

Article

Petrography, Geochemistry, and Genesis of the Sanchakou Contact-Metasomatic Tremolite Jade Deposit, Qinghai Province

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Abstract

The Sanchakou tremolite jade deposit in Qinghai Province represents a significant contact-metasomatic jade resource. Unlike typical contact-metasomatic (D-type) deposits—commonly associated with intermediate-to-acidic intrusions and magnesian carbonate protoliths—the Sanchakou deposit is genetically linked to a relatively SiO₂-poor gabbro intrusion and dolomite. This atypical geological setting raises fundamental questions concerning the sources of ore-forming components and the nature of metasomatic processes involved. To address these questions, this study integrates petrographic observations, whole-rock major- and trace-element geochemistry, and Sr isotopic analyses of tremolite jade, host dolomite wallrocks, gabbro, and their hydrothermally altered counterparts to constrain the origins of Ca, Mg, and Si and to reconstruct the metasomatic evolution of the system. Our results reveal a multi-sourced contribution to ore formation: Ca is derived exclusively from dolomite; >98% of Si originates from an external crustal fluid; and Mg is supplied predominantly (77%) from dolomite, with the remaining 23% sourced from altered gabbro. Strontium isotopic data further confirm the involvement of a gabbro-derived fluid characterized by elevated ⁸⁷Sr/⁸⁶Sr ratios but low Sr concentrations. A well-defined, continuous metasomatic sequence—comprising silicification → diopsidization → tremolitization → nephritization—is clearly documented. The deposit formed in a post-collisional extensional tectonic setting, driven by heat-induced double metasomatism. This study clarifies the provenance and evolutionary pathways of ore-forming materials in this atypical contact-metasomatic system and provides a genetic framework for analogous jade deposits associated with mafic intrusions.

Keywords: Sanchakou; Qinghai; tremolite jade; Sr isotopes; ore-forming materials; metallogenic mechanism



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1. Introduction

Tremolite jade (nephrite) is a variety of jade predominantly composed of tremolite—Ca₂Mg₅(Si₄O₁₁)₂(OH)₂—characterized by a micro-fibrous, felted texture and possessing substantial economic value [1]. Hetian in Xinjiang has long been recognized as China's premier traditional source of high-quality tremolite jade; however, prolonged mining activities have led to significant resource depletion [2]. Beyond China, major tremolite jade deposits are also found in Russia (East Sayan) [3], Canada (British Columbia) [4], New Zealand (South Island) [5], and South Korea (Chuncheon) [6]. Since the 1990s, several tremolite jade deposits have been identified in the Golmud region of Qinghai Province,

and this area is situated at the tectonic junction of the northern margin of the Qinghai–Tibet Plateau, the southern margin of the Qaidam Basin, and the East Kunlun Orogenic Belt. Among these, the Sanchakou deposit has emerged as the most important tremolite jade supply base outside Xinjiang [7], with verified recoverable reserves of approximately 5578 tons, an established annual production capacity of 500 tons [8], and material of exceptional quality—textural fineness and vibrant coloration—that gained worldwide recognition after its selection for the medals of the 2008 Beijing Olympic Games [9].

Globally, tremolite jade deposits are broadly classified into two genetic types: D-type (formed via contact metasomatism between intermediate–acidic intrusions and magnesian carbonate rocks) and S-type (associated with the serpentinization of ultramafic rocks) [10,11]. The Sanchakou deposit is genetically associated with mafic intrusions (gabbro), hosted within dolomite. In contrast to typical D-type deposits, these mafic intrusions display lower SiO₂ contents (~45–50 wt%) and the dolomitic wallrock exhibits a lower MgO content (19.41 wt%) than the magnesian carbonate host rocks characteristic of classic D-type deposits (typically 22–23 wt%). Consequently, a single source of ore-forming materials is likely insufficient, suggesting that mineralization at Sanchakou may involve contributions from multiple sources and the superposition of distinct hydrothermal fluid events [12,13]. Furthermore, both contact-metasomatic and hydrothermal vein-type orebodies occur within the mining area. The latter are characterized by sharp contacts with the wallrock and only weak hydrothermal alteration, and their precise genetic origin remains unresolved.

Previous studies of the Sanchakou deposit have predominantly centered on the mineralogical and gemmological properties of tremolite jade itself [14,15]. However, systematic geochemical investigations—particularly whole-rock major- and trace-element analyses and isotopic tracer studies—of the wallrock (dolomite), intrusive rock (gabbro), and associated hydrothermally altered rocks within the ore-forming system remain notably scarce. The absence of isotopic constraints, in particular, impedes a comprehensive understanding of the sources of ore-forming materials, the evolution of hydrothermal fluids, and the genetic mechanism of the deposit. To address this knowledge gap, this study focuses on the Sanchakou contact-metasomatic tremolite jade deposit in Qinghai Province. Through integrated field geological mapping and petrographic characterization, we conducted whole-rock major- and trace-element analyses, as well as Sr isotopic analyses, on representative samples—including tremolite jade, unaltered dolomite, silicified dolomite, gabbro, and hydrothermally altered gabbro. The primary objectives are: (1) to identify and trace the sources of key ore-forming elements (Ca, Mg, and Si); (2) to constrain the origin and evolutionary history of the ore-forming hydrothermal fluids; and (3) to develop a robust genetic model for the deposit. The results are expected to provide a solid geochemical foundation for the exploration of analogous tremolite jade deposits in the region.

2. Geological Background of the Deposit

2.1. Regional and Mining Area Geology

The Sanchakou tremolite jade mining area in Qinghai Province is situated on the southern flank of the East Kunlun Orogenic Belt, bounded between the Central Kunlun Fault to the north and the South Kunlun Fault to the south. Its geographic coordinates are 94°22.125' E, 35°54.627' N, at an elevation of approximately 4300 m above sea level—about 73.4 km north of Golmud City [11]; Figure 1a. The exposed stratigraphy is dominated by the Neoproterozoic Wanbaogou Group, within which carbonate formations—particularly thick-bedded dolomite and banded silicified dolomite—constitute the primary ore-hosting wallrock [11]. These carbonate units exhibit well-developed porosity, facilitating efficient hydrothermal fluid percolation.

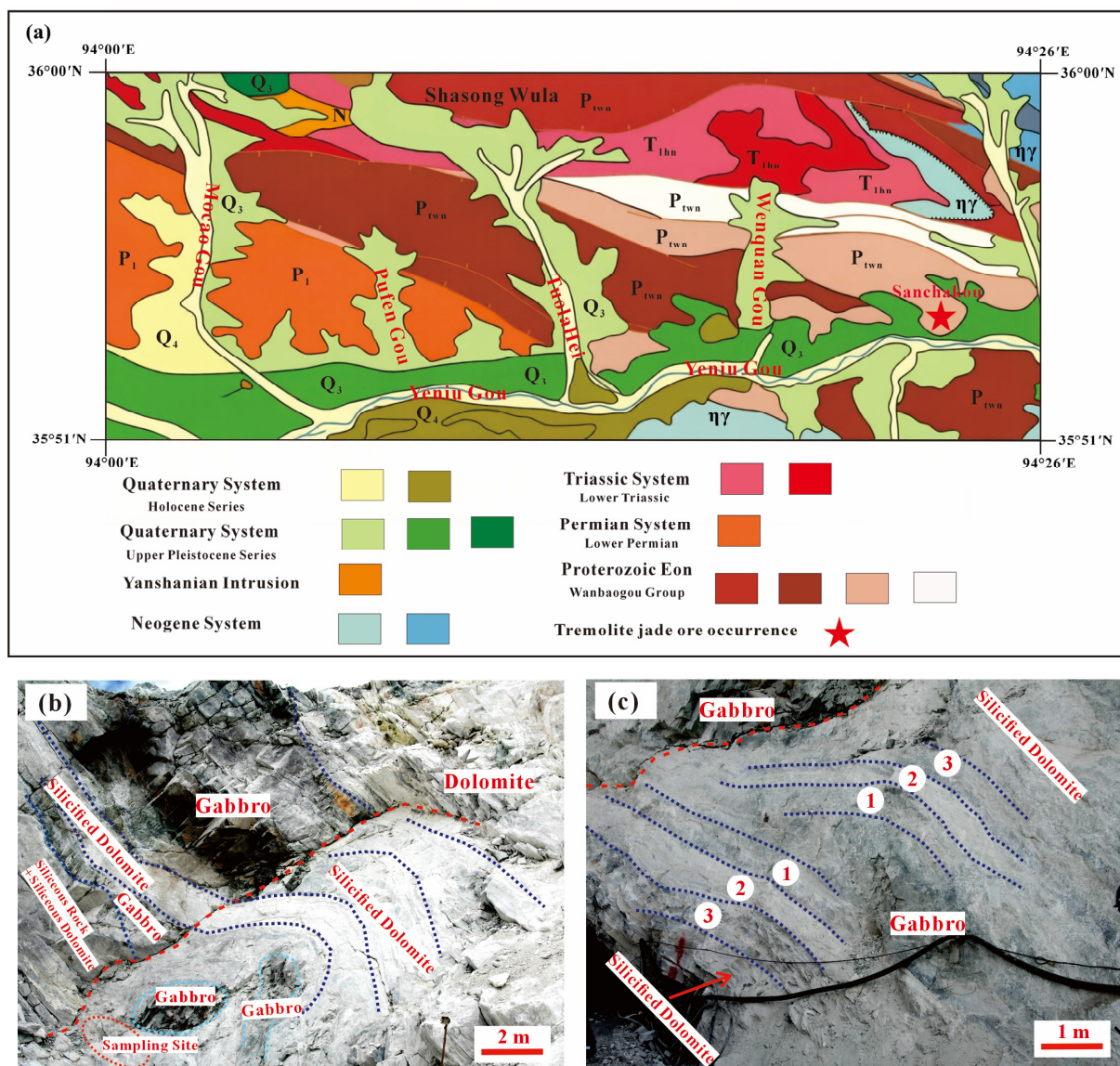


Figure 1. Mining area of tremolite jade in Sanchakou, Qinghai Province. (a) Geological map of the mining area, modified after Ma (2015) [16]; (b) Field photographs of the Sanchakou tremolite jade occurrence; (c) Banded contact-metasomatic tremolite jade orebody; ① Coarse-grained tremolite + Tremolite jade, ② Diopside + Tremolite jade, ③ Tremolitized marble + Tremolite jade.

