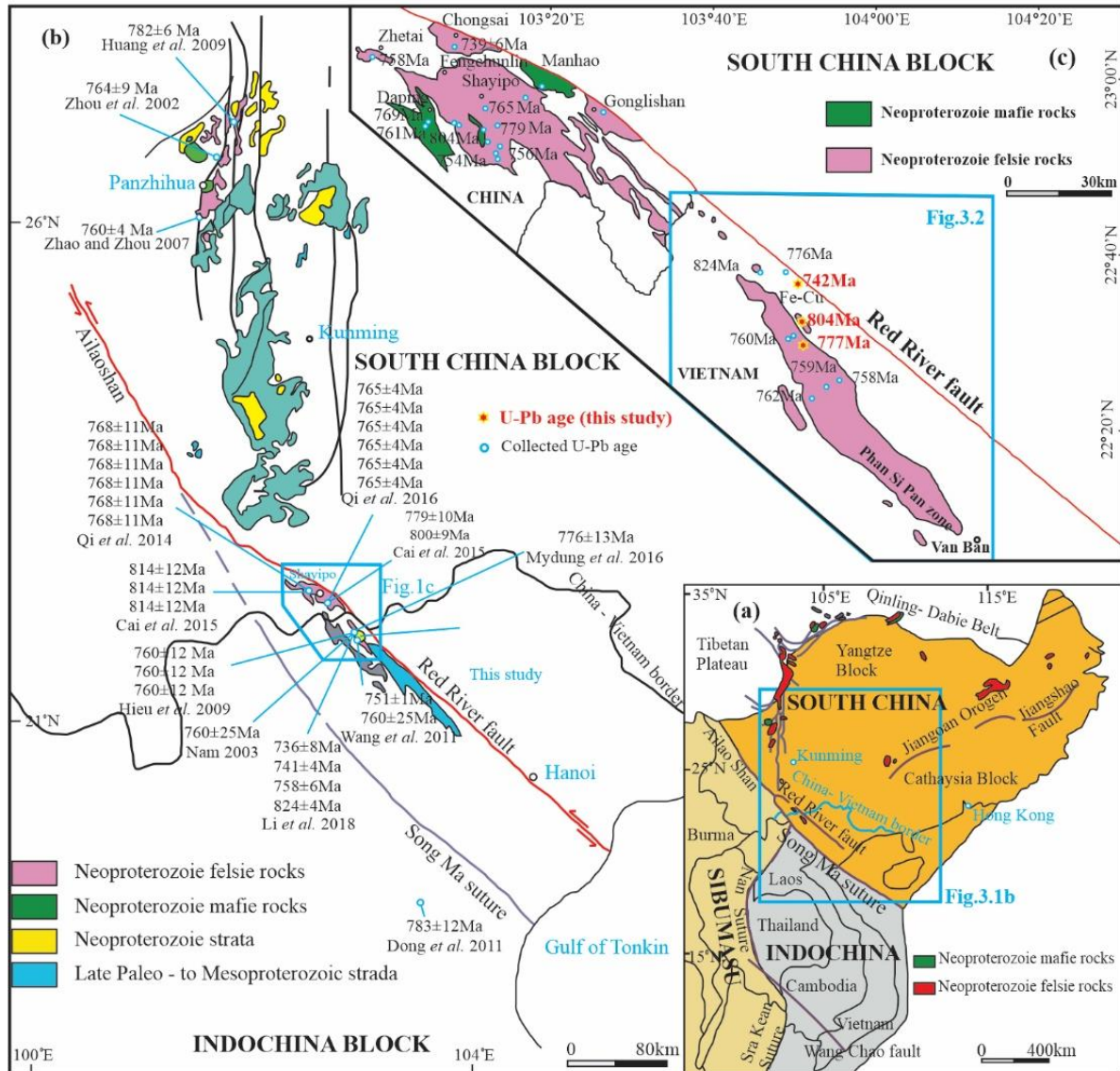


Fig. 1. Simplified tectonics map of NW Vietnam and adjoining areas (Pham et al., 2009; Wang et al., 2016; Qi et al., 2016; Minh et al., 2021 and references therein)

The Sin Quyen deposit is bordered by the Song Chay fault to the north and the Song Ma belt to the south (Tri & Khuc, 2011) (Fig. 2a). This region comprises three major tectonic units: the Phan Si Pan zone, the Song Da rift, and the Tu Le basin (Fig. 2a). The Song Da rift is an elongated, northwest-southeast trending structure characterized by Devonian to Middle Triassic sedimentary-volcanic sequences. A prominent feature of this rift is the well-developed Permo-Triassic alkaline basalts (~260 Ma), which are primarily distributed along the Da River (Polyakov et al., 1998). These basalts, along with silicic volcanic rocks, rest atop Early Permian limestone and are subsequently overlain unconformably by Triassic limestone and shale containing coal deposits (Anh et al., 2011; Metcalfe 2012). Some studies suggest that the Song Da volcanic suite is linked to the Emeishan plume (Faure et al., 2014; 2016; Minh et al., 2018). The Tu Le Basin is predominantly composed of rhyolite, trachyrhyolite, and trachydacite. Zircon U-Pb dating indicates that the rhyolites in this basin formed during the Late Permian (262–252 Ma), contemporaneous with the mafic rocks of the Song Da Rift (Usuki et al., 2015; Tran et al., 2015).

