

Article

Cassiterite U–Pb Geochronology of the Dahongliutandong Li Pegmatites, West Kunlun, NW China

Weiguang Yang^{1,2}, Wukeyila Wutiepu^{3,*} , Yusheng Gu^{1,2,*}, Haitao Shi^{1,2} and Shanshan Wang³¹ Urumqi Comprehensive Survey Center on Natural Resources, China Geological Survey, Urumqi 830057, China; yangwg_cugb@126.com (W.Y.); cgs6033@163.com (H.S.)² Innovation Base of Metallogenic Prediction and Prospecting in Central Asia Orogenic Belt, Geological Society of China, Urumqi 830057, China³ Xinjiang Key Laboratory of Mineral Resources and Digital Geology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; wangshanshan@ms.xjb.ac.cn

* Correspondence: wkylw@ms.xjb.ac.cn (W.W.); luluwanwan@aliyun.com (Y.G.)

Abstract

The West Kunlun represents one of the largest and most economically significant rare metal metallogenic belts in NW China. The newly discovered Dahongliutandong Li deposit is the first Li deposit identified within the Permian Huangyangling Group in this region, and its discovery has important implications for regional lithium exploration. In this study, whole-rock major and trace-element geochemistry and cassiterite U–Pb isotope data from both Li-poor and Li-rich pegmatites of the Dahongliutandong deposit were analyzed to constrain the mineralization age and tectonic setting. Geochemically, the pegmatites are characterized by high SiO₂ (70.57–78.50 wt%), low TiO₂, MnO, and MgO (<0.2 wt%), and strongly peraluminous signatures (A/CNK = 1.45–1.95). They exhibit coherent chondrite-normalized REE patterns with LREE enrichment and negative Eu anomalies (Eu/Eu* = 0.03–0.77), along with consistent enrichment in LILEs (e.g., Rb, U, K) and depletion in HFSEs (e.g., Nb, Ti) on primitive mantle-normalized spider diagrams, suggesting a common magmatic source or evolutionary path. Cassiterite U–Pb dating yielded consistent lower-intercept ages of 208 ± 11 Ma (MSWD = 0.86) for Li-poor pegmatites and 206 ± 5 Ma (MSWD = 1.7) for Li-rich pegmatites, both indicating Late Triassic mineralization. Combined with regional geology, these data suggest that Li mineralization was likely related to post-collisional extension following the closure of the Paleo-Tethys Ocean. This study provides new insights into regional rare metal mineralization in the West Kunlun orogenic belt.

Keywords: Cassiterite U–Pb Geochronology; Dahongliutandong; Li Mineralization; West Kunlun orogenic belt; NW China



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1. Introduction

Lithium is a strategic metal widely used in high-tech industries such as lithium-ion batteries, electric vehicles, nuclear applications, and other green sectors [1,2]. Rare metal pegmatites are key sources of Li, Be, Ta, Nb, and gem-quality minerals [3]. The West Kunlun in NW China is a significant pegmatite-type Li–Be metallogenic belt. In recent years, numerous large-scale Li–Be rare metal deposits have been discovered in this region [4,5], including Bailongshan (3.45 Mt Li₂O) and West 509–Daoban (3.48 Mt Li₂O). These deposits are temporally and spatially associated with Late Mesozoic peraluminous

granites and flysch sedimentary rocks [6,7]. In contrast, the recently discovered Dahongliutandong Li deposit represents one of the few pegmatite-type Li mineralizations hosted in Permian Huangyangling Group strata in this area [8], where limited understanding of its metallogenic characteristics hinders exploration.

Establishing precise geochronology for pegmatite-type deposits is critical to understanding regional tectono-metallogenic evolution [9,10]. In this context, determining a reliable mineralization age for the Dahongliutandong Li deposit is a crucial step, as it will elucidate the ore genesis and provide key constraints for regional metallogenic models. While zircon U–Pb dating is a long-established geochronological method, cassiterite and other ore-forming minerals in rare metal pegmatites have become increasingly common in recent geochronological studies [11,12]. Cassiterite (SnO_2) is not only a common accessory mineral in pegmatites but also the primary ore mineral for tin deposits [13,14]. It is an ideal mineral for U–Pb geochronology due to its low U content, high U–Pb isotopic closure temperature (560 °C to 860 °C), and structural stability [13,15]. Its crystal structure can incorporate various trace elements (e.g., Fe, Nb, Ta, U, Pb), and owing to its resistance to alteration and weathering, cassiterite is also well-suited for trace-element analysis to constrain ore-forming conditions [16].

In this study, whole-rock major and trace element compositions and cassiterite U–Pb isotope data from both Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit (West Kunlun, NW China) were analyzed to constrain the mineralization age and possible tectonic setting of the deposit. This study presents the first cassiterite U–Pb ages for the Dahongliutandong Li deposit and provides a detailed comparative characterization of Li-poor and Li-rich pegmatites within the same vein system. The results also provide insights into regional rare metal mineralization in the West Kunlun orogenic belt.