The mining area is structurally dominated by the Wenquanguo anticline, whose limbs display pronounced asymmetry in dip angle (Figure 1b: steeply dipping to the northwest and gently dipping to the southeast), reflecting a strongly compressional tectonic regime. This primary anticline has been subsequently overprinted by multiple generations of secondary folding and thrust faulting. Gabbro intrudes as NE-trending dikes that obliquely truncate the bedding of the host rocks along thrust faults (red dashed lines in Figure 1b) and generate pervasive fracture zones localized at anticlinal hinge regions. These fracture networks served as efficient conduits for hydrothermal fluid migration, thereby promoting mineralization within core dilation zones—particularly at gabbro intrusion sites—and at fault intersections (e.g., the Sampling Site indicated in Figure 1b).

2.2. Ore Body Characteristics and Mineralization Relationships

In the mining area, tremolite jade is predominantly of contact-metasomatic origin, closely associated with gabbroic intrusions emplaced along structural weaknesses. This

variety forms within the contact aureole between gabbro and silicified dolomite, and is characterized by intense silicification, marbleization, and diopsidization. Ore bodies typically display layered, massive, or lenticular morphologies (Figure 1c), with gradational and diffuse contacts against the host rock. The renowned grayish-purple jade from Sanchakou is a representative example of this type.

Intense hydrothermal metasomatism along the gabbro–host rock contact zone has produced banded tremolite jade orebodies (marked by the blue dotted line in Figure 1c), which exhibit well-defined compositional zonation. Moving outward from the gabbro contact zone into the host rocks, the following zonal sequence develops progressively: ① coarse-grained tremolite + tremolite jade (Site ①), ② diopside + tremolite jade (Site ②), and ③ tremolitized marble + tremolite jade (Site ③); all three zones are prospective for tremolite jade extraction.

3. Sample Collection and Analytical Methods

3.1. Sample Collection

Seven rock samples closely associated with mineralization were collected from the Sanchakou contact-metasomatic tremolite jade deposit; their sampling locations are indicated in Figure 1c. These samples comprise four primary tremolite jade specimens (Y-1 to Y-4; Figure 2a–d), each further subdivided based on their directly adjacent wallrocks: Y-1 is spatially associated with tremolitized marble (Y-1-1); Y-2 occurs in association with diopside (Y-2-1) and tremolitized diopside (Y-2-2); Y-3 is associated with tremolitized diopside (Y-3-1); and Y-4 coexists with coarse-grained tremolite (Y-4-1). Additionally, a dolomite sample (W-1; Figure 2e) was subdivided into two subsamples—quartz-poor, light gray (W-1-1) and quartz-rich, dark gray (W-1-2). Intrusive rock samples include fresh gabbro (H-1) and altered gabbro (H-2; Figure 2f,g). All samples were prepared as polished thin sections, electron microprobe mounts, and 200-mesh powders for petrographic, microanalytical, and whole-rock geochemical analyses.

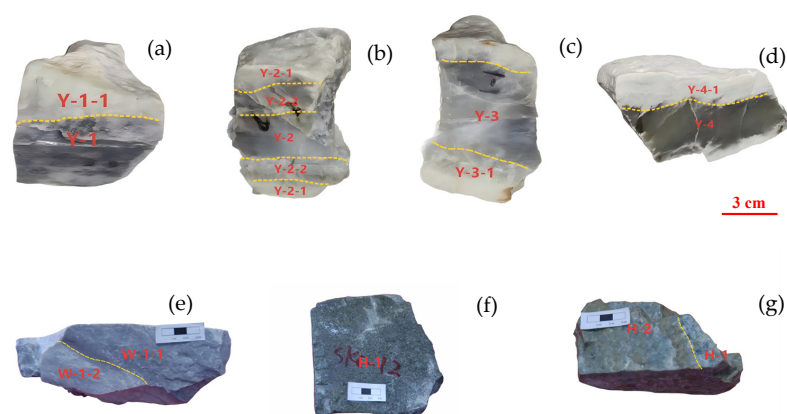


Figure 2. Photographs of Rock Samples from the Sanchakou Tremolite Jade Ore Occurrence. (a) Y-1 (tremolite jade) and Y-1-1 (tremolitized marble); (b) Y-2 (tremolite jade), Y-2-1 (diopside), and Y-2-2 (tremolitized diopside); (c) Y-3 (tremolite jade) and Y-3-1 (tremolitized diopside); (d) Y-4 (tremolite jade) and Y-4-1 (coarse-grained tremolite); (e) W-1-1 (quartz-poor dolomite) and W-1-2 (quartz-rich dolomite); (f) H-1 (gabbro); (g) H-2 (altered gabbro).

3.2. Analytical Methods

Optical observation and backscattered electron (BSE) imaging were performed using a polarizing microscope and a Zeiss Sigma field-emission scanning electron microscope (SEM, Cambridge, UK), respectively. All experiments were carried out at the Guangxi Key Laboratory of Exploration for Hidden Metallic Ore Deposits.

Major element concentrations were determined by wavelength-dispersive X-ray fluorescence spectrometry (XRF) using a Rigaku ZSX Primus II spectrometer (Rigaku, Tokyo, Japan). The detectable elemental range spans from fluorine (F) to uranium (U), with quantifiable concentrations ranging from parts per trillion (ppt) to 100 wt.%, measurement angular accuracy better than $\pm 0.0005^\circ$, and analytical precision of 2–5% relative standard deviation (RSD).

Trace element and rare earth element (REE) analyses, along with strontium (Sr) isotope measurements, were performed at the Hebei Quanxin Geological Laboratory. Trace elements and REEs were analyzed using an Agilent 7500cx inductively coupled plasma mass spectrometer (ICP-MS; Agilent, Santa Clara, CA, USA) equipped with a 193 nm excimer laser ablation system (maximum pulse energy: 200 mJ); analytical precision for trace elements and REEs is better than 2 $\mu\text{g/g}$ (RSD). Sr isotopic ratios were measured using a Thermo Fisher Neptune Plus multi-collector (MC-ICP-MS; Thermo Fisher, Waltham, MA, USA). Instrumental specifications include a mass resolution > 8000 (flat-top peak), an accelerating voltage of 10 kV, a Sr sensitivity of 24 V/ppm, external reproducibility for $^{87}\text{Sr}/^{86}\text{Sr}$ of ≤ 10 ppm (2σ), and abundance sensitivity < 0.5 ppm (measured with the reaction cell and peak-jumping quadrupole, RPQ).

4. Petrographic Characteristics of Samples

- (1) Tremolite jade hosted in tremolitized marble wallrock: The sample exemplifies a classic metasomatic jade-forming process. Within the tremolitized marble, calcite occurs as subhedral granular crystals, typically <200 μm in size. Tremolite preferentially nucleates and grows along calcite grain boundaries and internal microfractures; at calcite margins, a tremolitization metasomatic reaction takes place, yielding characteristic fibrous tremolite (indicated by the red box in Figure 3a,b). In the transitional zone between the altered wallrock and fully developed jade, calcite grain size progressively diminishes, while tremolite crystallizes radially on residual calcite grains—serving as nucleation substrates—with low crystallographic orientation (Figure 3c). Near the alteration front, minor remnants of unaltered calcite persist (Figure 3d).
- (2) Tremolite jade with diopside wallrock: The diopside wallrock (Di-1) is fine-grained. At the contact zone between the tremolite jade and the diopside wallrock, elongated prismatic diopside crystals (Di-2) are observed, with their long axes oriented toward the tremolite jade (Figure 3e). Clear evidence of tremolitization is present along the margins and within the interiors of these prismatic diopside crystals (Figure 3f). The tremolite jade adjacent to the diopside wallrock exhibits a long-fibrous texture, characterized by excellent crystallographic orientation and tightly interwoven fibers (Figure 3g). Fine-grained diopside inclusions can be seen within the tremolite jade (Figure 3h).
- (3) Tremolite jade with coarse-grained tremolite wallrock: The wallrock comprises tremolite crystals of variable grain size, including rhombic-sectioned tremolite (Tr-1) (Figure 3i). At the interface between the coarse-grained tremolite wallrock and the tremolite jade, unaltered rhombic-sectioned tremolite crystals (Tr-1) are preserved (Figure 3j). The tremolite jade associated with this coarse-grained tremolite wallrock displays a foliated texture with well-developed crystallographic orientation (Figure 3k). Visible granular calcite is dispersed among the aligned tremolite fibers, with its orientation parallel to that of the fibers (Figure 3l).
- (4) The dolomite samples display a massive structure and an inequigranular texture, characterized by alternating light-gray silicified dolomite bands (quartz-rich; sample W-1-2) and grayish-black dolomitic bands (sample W-1-1). The rock is predominantly composed of dolomite, with minor quartz and trace calcite (Figure 3m–p). Dolomite exhibits a microcrystalline fabric, with an average grain size of approx-

imately 5 μm ; the grains are predominantly tightly interlocked and display indistinct crystal boundaries—features indicative of rapid deposition or early diagenesis (Figure 3m). Quartz occurs as sand-sized, subhedral to anhedral grains (25–500 μm), primarily as fine veinlets within the dolomite matrix (Figure 3m,n, Qz-1) and, in quartz-enriched domains, as disseminated grains (Figure 3o,p, Qz-2). It displays first-order grayish-white interference colors and lacks undulatory extinction. Calcite is typically present as irregular, anhedral, fine grains infilling intergranular pores between dolomite and quartz; occasionally, larger crystals occur, exhibiting well-defined cleavage and characteristic interference colors (Figure 3m). Collectively, the morphology, spatial distribution, and optical properties of quartz and calcite support a hydrothermal sedimentary origin—most likely reflecting low-temperature hydrothermal overprinting of the primary dolomite.