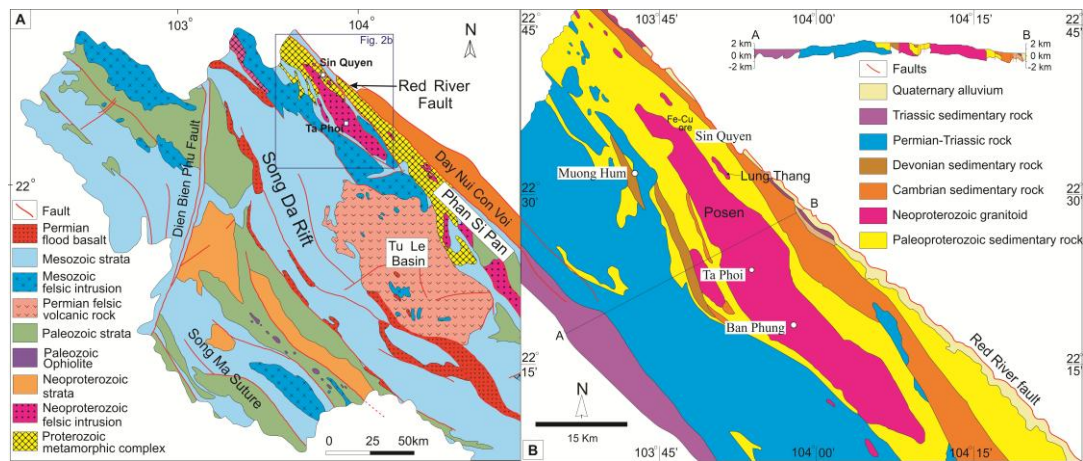


Fig. 2. Geological map of (a) northwestern Vietnam and (b) the Phan Si Pan zone and showing location of the Ta Phoi deposit (modified after DGMVN, 1995)

The Phan Si Pan zone serves as a tectonic link between two major crustal blocks: the North Vietnam–South China block and the Indochina block (Fig. 2b). It is positioned between the Red River shear zone and the Tu Le basin and is composed primarily of Mesoarchean to early Paleoproterozoic basement rocks, including biotite quartzite, quartz-biotite-garnet schist, and amphibolite (Minh et al., 2021; Pham et al., 2022). Paleo-Mesoproterozoic units in the zone consist of biotite schist, two-mica schist, and amphibolite (Minh et al., 2021; Pham et al., 2022). Precambrian magmatism in the Phan Si Pan zone is characterized by several granitoid and mafic intrusive events, including: Mesoarchean granitoids (2.9–2.8 Ga) (Pham et al., 2022; Lan et al., 2001; Nam 2003), Paleoproterozoic granitoids (1.8–2.2 Ga) (Pham et al., 2022; Nam 2003; Zhao et al., 2019; 2023), Paleoproterozoic mafic dykes (1.8–2.3 Ga) (Pham et al., 2022), and Neoproterozoic granitoids (760–751 Ma) (Pham et al., 2009; Wang et al., 2011; 2016; Minh et al., 2021).

The Mesoarchean–Paleoproterozoic crystalline basement is unconformably overlain by Paleozoic–Mesozoic meta-sedimentary and sedimentary sequences, which include quartz-sericite-chlorite schist, quartzite, limestone, and dolomite (Figs. 2a, b). In addition to the Precambrian granitoids, voluminous A-type granites were emplaced during the Late Permian–Early Triassic, closely associated with the Emeishan mantle plume (Wang et al., 2011; Usuki et al., 2015; Tran et al., 2015; Minh et al., 2021). Cenozoic plutons have also been identified in the region (Pham et al., 2013; Dung et al., 2023).

The Neoproterozoic granitoid intrusions in the Phan Si Pan zone include the Posen, Phin Ngan, and Lung Thang plutons, along with several smaller bodies and lenses (Fig. 2b) (Li et al., 2018). These intrusions are comparable to the widely distributed Neoproterozoic granitoids (~860–740 Ma) in the western and southwestern Yangtze Block (Fig. 1) (Zhou et al., 2002; Zhao & Zhou 2008; Cai et al., 2014; 2015; Li et al., 2018; Ngo et al., 2024).

3. The Sin Quyen deposit

The Sin Quyen-Lung Po district, situated within the northeastern Ailao Shan-Phan Si Pan tectonic belt, hosts over ten iron-copper deposits, constituting Vietnam's principal copper metallogenic province (Fig. 2b). Its largest deposit, Sin Quyen, possesses proven reserves of 52.8 million tonnes (Mt) grading 14% Fe, 0.91% Cu, 0.7% light rare earth elements (LREE: La, Ce, Nd), and 0.44 g/t Au (McLean, 2001). Recent deep drilling to 550 meters has delineated further resources exceeding 90 Mt averaging 0.9% Cu (Pham, 2015). Open-pit operations, commencing in 2006, yield approximately 30,000 tonnes of copper metal annually. Although LREE concentrations are significant, they remain unrecovered.

Mineralization comprises 17 lenticular to sheet-like ore bodies, predominantly east-west striking and steeply north- or south-dipping (Fig. 3a). Individual bodies measure 50–600 m in length, 5–100 m in width, and extend vertically up to 350 m (elevation: 50–450 m asl). These are hosted within mica schists and marbles of the Sin Quyen Formation and exhibit massive or banded textures. The deposit area is intruded by felsic dikes (monzogranite, granodiorite, granite). Figure 3b emplaced between 736 ± 8 Ma and 758 ± 6 Ma (U-Pb zircon; Li et al., 2017a). Mafic dikes, of unknown age, are also present and display variable greenschist/amphibolite-facies alteration to chlorite, actinolite, epidote, sericite, and magnetite.

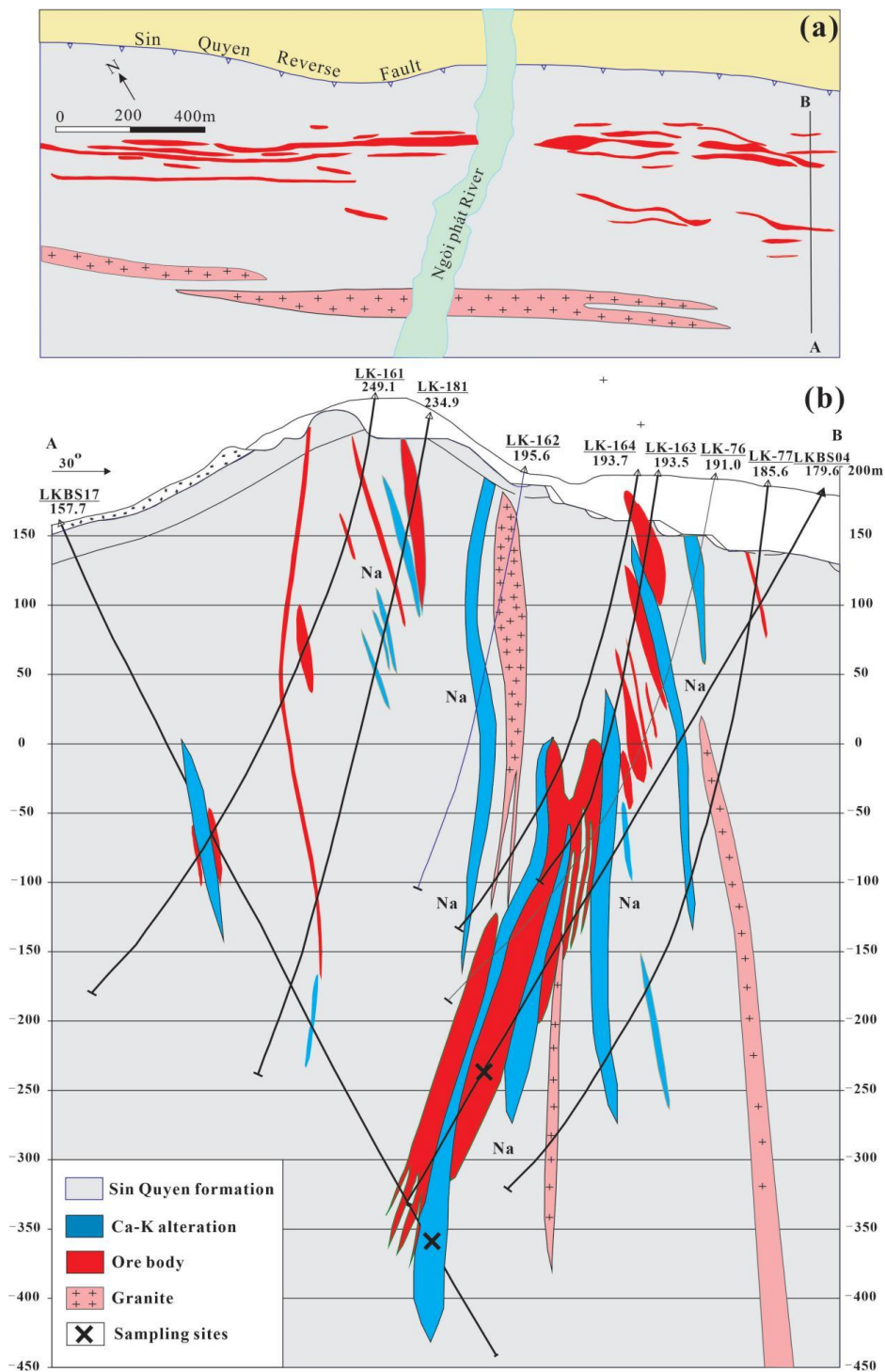


Fig. 3. Simplified geological map of the Sin Quyen deposit (modified from Ta, 1975)

While previous studies proposed three main alteration/mineralization stages (Li et al., 2017b, 2018), current field and petrographic evidence supports two distinct episodes (Fig. 4). Episode 1 features REE-dominant mineralization associated with Ca-skarn. It initiates with pre-ore Na-alteration in metasedimentary host rocks (Stage I-1; Fig. 5a), overprinted by localized, intense Ca-alteration and REE mineralization (Stage I-2). REE-rich samples contain abundant amphibole, allanite, and titanite, with subordinate biotite and epidote (Fig. 6b). Amphibole zonation suggests subsequent metasomatism. Coarse (200–1000 μm), euhedral to subhedral allanite is commonly partially replaced by epidote (Stage I-3; Figs. 5c,d). Episode 2 comprises four stages broadly correlating to prior descriptions: pre-ore Na-alteration (Stage II-1; albization; Figs. 5e,f), Ca-K alteration with Fe-LREE mineralization (Stage II-2; amphibole, titanite, magnetite, chalcopyrite; Figs. 5g,h), K-Fe alteration with Cu-Au mineralization (Stage II-3; biotite-chalcopyrite intergrowths; Fig. 5i), and post-ore quartz-sulfide veins (Stage II-4).

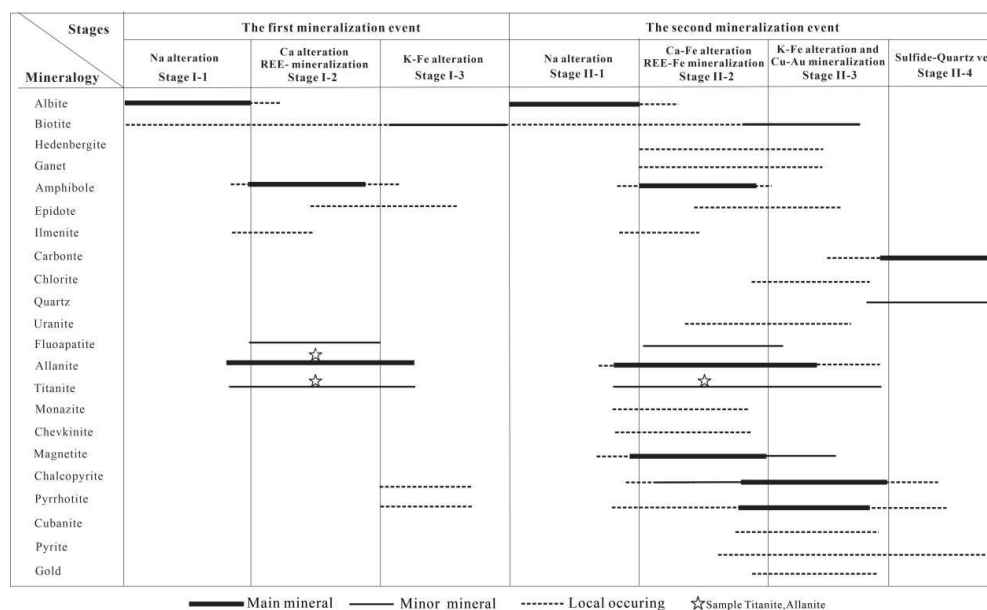


Fig. 4. Paragenetic sequence of mineralization and alteration in the Sin Quyen deposit. REE-minerals include allanite, titanite, monazite, xenotime; Carbonate minerals include calcite (after Ngo et al. 2020).