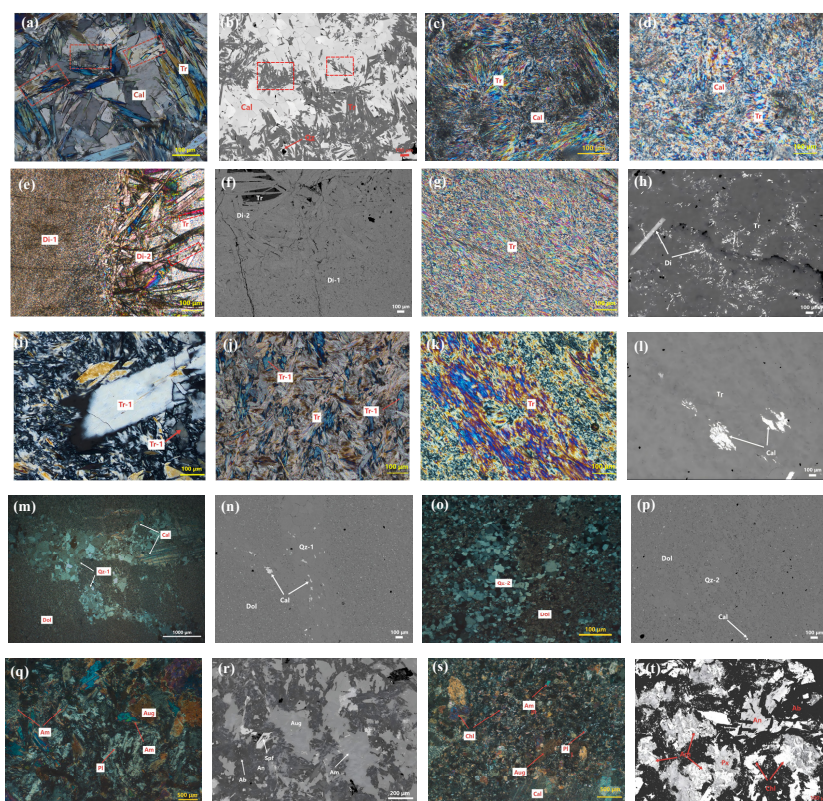


Figure 3. Cross-polarized photomicrographs (XPL) and backscattered electron (BSE) images of rock samples from the Sanchakou tremolite jade occurrence. (a,b) Y-1-1 (tremolitized marble); (c,d) Y-1 (tremolite jade); (e,f) transitional zone between diopside (Y-2-1) and tremolitized diopside (Y-2-2); (g,h) Y-2 (tremolite jade); (i) Y-4 (coarse-grained tremolite); (j,k) Y-4 (tremolite jade); (l,m) W-1-1 (quartz-poor dolomite); (n,o) W-1-2 (quartz-rich dolomite); (p,q) H-1 (gabbro); (r,s) H-2 (altered gabbro). XPL: (a,c–e,g,i–k,m,o,q,s); BSE: (b,f,l,n,p,r,t). Mineral abbreviations: Tr = tremolite, Di = diopside, Dol = dolomite, Cal = calcite, Qz = quartz, Pl = Plagioclase, Am = Amphibole, Aug = Augite, Spf = Sphene, An = Anorthite, Ab = Albite, Chl = Chlorite. Px = Pyroxene.

- (5) The gabbro is dark gray to gray-green in color, exhibiting a massive texture and preserving a relic gabbroic fabric. It consists predominantly of plagioclase (~50%), orthopyroxene (~36%), and hornblende (~12%), with accessory minerals including magnetite, ilmenite, and sphene (Figure 3q,r). Plagioclase crystals are subhedral to euhedral, commonly prismatic or columnar, with grain sizes < 0.5 mm; their surfaces appear turbid due to post-crystallization alteration, and polysynthetic twinning is largely obscured (Figure 3q). Backscattered electron imaging reveals that the plagioclase is compositionally dominated by anorthite, with minor albite (Figure 3r).

Orthopyroxene occurs as short prismatic or granular grains (<1 mm), frequently surrounded by hornblende reaction rims; some grains display amphibolization along cleavage planes or fractures (Figure 3q,r). Hornblende forms elongate prismatic or irregularly granular crystals, displaying interference colors ranging from second-order yellow to blue (Figure 3q). Collectively, these petrographic features indicate pervasive amphibolitization driven by fluid-rich metamorphic processes—consistent with the relatively high whole-rock SiO₂ content (54.40 wt%).

The altered gabbro is yellowish green, retaining a massive texture but displaying a transition from coarse-grained to cataclastic fabric. The original mineral assemblage has been substantially modified and is now dominated by albite, anorthite, residual pyroxene, hornblende, and chlorite. Albite abundance has increased markedly, whereas the grain sizes of both anorthite and residual pyroxene have decreased significantly, and the extent of pyroxene amphibolization has intensified. Locally, hornblende has been partially replaced by chlorite (Figure 3t), reflecting intense cataclasis and metasomatic alteration. In addition, inequigranular calcite with poor crystallinity occurs locally, forming a tightly interlocking mosaic; it exhibits first-order gray–white interference colors, flash extinction, and well-developed rhombohedral cleavage (Figure 3s).

5. Whole-Rock Geochemistry and Sr Isotope Composition

5.1. Major Element Characteristics

The theoretical oxide composition of pure dolomite (CaMg(CO₃)₂) is as follows: CaO ≈ 30.41 wt%, MgO ≈ 21.86 wt%, and CO₂ (corresponding to loss on ignition, LOI) ≈ 47.73 wt% [17]. Sample W-1-1 is a silicified dolomite, exhibiting CaO (28.57 wt%), MgO (19.41 wt%), and LOI (44.26 wt%) values all lower than the theoretical values (Table 1). This depletion reflects hydrothermal metasomatism involving partial removal of carbonate components. From the weakly silicified W-1-1 to the more strongly silicified W-1-2, SiO₂ content increases markedly, whereas CaO, MgO, and LOI decrease substantially, consistent with the petrographic features observed in the corresponding photomicrographs (Figure 3l,m for W-1-1 and Figure 3n,o for W-1-2).

The gabbro (sample H-1) from the study area exhibits geochemical characteristics distinctly different from those of regional mafic rocks: it is relatively enriched in SiO₂ (54.40 wt%), CaO (11.41 wt%), and MgO (10.51 wt%), but depleted in Al₂O₃ (11.96 wt%), TiO₂ (0.45 wt%), and total alkalis (K₂O + Na₂O = 1.81 wt%, with K₂O < Na₂O) (Table 1). Following hydrothermal alteration, the altered gabbro (sample H-2) shows a decrease in SiO₂ (to 52.02 wt%) and MgO (to 7.22 wt%), but marked increases in CaO (to 15.76 wt%), total iron (as TFe₂O₃, rising from 5.36 wt% to 7.84 wt%), and K₂O (rising from 0.36 wt% to 1.02 wt%), whereas Na₂O and Al₂O₃ contents remain essentially unchanged. In addition, LOI increases from 3.89 wt% in the gabbro to 2.65 wt% in the altered gabbro, consistent with the presence of calcite observed in the thin section (Figure 3o). These compositional changes indicate that the hydrothermal fluid was relatively enriched in Ca and K and reacted vigorously with the protolith—resulting in preferential leaching of Mg and Si. To verify the petrographic classification of the gabbro, two geochemical discrimination diagrams—both applicable to our dataset—were employed (Figure 4). On the TAS diagram (Figure 4a) [17], both samples plot within the gabbrodiorite field. In contrast, on the Nb/Y versus Zr/TiO₂ diagram (Figure 4b) [18]—which relies on immobile trace elements and is thus robust for altered rocks—both samples fall within the sub-alkaline basalt field, corroborating their primary basaltic–gabbroic affinity. Crucially, petrographic observations (Section 3.1) provide direct mineralogical evidence: the samples are composed predominantly of clinopyroxene and calcic plagioclase, with minor hornblende—a mineral assemblage diagnostic of gabbro. The TAS classification as “gabbrodiorite” reflects the overprinting effects of hydrothermal

alteration—including albitization and amphibolization—as further supported by elevated loss-on-ignition (LOI) values (2.65–3.89 wt%). Accordingly, the petrographic classification of gabbro is retained for the protolith.

Table 1. Data on major, trace, and rare earth element contents in rock samples from the Sanchakou tremolite jade deposit.

Sample	W-1-1	W-1-2	Y-1-1	Y-1	Y-2-1	Y-2-2	Y-2	Y-3-1	Y-3	Y-4-1	Y-4	H-2	H-1
Lithologies	Quartz-Poor Dolomite	Quartz-Rich Dolomite	Tremolitized Marble	Tremolite Jade	Diopside	Tremolitized Diopside	Tremolite Jade	Tremolitized Diopside	Tremolite Jade	Coarse-Grained Tremolite	Tremolite Jade	Altered Gabbro	Gabbro
Major Element Content (wt%)													
SiO ₂	7.33	35.70	37.65	51.72	54.77	54.51	59.36	54.72	58.41	58.36	58.89	53.45	50.76
TiO ₂	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.96	1.16
Al ₂ O ₃	0.02	0.02	0.15	0.17	0.11	0.12	0.04	0.08	0.04	0.09	0.16	15.54	15.88
TFe ₂ O ₃	0.12	0.16	0.30	0.38	0.02	0.15	0.11	0.14	0.11	0.11	0.10	6.84	10.45
MnO	0.00	0.01	0.03	0.02	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.16	0.17
MgO	19.41	13.57	15.77	22.29	19.39	20.33	25.21	20.81	25.07	25.02	25.52	3.22	7.51
CaO	28.57	19.75	29.26	18.40	23.51	23.32	14.20	22.61	15.41	14.59	13.34	12.76	9.41
Na ₂ O	—	—	0.02	0.03	0.05	0.07	0.06	0.03	0.07	0.06	0.04	2.06	1.05
K ₂ O	0.01	0.01	0.01	0.03	0.02	0.02	0.04	0.02	0.03	0.03	0.06	2.02	1.36
P ₂ O ₅	0.03	0.02	0.02	0.03	0.02	0.03	0.01	0.04	0.02	0.03	0.02	0.16	0.18
LOI	44.26	30.60	16.51	6.76	2.08	1.21	0.83	1.34	0.71	1.54	1.73	1.95	1.49
Σ	99.76	99.85	99.73	99.84	99.98	99.79	99.88	99.81	99.89	99.85	99.88	99.12	99.42
Trace Element Content (×10 ^{−6})													
Be	0.27	0.25	0.32	0.50	0.06	0.35	0.21	0.28	0.22	0.25	0.42	0.89	0.54
P	86.30	55.03	43.75	85.05	101.11	92.95	17.80	111.88	25.93	64.21	12.09	776.75	708.20
Ti	36.56	38.44	44.83	81.25	139.42	124.49	94.32	82.97	90.15	34.92	40.03	1882.20	2676.60
V	1.64	1.65	5.75	7.29	7.83	5.12	2.67	4.32	2.89	4.18	4.89	94.50	179.10
Cr	4.51	5.13	0.81	1.35	15.01	0.66	2.81	0.79	1.23	0.46	2.28	361.90	598.00
Mn	43.20	53.89	238.80	167.63	70.56	58.51	17.49	55.93	17.81	63.07	60.09	35.62	53.43
Co	0.85	0.70	1.36	1.34	12.81	0.81	46.47	0.81	7.39	0.73	39.03	15.60	34.02
Ni	6.39	4.62	6.67	5.20	8.34	5.45	18.81	5.39	6.09	3.95	15.78	101.60	156.50
Cu	2.64	1.24	1.91	4.38	0.59	1.89	3.37	3.60	3.40	5.25	3.58	2.89	9.59
Zn	7.94	7.43	22.45	18.38	12.92	29.23	26.16	28.38	25.80	100.88	91.42	37.36	57.76
Rb	0.32	0.25	0.94	1.21	1.19	1.02	0.79	0.92	0.93	0.83	1.70	10.15	2.90
Sr	85.57	41.86	123.77	83.72	32.84	28.49	24.54	25.52	22.18	15.70	18.60	691.00	800.90
Y	0.65	0.61	0.74	0.61	0.88	0.46	0.38	0.41	0.36	0.30	0.42	25.92	30.89
Zr	5.79	5.55	5.86	6.01	7.69	6.15	7.12	6.59	6.36	5.15	5.00	164.30	176.90
Nb	0.08	0.10	0.12	0.24	0.23	0.18	0.24	0.14	0.14	0.08	0.24	10.60	12.47
Mo	0.14	0.13	0.13	0.18	0.03	0.14	0.16	0.13	0.14	0.14	0.16	0.14	0.23
Cs	0.05	0.06	0.12	0.49	0.21	0.08	0.13	0.06	0.11	0.11	1.34	0.04	0.04
Ba	27.47	19.55	7.09	8.12	32.28	15.57	4.69	24.59	4.65	8.24	8.68	1379.00	856.60
Hf	0.05	0.04	0.05	0.06	0.05	0.06	0.07	0.06	0.06	0.04	0.04	4.46	4.98
Ta	0.03	0.03	0.03	0.07	0.15	0.18	0.15	0.07	0.06	0.18	0.17	0.70	0.78
Pb	4.06	3.39	2.97	3.30	11.60	11.51	10.98	9.18	8.70	2.84	4.64	5.14	13.80
Th	0.02	0.02	0.02	0.05	0.12	0.05	0.07	0.05	0.08	0.01	0.03	12.42	18.38
U	0.15	0.10	0.19	0.50	0.57	0.45	0.39	0.36	0.39	0.22	0.55	2.98	3.00
Rare Earth Element Content (×10 ^{−6})													
La	0.733	0.700	0.459	0.459	0.823	0.269	0.168	0.312	0.163	0.182	0.444	60.760	100.600
Ce	1.558	1.555	0.521	0.453	2.040	0.674	0.401	0.676	0.393	0.382	0.767	127.800	203.900
Pr	0.386	0.380	0.113	0.109	0.395	0.173	0.112	0.142	0.113	0.106	0.140	13.610	20.650
Nd	0.776	0.717	0.399	0.317	0.746	0.432	0.194	0.306	0.181	0.145	0.245	55.590	81.050
Sm	0.253	0.241	0.117	0.111	0.232	0.077	0.066	0.088	0.062	0.055	0.072	8.667	11.720
Eu	0.113	0.109	0.048	0.036	0.077	0.035	0.027	0.035	0.028	0.030	0.039	2.511	2.385
Gd	0.129	0.109	0.082	0.061	0.106	0.051	0.025	0.038	0.021	0.011	0.030	8.235	10.050
Tb	0.048	0.047	0.026	0.024	0.050	0.019	0.015	0.017	0.014	0.013	0.016	0.972	1.143
Dy	0.044	0.034	0.070	0.056	0.047	0.030	0.009	0.018	0.006	0.006	0.013	5.283	6.435
Ho	0.017	0.012	0.016	0.015	0.022	0.006	0.004	0.005	0.003	0.002	0.005	0.882	1.161
Er	0.062	0.060	0.036	0.028	0.074	0.024	0.019	0.021	0.018	0.013	0.023	2.556	3.411
Tm	0.004	0.004	0.002	0.001	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.297	0.396
Yb	0.058	0.051	0.026	0.026	0.048	0.024	0.021	0.021	0.020	0.013	0.023	2.160	3.051
Lu	0.022	0.020	0.010	0.009	0.008	0.008	0.007	0.007	0.007	0.005	0.008	0.297	0.369
ΣREE	4.20	4.04	1.93	1.70	4.67	1.82	1.07	1.69	1.03	0.97	1.83	289.62	446.32
(La/Yb) _N	8.53	9.20	11.69	12.06	11.53	7.70	5.49	10.06	5.46	9.37	13.02	18.96	22.23
(La/Sm) _N	1.82	1.83	2.46	2.60	2.23	2.19	1.60	2.23	1.66	2.09	3.91	4.41	5.40
(Gd/Yb) _N	1.80	1.71	2.50	1.91	1.78	1.73	0.97	1.48	0.86	0.69	1.04	3.08	2.66
δCe	0.70	0.72	0.54	0.47	0.86	0.73	0.68	0.77	0.67	0.65	0.73	1.03	1.02
δEu	1.71	1.78	1.43	1.21	1.31	1.62	1.70	1.57	1.94	2.54	2.21	0.90	0.66

Note: “—” denotes data below the detection limit.

The tremolite jade samples Y-2, Y-3, and Y-4 exhibit SiO₂ (58.41–59.36 wt%), MgO (25.07–25.52 wt%), and CaO (13.34–15.41 wt%) contents that closely match the theoretical composition of ideal tremolite (SiO₂: 59.17 wt%; MgO: 24.81 wt%; CaO: 13.80 wt%) [19] (Table 1). Moreover, they display exceptionally low concentrations of Al₂O₃, total Fe as Fe₂O₃ (TFe₂O₃), and alkalis, confirming their composition as nearly pure tremolite aggregates—a finding fully consistent with petrographic observations. In contrast, sample Y-1 shows markedly lower SiO₂ (51.72 wt%) and significantly elevated CaO (18.40 wt%) and loss on ignition (LOI; 6.76 wt%). This distinctive geochemical signature aligns with the microscopic observation of residual calcite, indicating incomplete metasomatism of the dolomitic wallrock during the formation of Y-1.

The major-element variations observed in different altered wallrocks reflect the staged evolution of hydrothermal fluid composition and associated mineralization.