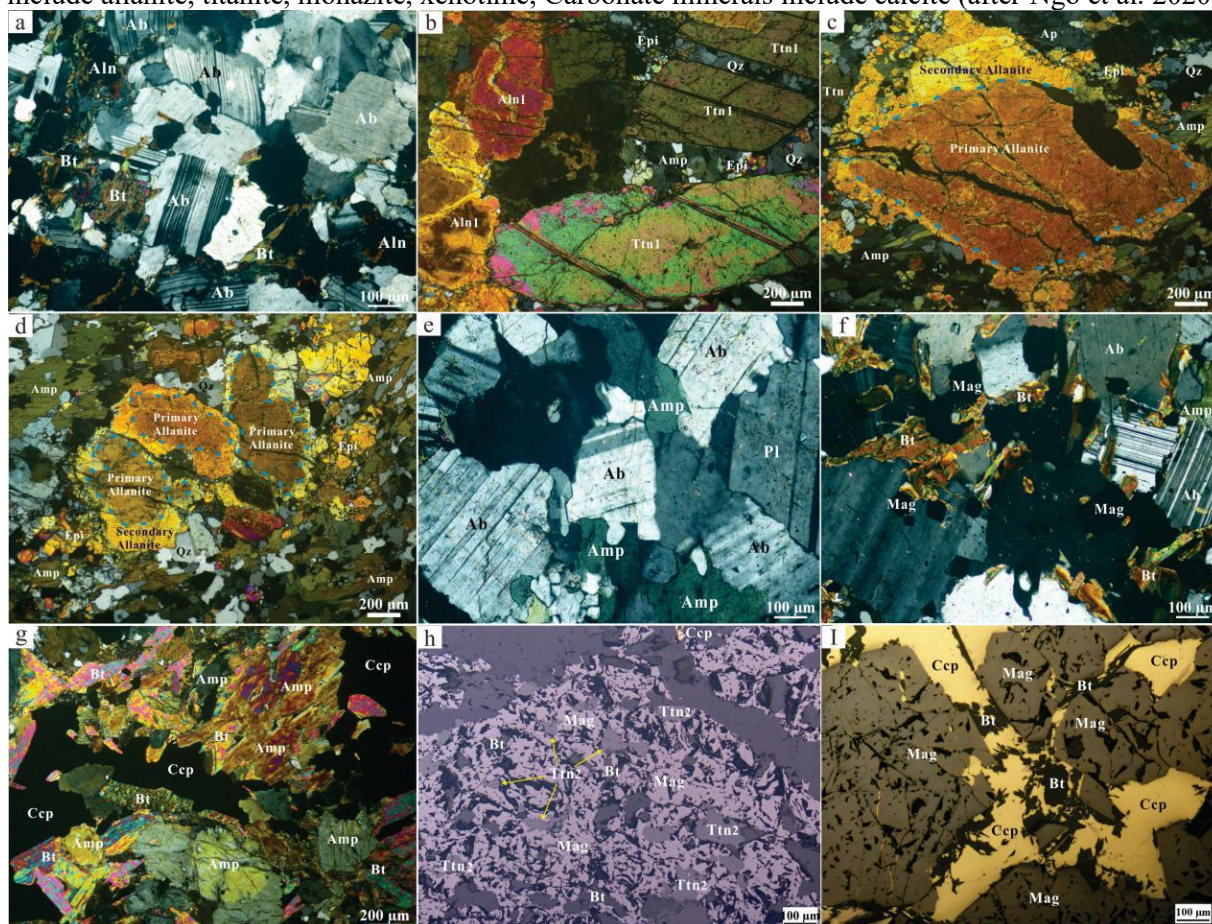


Fig. 5. Photomicrographs of representative alteration minerals of episode 1 (a–d) and 2 (e–i). (a) Early-stage albite grains overprinted by late-stage allanite and biotite of episode 1 mineralization event. (b) Big allanite and titanite (Ttn 1) grains associated with amphibole and less amount of epidote. (c–d) Allanite grain have been variably altered to form secondary allanite, which are overprinted by late-stage epidote. (e) The country rocks with extensive albitization of episode 2. (f) Early stage albite grains overprinted by late-stage amphibole, biotite and magnetite. (g) Amphibole grains overprinted by biotite and chalcopyrite. (h) Small titanite grains (Ttn2) from the second mineralization event associated with magnetite, and biotite. (i) Biotite intergrown with chalcopyrite and magnetite (after Ngo et al., 2020)

4. Methodology

4.1. Study material and petrography observation

A total of 50 mineralogical samples were collected from both surface and subsurface locations across the copper ore bodies. Additionally, five sulfide copper ore samples were analyzed using SEM to determine suitable locations for analyzing titanite associated with ore minerals. From these, two samples were selected for Nd isotopic analysis, while five quartz samples associated with sulfide ores were used for fluid inclusion microthermometry.

This study utilized sulfide copper ore samples and associated gangue minerals, including titanite and quartz, collected from both surface and subsurface exposures of the Sin Quyen deposit. Selected samples were prepared as polished sections and observed under optical microscopy and Scanning Electron Microscopy (SEM) for mineral identification, textural relationships, and alteration features of titanite and associated minerals.