From silicified dolomite (W-1-2) to tremolitized marble (Y-1-1), SiO_2 contents remain broadly similar, whereas MgO exhibits only a modest increase, and CaO shows a pronounced rise. Coupled with petrographic observations—namely, disseminated quartz in W-1-2 and pervasive calcite alteration in Y-1-1—these geochemical trends indicate a temporal shift in hydrothermal activity: from early-stage decarbonation and silica injection to later-stage mobilization and reprecipitation of Ca from the wallrock. The diopside-bearing wallrock sample Y-2-1 displays a major-element composition ($\text{SiO}_2 = 54.77 \text{ wt\%}$; $\text{MgO} = 19.39 \text{ wt\%}$; $\text{CaO} = 23.51 \text{ wt\%}$) closely matching that of theoretical diopside ($\text{CaMgSi}_2\text{O}_6$) [20], along with a low loss-on-ignition (LOI) value of 2.08 wt%, suggesting a water-poor silicate protolith. In contrast, the altered samples Y-2-2 and Y-3-1 exhibit compositional trends intermediate between diopside and tremolite, characterized by progressive MgO enrichment and CaO depletion—consistent with a metasomatic tremolitization process. Coarse-grained tremolite (Y-4-1) and the adjacent tremolite jade (Y-4) possess nearly identical major-element compositions. Moreover, Y-4 jade displays a distinct preferred orientation of micro-fibrous tremolite crystals, indicating that it likely formed via dynamic recrystallization of pre-existing coarse-grained tremolite under directed stress—yielding a dense, oriented jade aggregate.

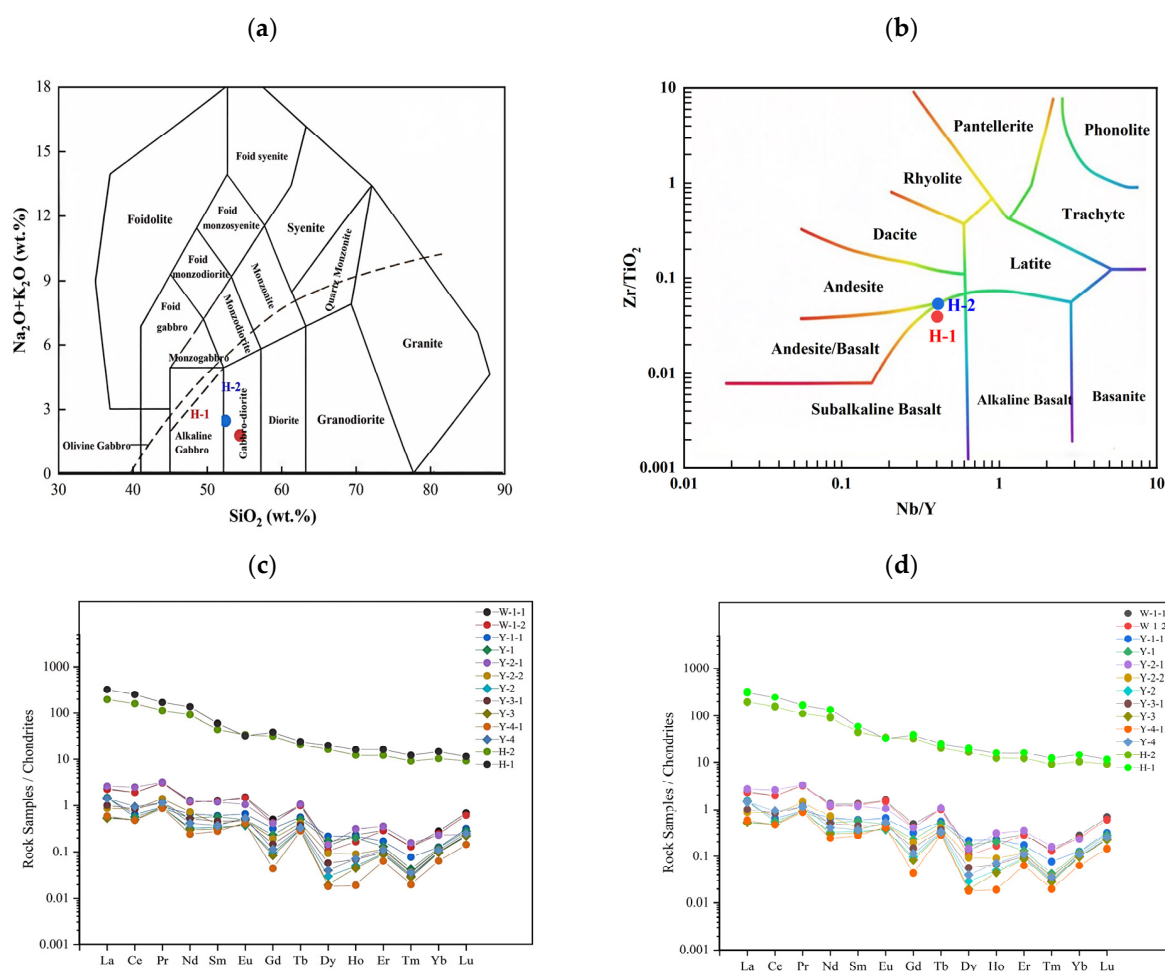


Figure 4. (a) TAS diagram of intrusive rocks [17]; (b) $\text{Nb/Y} \cdot 10,000 \times \text{Zr/TiO}_2$ rock classification diagram [18]; (c) chondrite-normalized REE patterns [21] and (d) primitive mantle-normalized trace element spider diagrams [22] for rock samples from the Sanchakou tremolite jade occurrence.

5.2. Trace Element Geochemistry

The trace element and rare earth element (REE) distribution patterns of dolomite, tremolite jade wallrocks, and tremolite jade are broadly similar (Figure 4c). Their total REE

contents (ΣREE) are exceptionally low—typically <5 ppm. Chondrite-normalized REE patterns exhibit a pronounced rightward inclination, with $(\text{La}/\text{Yb})_{\text{N}}$ ratios ranging from 5.49 to 13.02, indicating marked light rare earth element (LREE) enrichment. The $(\text{La}/\text{Sm})_{\text{N}}$ ratios vary between 1.60 and 3.91, and the $(\text{Gd}/\text{Yb})_{\text{N}}$ ratios range from 0.97 to 2.50, collectively reflecting stronger LREE fractionation relative to heavy rare earth elements (HREE) (Table 1). All samples display distinct negative cerium anomalies ($\delta\text{Ce} = 0.472\text{--}0.857$) and positive europium anomalies ($\delta\text{Eu} = 1.214\text{--}2.542$). In primitive mantle-normalized trace element spider diagrams, the patterns are essentially flat, characterized by positive anomalies for U, Pb, and Ta; negative anomalies for Th, Nb, La, Ce, and Ti; and no significant anomalies for other elements (Figure 4d).

The normalized REE pattern exhibits a rightward inclination, reflecting strong LREE enrichment and pronounced intra-LREE fractionation (Figure 4c; $(\text{La}/\text{Sm})_{\text{N}} = 5.40$), whereas HREE fractionation is comparatively muted ($(\text{Gd}/\text{Yb})_{\text{N}} = 2.69$). Overall, LREE/HREE fractionation is substantial ($(\text{La}/\text{Yb})_{\text{N}} = 22.23$). The pattern displays no discernible cerium anomaly ($\delta\text{Ce} \approx 1.0$) but features a clear negative europium anomaly ($\delta\text{Eu} = 0.66$). In the primitive mantle-normalized trace element spider diagram, most elements are enriched, and the pattern is sub-horizontal to slightly rightward-inclined, characterized by marked depletions in P and Ti and strong enrichments in Ba, Th, LREEs (La, Ce, Nd), and Hf. Collectively, these geochemical signatures—elevated total REE concentration (ΣREE), pronounced LREE/HREE fractionation, a significant negative Eu anomaly, and enrichment in large-ion lithophile elements (LILEs) coupled with depletion in high-field-strength elements (HFSEs)—indicate that the parental magma originated from an enriched mantle source and subsequently underwent variable degrees of crustal contamination. Following hydrothermal alteration, the altered gabbro exhibits a reduced total REE content ($\Sigma\text{REE} = 289.62 \times 10^{-6}$; Table 1). Its chondrite-normalized REE pattern remains rightward-inclined and LREE-enriched, closely mirroring that of the unaltered gabbro, although the negative Eu anomaly is notably attenuated ($\delta\text{Eu} = 0.90$). Its primitive mantle-normalized trace element pattern is highly consistent with that of the original gabbro, preserving the same characteristic enrichments and depletions (Figure 4d). This implies that hydrothermal alteration induced partial REE leaching and moderated the Eu anomaly, yet did not fundamentally alter the overall trace element signature inherited from the primary magma.

In rock geochemistry, strontium (Sr) isotopes are widely employed to trace the provenance of geological materials; however, measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios must be corrected for the time elapsed since rock formation. This correction is essential because the radioactive parent isotope ^{87}Rb decays continuously to radiogenic ^{87}Sr , causing the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a rock to increase progressively after crystallization [23]. To enable robust comparison of source characteristics among rocks of different ages, the post-formation radiogenic ^{87}Sr component must be removed, and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (denoted as $^{87}\text{Sr}/^{86}\text{Sr}_i$) at the time of formation must be calculated [24].

Data quality was rigorously monitored throughout this study by interspersing international and domestic rock reference materials—including BIR-1, BHVO-2, GSR-3, and GSR-7—within the analytical sequence [25]. All measured $^{87}\text{Sr}/^{86}\text{Sr}$ values agreed with their recommended reference values within stated uncertainties, thereby validating the accuracy and reliability of the entire analytical procedure. Furthermore, repeated analyses of the NIST SRM 987 standard solution yielded an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.710245 ± 0.000015 (2σ), establishing the analytical precision for this batch of data (Table 2).

Table 2. Sr isotope measurement data and correction results for different rocks from the Sanchakou tremolite jade deposit.

Sample	Rb ($\times 10^{-6}$)	Sr ($\times 10^{-6}$)	Rb/Sr	Measure $^{87}\text{Sr}/^{86}\text{Sr}$	Corrected $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ (247 Ma)	Error
W-1-1	0.32	85.57	0.00	0.70768	0.70763	0.0000164
W-1-2	0.25	41.86	0.01	0.70820	0.70814	0.0000156
Y-1-1	0.94	123.77	0.01	0.70966	0.70958	0.0000172
Y-1	1.21	83.72	0.01	0.70971	0.70948	0.0000193
Y-2-1	1.19	32.84	0.04	0.70994	0.70983	0.0000184
Y-2-2	1.02	28.49	0.04	0.70990	0.70975	0.0000179
Y-2	0.79	24.54	0.03	0.70983	0.70961	0.000018
Y-3-1	0.92	25.52	0.04	0.70985	0.70971	0.0000152
Y-3	0.93	22.18	0.04	0.70986	0.70970	0.0000163
Y-4-1	0.83	15.70	0.05	0.71023	0.71008	0.0000183
Y-4	1.70	18.60	0.09	0.71024	0.70991	0.000014
H-2	10.15	691.00	0.01	0.71027	0.71021	0.0000162
H-1	2.90	800.90	0.00	0.71028	0.71026	0.0000172

A well-constrained metallogenic age is fundamental for accurate isotopic age correction. In this study, we adopt the high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating results reported previously [26]. 247.86 ± 0.64 Ma and use 247 Ma as the reference age for correction. Applying the decay constant $\lambda(^{87}\text{Rb}) = 1.42 \times 10^{-11} \text{ yr}^{-1}$, together with the measured Rb and Sr concentrations for each sample, we performed backward age corrections to derive the initial $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios at the time of mineralization. These corrected values thus faithfully represent the Sr isotopic composition of the ore-forming fluid during metallogenesis. The corrected data clearly reveal the isotopic compositions of distinct end-members within the ore-forming system and elucidate key fluid–rock interaction processes:

Unaltered dolomite (sample W-1-1) exhibits a very low Rb/Sr ratio (0.0038) and a relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratio (0.70763), characteristic of marine carbonate rocks [27]. With progressive silicification, its initial $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratio increases to 0.70814 (sample W-1-2). The exceptionally low Rb/Sr ratios of both samples preclude significant contributions from in situ radiogenic ingrowth; thus, the observed increase unequivocally reflects fluid–rock exchange: the silicifying hydrothermal fluid introduced strontium with a higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, which mixed with and isotopically overprinted the original carbonate host.

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the gabbro samples (0.71021–0.71026) are markedly elevated. These values align closely with those reported by Zhao et al. (2018) [28] for the An’age hornblende gabbro (0.70880–0.71036) in the East Kunlun orogenic belt, indicating that high $^{87}\text{Sr}/^{86}\text{Sr}$ signatures are regionally pervasive among coeval mafic rocks in the East Kunlun area. Coupled with trace element systematics—including enrichment in large-ion lithophile elements (LILE) and light rare earth elements (LREE), depletion in high-field-strength elements (HFSE), Nb/Ta ratios of ~15–16, and Zr/Hf ratios of ~35–37—these isotopic data imply that the parental magma originated from an enriched lithospheric mantle source that had undergone metasomatism by subduction-derived fluids, with only minor crustal contamination during magmatic ascent. Late-stage amphibolization and albitization did not generate the elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios; rather, they preserved the high initial $^{87}\text{Sr}/^{86}\text{Sr}$ signature inherited from the mantle source via fluid–rock interactions, which were subsequently incorporated into the alteration minerals.

All jade samples (Y-1 to Y-4) display highly homogeneous initial $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratios tightly clustered within the narrow range of 0.70948–0.70991 (mean = 0.70962 ± 0.00012 , 2σ), implying that the ore-forming fluid responsible for jade formation possessed a uniform Sr isotopic composition. Furthermore, the initial $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratios of tremolite jade and its immediate wallrock—such as tremolitized marble—are indistinguishable within analytical uncertainty, indicating rapid attainment of Sr isotopic equilibrium between the ore-forming fluid and the host rock.

6. Ore-Forming Material Sources and Metallogenic Mechanism

Integrating petrographic, geochemical, and Sr isotope data, we systematically elucidate the sources of ore-forming materials of the Sanchakou tremolite jade and construct a complete “heat-driven double metasomatism” metallogenic model.

6.1. Sources of Ore-Forming Materials

6.1.1. Major and Trace Elements and Mass Balance Tracing

- (1) REE and trace element evidence: The tremolite jade exhibits right-inclined, LREE-enriched chondrite-normalized REE patterns, characterized by a negative Ce ($\delta\text{Ce} = 0.47\text{--}0.86$) anomaly and a positive Eu anomaly ($\delta\text{Eu} = 1.21\text{--}2.54$), along with extremely low concentrations of high-field-strength elements (HFSEs), including Ti, Zr, and Nb. These geochemical signatures closely resemble those of the wallrock dolomite but are markedly distinct from those of the gabbro—specifically, the gabbro displays significantly higher total REE (ΣREE) contents and a negative Eu anomaly. This strong geochemical affinity strongly indicates that the dolomite serves as the principal source end-member for the ore-forming system.
- (2) Quantitative mass-balance constraints on Mg and Ca sources

Petrographically, quartz in the silicified dolomite (W-1-1 and W-1-2) is of hydrothermal origin (Figure 3j,k), and hydrothermal fluids are extremely low in Zr [28], supporting the immobility of Zr. Isocon analysis between W-1-1 and W-1-2 gives $k_{\text{dolomite}} = Zr_{\text{protolith}}/Zr_{\text{altered}} = 5.79/5.55 \approx 1.043$ [29], which is close to 1, indicating minor mass change from the original dolomite to W-1-1. Thus, the original (“Si-free”) dolomite composition can be approximated by removing the hydrothermal SiO_2 from W-1-1 and renormalizing. Given that the measured W-1-1 contains 73.3 g SiO_2 , 194.1 g MgO, and 285.7 g CaO per 1000 g rock (Table 1), subtracting the hydrothermal SiO_2 leaves a residue of 926.7 g. Normalizing this residue to 100 wt% yields $\text{MgO} = (194.1/926.7) \times 100 = 20.94 \text{ wt\%}$ and $\text{CaO} = (285.7/926.7) \times 100 = 30.82 \text{ wt\%}$.

Complete alteration of 1000 g of this pristine dolomite would release up to 209.4 g MgO and 308.2 g CaO, whereas 1000 g of tremolite jade (sample Y-2) requires 252.1 g MgO and 142.0 g CaO. Hence, even under ideal conditions, a Mg deficit of ~42.7 g remains, while Ca is markedly in excess. Dolomite is therefore the exclusive source of Ca and the dominant (though not sole) source of Mg.

For gabbro alteration (H-1 $\rightarrow$ H-2), isocon analysis using immobile Al_2O_3 ($k_{\text{gabbro}} = \text{Al}_2\text{O}_3_{\text{protolith}}/\text{Al}_2\text{O}_3_{\text{altered}} = 11.96/11.54 \approx 1.036$) shows that altered gabbro releases MgO (~30.3 g per 1000 g rock; Table 3) while incorporating CaO, confirming it as a supplementary Mg source. Combining the Sr-isotope mixing ratio (dolomite: gabbro $\approx 77:23$) with the above release capacities yields geologically reasonable rock masses ($x \approx 0.93 \text{ kg}$ dolomite and $y \approx 1.91 \text{ kg}$ gabbro per 1000 g tremolite jade), demonstrating full consistency with the Mg demand.

(3) Independent Silica Source

During dolomite silicification (W-1-1 $\rightarrow$ W-1-2), isocon analysis—using immobile Zr as a reference element—indicates a net gain of +299.1 g SiO_2 per 1000 g protolith (Table 3). In contrast, the altered gabbro exhibits a negligible SiO_2 loss of only -5.1 g per 1000 g rock. To supply the observed SiO_2 budget solely from gabbro would require an implausibly large mass of ~106.4 kg of gabbro, which would simultaneously introduce a substantial excess of MgO inconsistent with the observed bulk composition. Consequently, over 98% of the SiO_2 in the tremolite jade must have been derived from an external, silica-rich hydrothermal fluid.

Table 3. Quantitative constraints on ore-forming material sources for the Sanchakou tremolite jade deposit.