4.2. Analytical methods

4.2.1. SEM analysis

SEM observations were conducted using an FEI Quanta 200 microscope equipped with an EDS system at 20 kV and 20 nA. Back-scattered electron (BSE) imaging was applied to study zoning, morphology, and alteration features of titanite. Analyses were performed at the National Key Laboratory, China University of Geosciences (Wuhan).

4.2.2. Fluid inclusion microthermometry

A total of 5 quartz-hosted fluid inclusion samples, associated with chalcopyrite mineralization, were selected for temperature and pressure conditions analysis of ore formation. Doubly polished quartz sections (~0.20 mm thick) were analyzed using a Linkam THMSG 600 heating-freezing stage mounted on an Olympus BX51 microscope. The fluid inclusion study focused on primary, pseudosecondary, and secondary inclusions based on established classification criteria (Roedder, 1984; Van den Kerkhof & Hein, 2001). Eutectic and melting temperatures were used to estimate salinity and fluid density, with calculations performed using the FLINCOR software. Temperature accuracy was $\pm 0.2^\circ\text{C}$ between -20°C and $+20^\circ\text{C}$.

4.2.3. Sulfur isotope analysis

Sulfur isotope measurements were conducted using a Delta V Plus mass spectrometer at the CNNC Beijing Research Institute of Uranium Geology. Results are reported in $\delta^{34}\text{S}$ values relative to the V-CDT standard, with analytical precision better than $\pm 0.2\text{‰}$ (2σ).

4.2.4. Nd isotope analysis

The samples analyzed were obtained from drill cores and show no signs of weathering. Neodymium (Nd) isotopic analyses of titanite were conducted using a Neptune Plus MC-ICP-MS equipped with a Geolas HD excimer ArF laser ablation system (Coherent, Göttingen, Germany) at the China University of Geosciences. Helium was used as the carrier gas for the ablation process, with argon introduced as a make-up gas after ablation. To enhance the sensitivity of Nd isotope measurements, a small amount of nitrogen was introduced into the argon gas stream, following the method proposed by Xu et al. (2015). The laser spot size was set to 90 μm , adjusted according to the Nd signal intensity. The laser repetition rate was set at 10 Hz, with a fluence maintained at approximately 8 J/cm². A signal-smoothing device was employed to effectively reduce short-term signal fluctuations and remove mercury from the background, as described by Hu et al. (2015). Mass bias correction for $^{143}\text{Nd}/^{144}\text{Nd}$ was applied using the exponential law, normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Interference of ^{144}Sm on ^{144}Nd was corrected using $^{144}\text{Sm}/^{149}\text{Sm} = 0.2301$ and the monitored ^{149}Sm signal. To verify the accuracy of the calibration method for Nd isotope analysis in titanite, two reference materials, MKED1 and SP-Ttn-01, were used as standards.

5. Results and Discussion

5.1. Insights into Fluid Sources and Hydrothermal Processes in a Multi-Stage IOCG Deposit

The Sin Quyen deposit records a complex, multi-stage hydrothermal evolution, with distinct fluid compositions, sources, and temperature–pressure conditions across different mineralization episodes. Integration of fluid inclusion microthermometry, rare earth element (REE) mineral chemistry, and isotopic datasets (Nd, S), together with regional geochronological and petrological evidence, reveals a progressive transition from crustal-derived magmatic brines to mixed and meteoric-dominated fluid systems. These stages are closely tied to tectonomagmatic activity and structural evolution along the Ailao Shan–Red River suture zone.

5.1.1. Early-stage REE Mineralization (~880 Ma)

This earliest hydrothermal episode is interpreted as being controlled by high-temperature (300–400°C), moderately saline brine fluids exsolved from evolved felsic magmas. Fluid inclusion microthermometric data from quartz (Tab. 1; samples Nos. 2, 3, 5, 7, 10, 13) show homogenization temperatures of 300–386°C, salinities of 3.0–5.2 wt.% NaCl equivalent, and fluid densities of 0.71–0.77 g/cm³, with estimated formation depths around 3.5–4.5 km. These characteristics point to a hybrid fluid system formed by interaction of magmatic brines with circulating basinal or meteoric waters under oxidized conditions.

Isotopic evidence supports this interpretation. Titanite and allanite associated with REE ores show highly negative $\epsilon\text{Nd}(t)$ values ranging from –7.0 to –5.4 (Tab. 2; sample X147), indicating derivation from crustal sources with partial assimilation of metasedimentary basement rocks. As shown in Figure 6, these REE-stage titanites (light blue) overlap significantly with $\epsilon\text{Nd}(t)$ values of meta-sedimentary rocks (orange) and Sin Quyen granitoids (blue), reinforcing the crustal affinity of the early fluid sources.

SEM–EPMA data from primary allanite grains (U–Pb age ~880 Ma) show strong LREE enrichment (La_2O_3 : 5.73 wt.%; Ce_2O_3 : 7.87 wt.%), while secondary alteration rims exhibit LREE depletion (Ngo et al., 2020), suggesting partial remobilization of REE during later-stage hydrothermal overprints. This points to redox-controlled fluid–rock interactions and early mineral zoning typical of high-temperature IOCG-type systems.

5.1.2. Main-stage Fe–Cu Mineralization (~840 Ma)

The second hydrothermal stage, dated at ~840 Ma, reflects a shift toward lower-temperature (250–350°C) fluid regimes with continuing magmatic contributions, but with a greater role for mantle-derived inputs. Fluid inclusions from this stage (Tab. 1; Nos. 14–28, 32–40) show salinities of 2.86–6.01 wt.% NaCl, variable densities (0.59–0.77 g/cm³), and pressure estimates up to ~1300 bar, indicating moderately saline, Fe–Cu-rich fluids emplaced at depths of 4–5 km.