Item	SiO ₂ (g)	MgO (g)	CaO (g)	Remarks
I. Dolomite-related				
Measured W-1-1 (per 1000 g rock)	73.3	194.1	285.7	Raw data
Si-free dolomite end-member (per 1000 g end-member)	0	209.4	308.2	Normalized after removing SiO ₂
Theoretical maximum release (per 1000 g end-member, complete decomposition)	0	−209.4	−308.2	Negative = released from rock
II. Gabbro alteration (per 1000 g protolith)				
Protolith H-1 measured	544	105.1	114.1	Adjusted to the same mass basis as the protolith Negative = released; positive = added
Altered H-2 measured	520.2	72.2	157.6	
Corrected H-2 (× <i>k</i> = 1.036)	538.9	74.8	163.3	
Net mass change (H-1 → H-2)	−5.1	−30.3	49.2	
III. Tremolite jade requirement (per 1000 g tremolite jade)				
Measured composition of sample Y-2	593.6	252.1	142	Approximate theoretical values [20]

6.1.2. Sr Isotope Evidence

The $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ –1000/Sr relationship further constrains the end-member characteristics of the ore-forming fluid. Samples plot along a well-defined linear trend on the $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ –1000/Sr diagram, bracketed between (i) a high- $^{87}\text{Sr}/^{86}\text{Sr}$ (>0.710), low-Sr hydrothermal end-member and (ii) a low- $^{87}\text{Sr}/^{86}\text{Sr}$ (≈ 0.708), high-Sr silicified dolomite end-member—indicating a clear binary mixing process (Figure 5a,b). Linear regression of this trend ($R^2 = 0.96$, $n = 9$, $p < 0.001$) yields the following end-member compositions: (1) silicified dolomite end-member: $^{87}\text{Sr}/^{86}\text{Sr}(\text{i}) \approx 0.70814$, Sr ≈ 380 ppm; (2) external hydrothermal end-member: $^{87}\text{Sr}/^{86}\text{Sr} \approx 0.7108$, Sr ≈ 5 ppm. Although the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of this hydrothermal end-member overlaps with that of gabbro, its Sr concentration is exceptionally low; moreover, the Y-series samples do not define a mixing trend with either fresh or altered gabbro. This implies that the ore-forming fluid is not a direct magmatic derivative of gabbro but rather an independent hydrothermal fluid that inherited gabbro's radiogenic Sr signature while being profoundly depleted in Sr. The concurrent increase in $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ and decrease in Sr concentration during silicification further corroborates the influx of this external fluid. In contrast, alteration of the gabbro itself preserved a Sr-rich, isotopically stable composition—consistent with the operation of internally buffered, rock-buffered fluid systems. On this basis, quantitative correlations between strontium isotopes and major elements provide more refined constraints on the coupling between element migration behavior and specific fluid end-members:

- (1) SiO₂ source: The initial $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratio exhibits a very strong positive correlation with SiO₂ content (Figure 5c; $r = 0.87$), indicating that the bulk of the silicon required for tremolite-jade formation is not derived from local wallrock (dolomite) or the intrusive gabbro, but rather originates from an external, independent, silica-rich hydrothermal system characterized by elevated $^{87}\text{Sr}/^{86}\text{Sr}$.
- (2) CaO removal: $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ displays a moderate negative correlation with CaO (Figure 5d; $r = -0.54$), suggesting that the high- $^{87}\text{Sr}/^{86}\text{Sr}$ fluid actively mobilized and removed calcium from the dolomite host rock. This influx of low- $^{87}\text{Sr}/^{86}\text{Sr}$ Ca diluted the overall strontium isotopic composition of the fluid.

- (3) MgO behavior: No significant correlation exists between $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ and MgO (Figure 5e; $r = 0.005$), providing quantitative support for a “dual Mg supply” model—i.e., magnesium was sourced concurrently from both low- $^{87}\text{Sr}/^{86}\text{Sr}$ dolomite and high- $^{87}\text{Sr}/^{86}\text{Sr}$ altered gabbro, such that their opposing isotopic signatures effectively canceled one another.

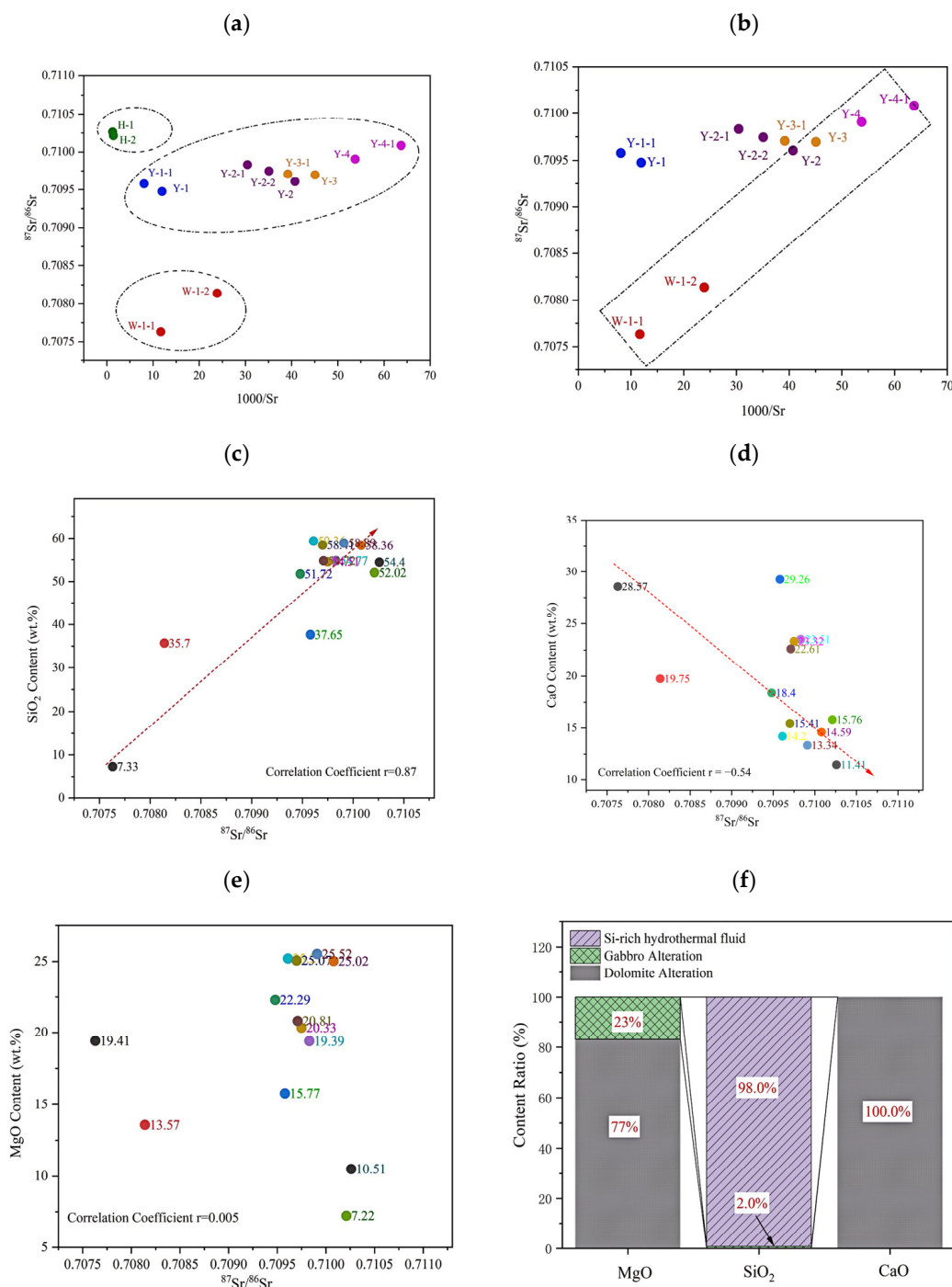


Figure 5. Sanchakou Rock Sample: $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ – $1000/\text{Sr}$ Diagrams (a,b); $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ versus CaO , MgO , and SiO_2 Content Diagrams (c–e); Source-Diagnostic Diagrams for MgO , CaO , and SiO_2 in Tremolite Jade-Forming Materials (f).

6.1.3. Integrated Source Model

The ore-forming materials of the Sanchakou tremolite jade exhibit a well-defined “multi-source, partitioned supply” pattern: Si (>98%) is derived from crustal, Si-rich hy-

drothermal fluids; Ca is sourced exclusively from dolomite and is removed during mineralization; and Mg is predominantly (~77%) supplied by dolomite, with the remainder (~23%) contributed by altered gabbro (Figure 5f). This ratio is quantitatively constrained by the Sr isotope mixing line (dolomite: gabbro $\approx$ 77:23; Figure 5a,b), which is independently supported by mass-balance calculations showing that the Mg deficit from dolomite (~42.7 g per 1000 g tremolite jade) is compensated by Mg released from altered gabbro (~30.3 g per 1000 g rock; Table 3). It should be noted that the precise origin of the “external siliceous hydrothermal fluid” identified in this study remains unconstrained. The elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (>0.710) effectively excludes a direct contribution from either the juvenile mantle or young crustal sources; however, Sr isotopic data alone are insufficient to discriminate among potential fluid end-members—such as metamorphic fluids, basin-derived brines, or deeply circulated meteoric waters. Consequently, the exact provenance of this fluid awaits further clarification through integrated H–O isotopic and fluid inclusion analyses.

6.2. Metallogenic Mechanism

6.2.1. Tectono-Thermal Setting

To constrain the tectonic setting, the discrimination scheme of Li et al. (2015) [30] was employed. Samples H-1 and H-2 yield $\text{Th} \times \text{Ta}/\text{Hf}^2$ ratios of 0.578 and 0.437 (both significantly exceeding 0.035), $\text{La} \times \text{Nb}/\text{Zr}^2$ ratios of 0.040 and 0.024 (both above the threshold of 0.02), and Th/Ta ratios of 23.56 and 17.74—values markedly higher than those typical of within-plate basalts. Collectively, these geochemical signatures point unequivocally to a continental margin arc (i.e., volcanic arc) setting for the Sanchakou gabbro, effectively excluding both continental collision and intraplate extensional environments. This interpretation is consistent with the Early–Middle Triassic subduction of the Paleo-Tethys Ocean along the East Kunlun orogenic belt [28,29].

To constrain the timing of tremolite jade mineralization, $^{40}\text{Ar}/^{39}\text{Ar}$ dating on whole-rock tremolite jade samples (including the smoky cyan jade) from the Sanchakou deposit was conducted, with results published in Yu et al. (2018) [31]. The analysis of the smoky cyan jade from the Sanchakou deposit yielded a well-defined plateau age of 247.86 ± 0.64 Ma [31]. This age is consistent with analytical uncertainty with the published ages of the regional gabbro intrusions (240–250 Ma) [28,29], demonstrating a temporal coupling between gabbro magmatism and tremolite jade formation. During this subduction-to-collision transition, gabbro intrusion initiated a deep-seated hydrothermal system, promoting circulation of silica-rich fluids and associated metasomatism. The jade exhibits homogeneous initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70948–0.70971)—close to, yet distinctly resolvable from, those of the host gabbros, with no evidence of isotopic mixing. This confirms that the gabbros served solely as a thermal driver rather than as a direct source of material. Consequently, a clear “heat-driven $\rightarrow$ mineralization response” chronosequence is established.

6.2.2. “Heat-Driven Double Metasomatism” Mineralization Process

Based on the multi-source supply model, the mineralization process of the Sanchakou tremolite jade can be delineated into three distinct stages:

- (1) Heat source emplacement and fluid generation: Under a post-collisional extensional tectonic regime, the emplacement of gabbro provided the primary thermal energy, driving the circulation of deep-seated, silica-rich fluids (Figure 6a).
- (2) Multi-source material activation and fluid mixing: The circulating fluids reacted with the gabbroic intrusion, inducing its hydrothermal alteration and releasing magnesium—characterized by a high $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic signature. Concurrently, the fluids infiltrated the dolomitic wallrock, triggering decarbonation and silicification, thereby liberating calcium and the majority of magnesium—bearing a low

$^{87}\text{Sr}/^{86}\text{Sr}$ signature. In addition, a deep-sourced, silica-rich main fluid—of crustal affinity—was continuously introduced. These three end-member fluids mixed proximal to the gabbro–dolomite contact zone, generating a homogeneous, Ca–Mg–Si-rich ore-forming fluid (Figure 6b).

- (3) Wall-rock alteration and tremolite jade formation: In the contact zone, as temperature, pressure, and fluid composition change, the wall rock undergoes successive metamorphic processes, including marbleization and diopside alteration. As temperature decreases, diopside and marble are transformed into tremolite jade through tremolitization. In open fractures within gabbro, coarse-grained tremolite crystals form, whereas in closed, low-permeability zones, fine fibrous and tightly interwoven tremolite precipitates. Controlled by the bedding planes of the host rock and the alteration zone, tremolite commonly occurs along structural weaknesses such as foliation surfaces, causing newly formed nephrite fibers to grow preferentially parallel to these planes. Consequently, fibrous tremolite from the contact zone between the Sanchaokou gabbro and surrounding wall rocks typically exhibits a well-developed preferred orientation. Among them, tremolite jade derived from diopside alteration generally features finer fibers, a more delicate texture, and superior quality.

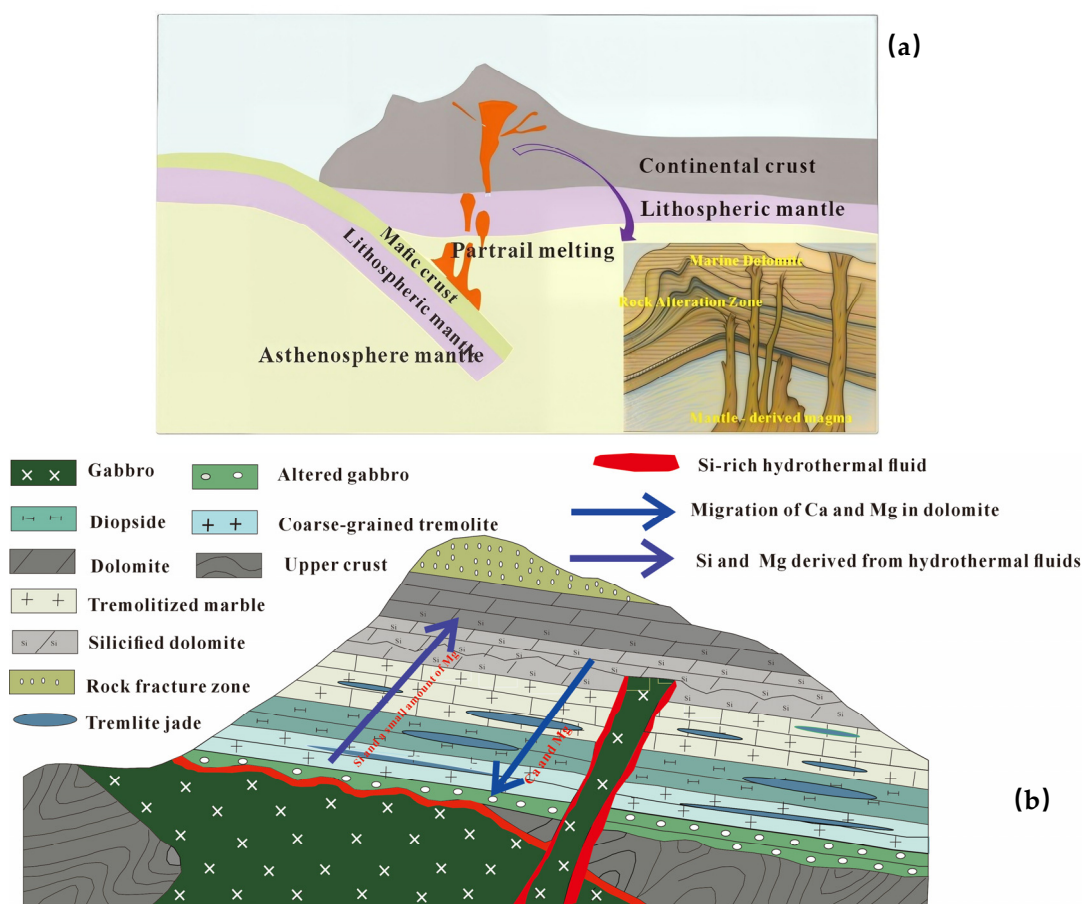


Figure 6. Mineralization model diagram of the hydrothermal-filling-type tremolite jade deposit at Sanchakou, Qinghai Province. (a) Geodynamic model for the origin of the hydrothermal system in the Sanchakou tremolite jade deposit, showing mantle upwelling and partial melting of the lithosphere; (b) Shallow geological cross-section illustrating the structural controls, wall-rock alteration, and hydrothermal fluid pathways for tremolite jade mineralization at Sanchakou.

6.2.3. Genetic Model

The proposed “heat-driven double metasomatism” model accounts for all geological and geochemical observations presented in this study. In this model, gabbro emplacement within a continental volcanic arc setting provided the thermal energy to mobilize and mix multiple material sources—deep-seated Si-rich fluids, dolomitic wallrock, and altered gabbro—leading to tremolite precipitation via double metasomatism at the intrusion–country rock contact. This model offers a novel genetic framework for understanding tremolite jade deposits associated with mafic intrusions.

7. Conclusions

Based on systematic petrographic, major- and trace-element, and Sr-isotope geochemical investigations of the Sanchakou tremolite jade deposit in Qinghai Province, the following principal conclusions are drawn:

- (1) Quantitative constraints on material sources: The ore-forming components of the tremolite jade exhibit a “multi-source, partitioned supply” pattern. Calcium is exclusively derived from the dolomitic wallrock and is present in substantial excess; magnesium is predominantly (~77%) sourced from dolomite dedolomitization, with the remaining portion (~23%) supplied by alteration of gabbro; silicon is overwhelmingly (>98%) contributed by an external, Si-rich hydrothermal fluid, whereas gabbro alteration contributes negligibly to the Si budget.
- (2) Sr-isotope tracing: The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the tremolite jade are highly homogeneous (0.7095–0.7098), closely resembling—but systematically distinct from—those of the coexisting gabbro (0.7101–0.7102). The $^{87}\text{Sr}/^{86}\text{Sr}(\text{i})$ ratio exhibits a strong positive correlation with SiO_2 content ($r = 0.87$), indicating a crustal origin for the Si-rich hydrothermal fluid; shows no significant correlation with MgO ($r = 0.005$), thereby independently corroborating the dual-source Mg mixing model; and displays a moderate negative correlation with CaO ($r = -0.54$), suggesting that the external hydrothermal fluid facilitated the mobilization and removal of Ca from the dolomitic wallrock.
- (3) Metallogenic model: A “heat-driven double metasomatism” model is proposed. In a post-collisional extensional tectonic setting, the emplacement of gabbro provided the thermal energy necessary to mobilize Si-rich fluids derived from the deep crust. These fluids migrated upward along fault systems and induced metasomatic reactions at the gabbro–carbonate contact zone—either sequentially or concurrently—metasomatizing both the gabbro (releasing Mg) and adjacent dolomite (releasing Ca and part of its Mg). The resulting mixing of these three end-member fluid components generated a homogeneous Ca–Mg–Si-rich ore-forming fluid. Tremolite precipitated from this fluid in response to evolving temperature and pressure conditions, giving rise to the observed spatial zonation—from tremolitized marble through transitional zones to massive tremolite jade.
- (4) Exploration indicators: Key exploration criteria for analogous tremolite jade deposits in the region include (i) the intensity of silicification within dolomitic host rocks; (ii) structural characteristics of the gabbro–carbonate contact zone (e.g., brecciation, shear development, and fluid-pathway networks); and (iii) a distinctive geochemical signature characterized by elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (>0.709) coupled with low bulk-rock Sr concentrations. Collectively, these features constitute robust geochemical and structural indicators for targeting similar deposits.

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