Nd isotopic compositions of titanite from this stage (sample H505, Tab. 2) yield $\epsilon\text{Nd}(t)$ values of –4.3 to –2.0, significantly less negative than those of the REE-stage titanites. In Figure 6, these Fe–Cu titanites (pink) plot closer to the fields of the Lung Thang intrusion (cyan) and Po Sen granitoids (magenta), reflecting an increased contribution from juvenile mantle-derived magmas. These isotopic trends suggest that the Fe–Cu mineralization was genetically linked to renewed felsic–mafic magmatism, possibly triggered by tectonic reactivation and crust–mantle interaction.

Additionally, sulfur isotope data ($\delta^{34}\text{S} = 0 \pm 3\text{‰}$) from associated sulfides support a dominantly magmatic sulfur source, with limited crustal contamination. The alteration patterns during this stage—marked by Na- and K-rich halos—are consistent with widespread hydrothermal overprinting and metal redistribution within the IOCG system.

5.1.3. Late-stage Cu–Au Mineralization (~35 Ma)

The final hydrothermal event at Sin Quyen is associated with Paleogene tectonic reactivation along the Red River Fault Zone. It is characterized by low-temperature (<250°C), low-salinity fluids dominated by meteoric water. Fluid inclusion data (Tab. 1; e.g., sample No. 50) show homogenization temperatures of 220°C, salinity of 4.65 wt.% NaCl, and fluid density of 0.877 g/cm³, consistent with surface-derived fluids circulating through reactivated fault networks.

This stage resulted in localized Cu–Au enrichment and formed an epithermal overprint on the pre-existing REE and Fe–Cu ore system. Despite its limited spatial extent, it provides evidence of late-stage fluid ingress and remobilization linked to tectonic rejuvenation.

Figure 6 clearly illustrates the temporal evolution of $\epsilon\text{Nd}(t)$ values across different mineralization stages. Early REE-stage titanites exhibit overlap with Sin Quyen granitoids and metasedimentary rocks, consistent with crustal-dominated sources. In contrast, Fe–Cu titanites plot closer to more juvenile signatures represented by the Lung Thang and Po Sen intrusions, reflecting increasing mantle involvement. This evolution supports a progressive deepening of magmatic input over time and the influence of successive felsic–mafic magmatic pulses.

Overall, the integrated data from fluid inclusions, REE chemistry, and Nd isotopes confirm that the Sin Quyen deposit formed through a polyphase hydrothermal system, controlled by episodic felsic magmatism, structural focusing, and dynamic crust–mantle fluid interaction. The coupling of magmatic evolution with structural permeability changes (e.g., fault reactivation) played a key role in spatially and temporally separating REE and Fe–Cu mineralization, with a late-stage epithermal event overprinting the entire system.

Tab. 1. Fluid inclusion microthermometry data of quartz (after Ngo et al., 2022)

Number	T _{m.ice} (°C)	T _h (°C)	Salinity wt% NaCl	Density (g/cm ³)	Pressure (Pa)	Depth (Km)
1	-2.6	296	4.34	0.762	978	3.58
2	-2.7	302	4.49	0.753	1003	3.71
3	-2.5	304	4.18	0.746	968	3.50
4	-2.2	307	3.71	0.735	971	3.52
5	-2.4	310	4.03	0.733	955	3.40
6	-2.1	311	3.55	0.725	969	3.51
7	-2.3	319	3.87	0.714	965	3.48
8	-2.5	300	4.18	0.753	953	3.39
9	-2.6	321	4.34	0.717	972	3.53
10	-2.7	290	4.49	0.774	984	3.63
11	-2.8	295	4.65	0.767	990	3.67
12	-2.9	299	4.80	0.762	1225	4.50
13	-2.5	320	4.18	0.717	996	3.69
14	-2.1	350	3.55	0.647	1111	4.00
15	-2.6	318	4.34	0.723	1118	4.20
16	-2.5	345	4.18	0.668	1261	4.68
17	-2.1	348	3.55	0.651	1182	4.35
18	-2.4	355	4.03	0.644	1215	4.40
19	-2.1	372	3.55	0.598	1152	4.21
20	-2,3	375	3.87	0.597	1126	4,10
21	-2,4	380	4.03	0.589	1110	3,99
22	-2	385	3.39	0.564	1143	4,15
23	-1,8	300	3.06	0.739	997	3,70
24	-1,9	308	3.23	0.727	1104	3,73
25	-2,3	332	3.87	0.689	1289	4.80
26	-3.5	339	5.71	0.702	1276	4.72
27	-3.6	345	5.86	0.693	1262	4.69
28	-3.2	350	5.26	0.674	1237	4.50
29	-2.9	328	4.80	0.710	907	3.00
30	-2.8	313	4.65	0.736	923	3.15
31	-3.7	272	6.01	0.818	1275	4.71
32	-3.5	275	5.71	0.811	1282	4.74
33	-3.3	380	5.41	0.615	1320	4.95
34	-2.3	386	3.87	0.572	1267	4.40
35	-2.4	295	4.03	0.760	940	5.10
36	-2.6	318	4.34	0.723	924	3.40
37	-2.4	355	4.03	0.644	942	2.80
38	-2.5	272	4.18	0.799	1280	4.20
39	-2.8	375	4.65	0.612	1339	3.30
40	-2.3	280	3.87	0.783	1267	4.70
41	-2.9	285	4.80	0.785	1251	4.55
42	-4.3	300	5.41	0.768	1234	4.50
43	-3.5	308	4.49	0.743	1368	5.00
44	-3.3	332	5.41	0.711	1386	5.10
45	-2.5	339	5.71	0.702	1252	4.57
46	-2.7	345	4.49	0.673	1279	4.76
47	-3.3	350	4.49	0.662	1240	4.52
48	-3.5	328	5.41	0.719	1124	4.00
49	-2.7	313	5.71	0.749	1181	4.34
50	-2.8	220	4.65	0.877	986	3.65

Tab. 2. Nd isotope compositions of titanite from metamorphic sediments and felsic intrusive rocks in the Sin Quyen deposit

Sample	Number	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{\text{Nd}}(\text{t})$
Rare earth ores	X147	0.11887	0.51190	-5.7
		0.11638	0.51185	-6.3
		0.12982	0.51193	-6.3
		0.12146	0.51189	-6.2
		0.11561	0.51187	-5.8
		0.11551	0.51185	-6.3
		0.10767	0.51180	-6.4
		0.10057	0.51178	-5.9
		0.11150	0.51185	-5.8
		0.12224	0.51191	-5.8
		0.11375	0.51185	-6.0
		0.13044	0.51194	-6.1
Fe-Cu ores	H505	0.08525	0.51187	-3.0
		0.07618	0.51182	-2.9
		0.11481	0.51202	-3.3
		0.07818	0.51188	-2.0
		0.08655	0.51184	-3.8
		0.10091	0.51194	-3.3
		0.11004	0.51203	-2.5
		0.10292	0.51201	-2.2
		0.08370	0.51183	-3.6
		0.12181	0.51201	-4.3
		0.09487	0.51189	-3.7
		0.07033	0.51174	-4.0
Lung Thang granitoids (Ngo et al., 2022)	LT1	0.1025	0.51189	-6.0
	LT2	0.09599	0.51183	-6.2
Granite of Po Sen complex (Ngo et al., 2022)	PS1	0.09571	0.51193	-4.1
	PS2	0.13065	0.51193	-4.2
Granitoids in the Sin Quyen deposit (Ngo et al., 2022)	SQ1	0.13301	0.512	-6.2
	SQ2	0.11187	0.51203	-6.0
Granitoids of the Phin Ngan massif (Li et al., 2018)	PN-03	0.1149	0.511767	-8.4
	PN-04	0.1032	0.511841	-5.7
	PN-05	0.1007	0.511855	-5.2
Granitoids in the Sin Quyen mine (Li et al., 2018)	SQ-05	0.1198	0.512016	-4.8
	SQ-06	0.1177	0.51203	-4.3
	SQ-80	0.1364	0.512006	-6.6
	SQ-127A	0.1189	0.511968	-5.6
	SQ-129A	0.1133	0.511975	-4.9
Metamorphic rocks of the Sin Quyen formation (Li et al., 2018)	SQ14-12	0.119	0.511911	-6.7
	SQ14-14	0.119	0.511857	-7.8
	SQ14-15	0.1116	0.511862	-7.0

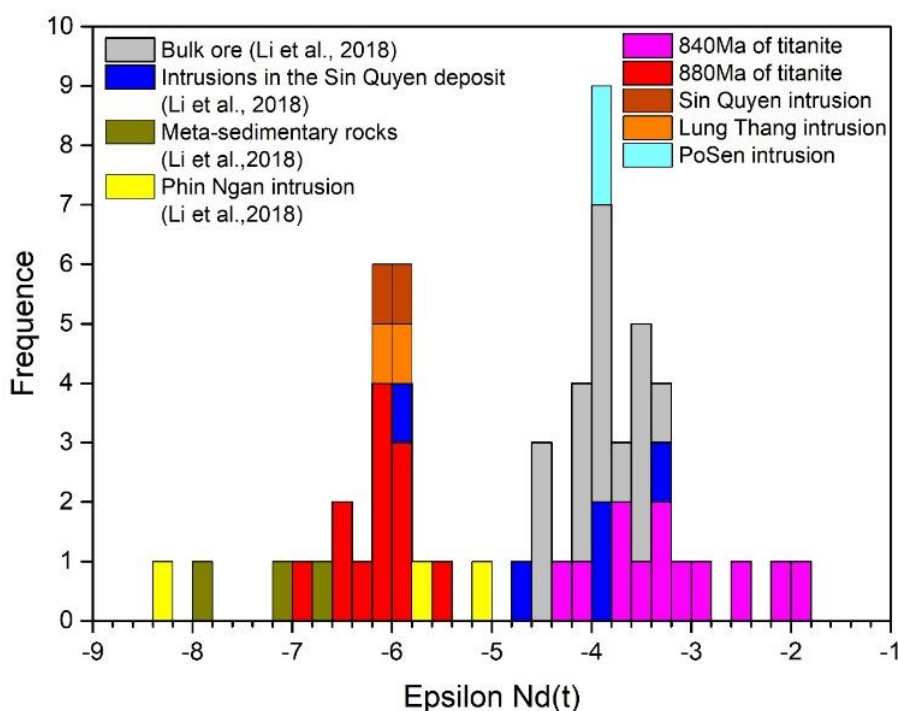


Fig. 6. $\epsilon\text{Nd}(t)$ values of two titanite types compared with regional felsic intrusions, metasedimentary rocks, and the Sin Quyen deposit (758–736 Ma) (Li et al., 2017a; Ngo et al., 2022) and the Lung Thang pluton (800 Ma) (Ngo et al., 2022)

5.2. Origin of the Sin Quyen Deposit

The Sin Quyen deposit is interpreted to have formed through a polyphase hydrothermal system associated with long-lived felsic magmatism and structurally focused fluid flow. Isotopic (S, Nd) and geochronological constraints (U–Pb dating of allanite and zircon/monazite) indicate that the ore-forming materials were primarily sourced from magmatic reservoirs, with variable involvement of crustal components (Li et al., 2018; Ngo et al., 2020).

As illustrated in Figure 7, the deposit is situated within a tectonic framework characterized by subduction rollback and back-arc extension. This setting facilitated the ascent of Cl-rich fluids from the subducted slab into the overlying mantle wedge and lower crust. Partial melting of the metasomatized lower crust gave rise to REE-enriched felsic magmas. These magmas intruded into the upper crust and released high-temperature magmatic fluids rich in REE, Cl, and S during degassing. These fluids migrated upward through brittle fracture systems and accumulated in favorable structural traps, leading to the precipitation of REE minerals (mainly allanite, monazite, and titanite) during the first hydrothermal event at ~880 Ma.

The second hydrothermal stage, dated at ~840 Ma, was linked to renewed felsic to mafic magmatic activity and accompanied by tectonic reactivation (Fig. 7b). During this stage, Fe–Cu-rich fluids, possibly derived from deeper intrusions or hybrid magmas, ascended through the same or newly activated fault systems. This phase was associated with moderate-temperature fluids (250–350°C), moderate salinities, and strong alteration zonation, including K- and Na-dominated hydrothermal halos. Sulfur isotope compositions ($\delta^{34}\text{S} \approx 0 \pm 3\%$) indicate a dominantly magmatic sulfur source, while Nd isotopes from titanite ($\epsilon\text{Nd}(t) = -4.3$ to -2.0) reflect increasing mantle input compared to the earlier REE stage.

The structural architecture of the region played a critical role in focusing ascending fluids. During both mineralization stages, ore-forming fluids migrated along deep-seated fault zones and were further channeled upward by secondary fractures. With decreasing pressure and temperature, these fluids precipitated ore minerals in structurally controlled traps, forming discrete REE and Fe–Cu orebodies.

Overall, the Sin Quyen deposit represents a deep-seated hydrothermal system developed in an active continental margin setting, where episodic magmatic pulses and fluid injections led to spatially and temporally distinct REE and Fe–Cu mineralization. This model not only explains the complex mineral assemblages and alteration patterns observed in the field but also highlights the genetic connection between subduction-driven magmatism and IOCG-type ore formation in northern Vietnam (Fig. 7).

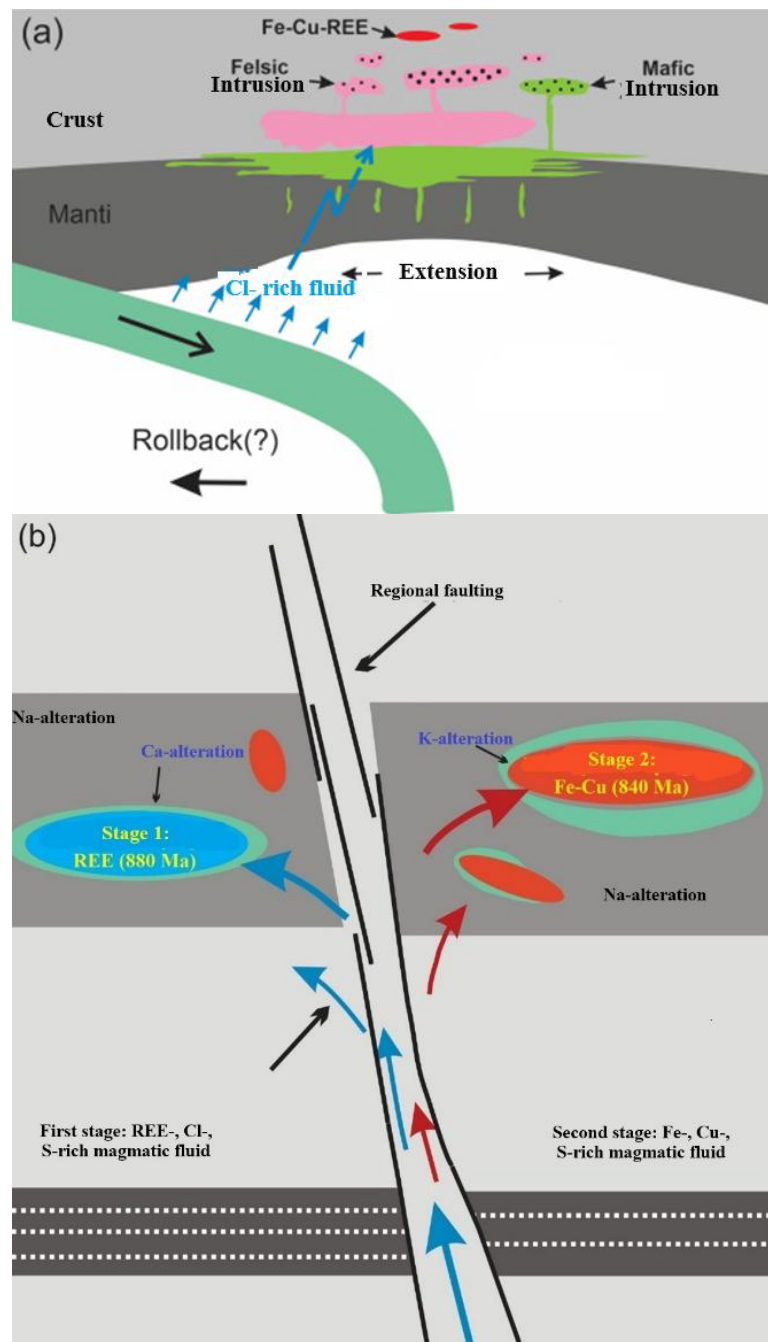


Fig. 7. Genetic model for the formation of IOCG-type mineralization at the Sin Quyen deposit

6. Conclusion

The Sin Quyen deposit formed through a polyphase hydrothermal system, involving three major mineralization stages: (i) early REE mineralization (~880 Ma), (ii) main Fe–Cu mineralization (~840 Ma), and (iii) late Cu–Au overprint (~35 Ma).

Early REE mineralization was driven by high-temperature magmatic brines derived from felsic intrusions, with crustal isotopic signatures ($\epsilon\text{Nd}(t) = -7.0$ to -5.4). The main Fe–Cu stage involved lower-temperature fluids with more juvenile isotopic values ($\epsilon\text{Nd}(t) = -4.3$ to -2.0), reflecting mantle input and fluid mixing. The final Cu–Au stage was epithermal, associated with meteoric waters and fault reactivation.

Tectonically, the deposit formed in an active continental margin setting, influenced by subduction rollback and back-arc extension. Structural controls played a key role in focusing fluid flow and ore deposition.

These results highlight the importance of episodic magmatism, fluid mixing, and tectonic structures in IOCG-type mineralization, offering valuable insights for regional exploration.

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