2. Geologic Setting

2.1. Regional Geology

The West Kunlun orogenic belt (WKO) is located on the Tibetan Plateau to the south and the Tarim Basin to the north (Figure 1a) [17,18]. The tectonic evolution of the WKO was primarily controlled by Proto- and Paleo-Tethyan subduction and subsequent terrane collision from the early Paleozoic to early Mesozoic [17,19,20]. The belt comprises, from north to south, the North Kunlun, South Kunlun, Tianshuihai, and Karakorum terranes. The Tianshuihai terrane, which hosts numerous Li–Rb–(Be–Nb–Ta) rare metal deposits, extends NW–SE between the Mazha–Kangxiwa suture zone to the north and the Hongshanhu–Qiaoertianshan suture zone to the south (Figure 1b) [4,19,21].

The rare metal pegmatites in the Dahongliutan ore field are primarily hosted within the Triassic Bayanharshan Group, the main lithostratigraphic unit in this terrane, which is composed of metasandstones, sericite–quartz schist, and two-mica schist [4,6]. Minor occurrences are also observed within the Permian Huangyangling Group (Figure 2). These pegmatites, predominantly trending NW–SE and spanning from tens of meters to over a kilometer in length and several to over a hundred meters in width, formed during mineralization ages of ca. 220–205 Ma [6,22–24]. The ore field is spatially associated with the composite Dahongliutan Mesozoic granite batholith (220–205 Ma), which consists of biotite monzogranite and garnet (tourmaline)-bearing monzogranite in the east and two-mica granite, biotite granite, and granodiorite in the southwest [7,25–28]. The spatial proximity (typically 2–3 km) and consistent Late Triassic ages (ca. 205–220 Ma) between the pegmatites and the Dahongliutan batholith suggest a genetic link between the rare metal pegmatites and the granitic system. This interpretation is further supported by

regional geophysical data, which reveal the subsurface extent of the batholith and indicate a large-scale felsic magma reservoir at depth [29].

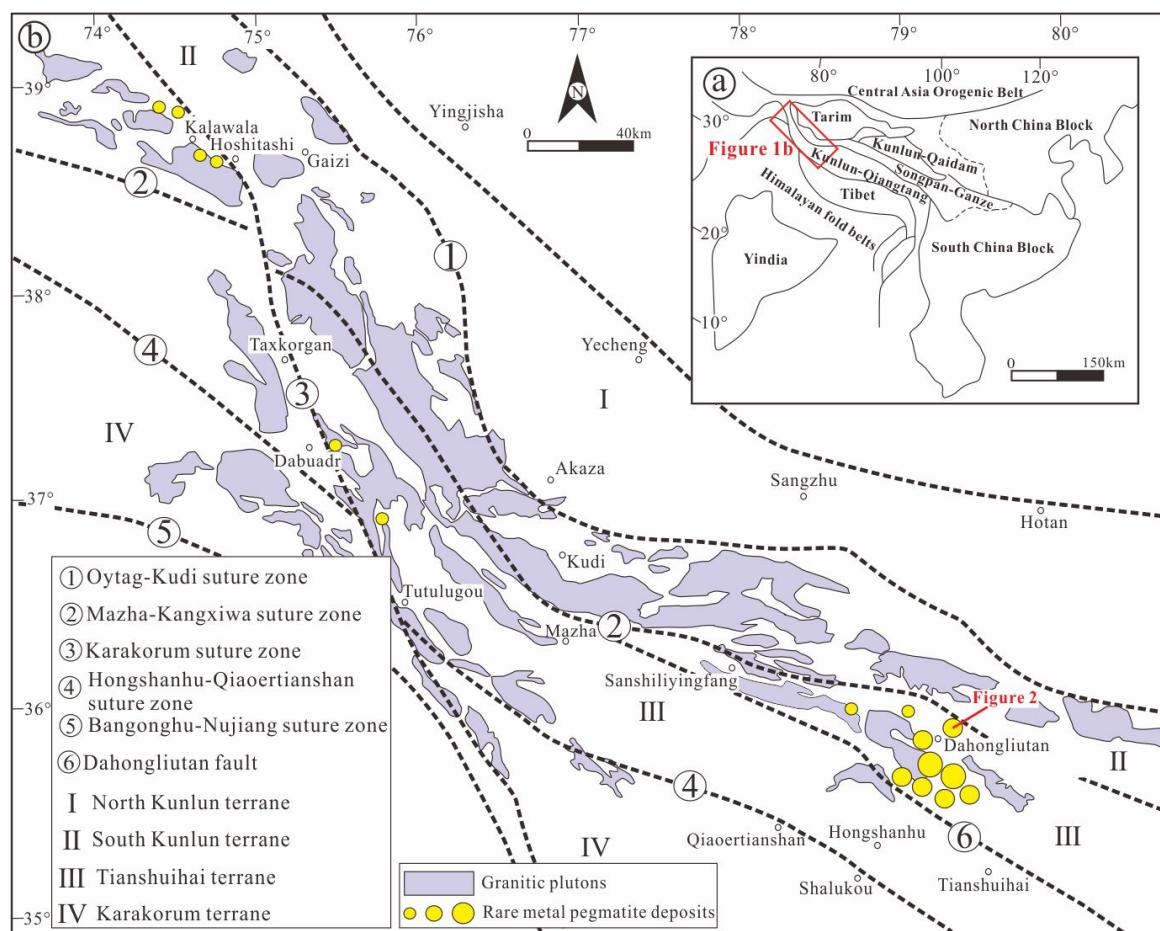


Figure 1. (a) Regional map of eastern Asia [18]; (b) tectonic map of the West Kunlun orogenic belt in NW China showing the major rare metal pegmatite deposits [22,23].

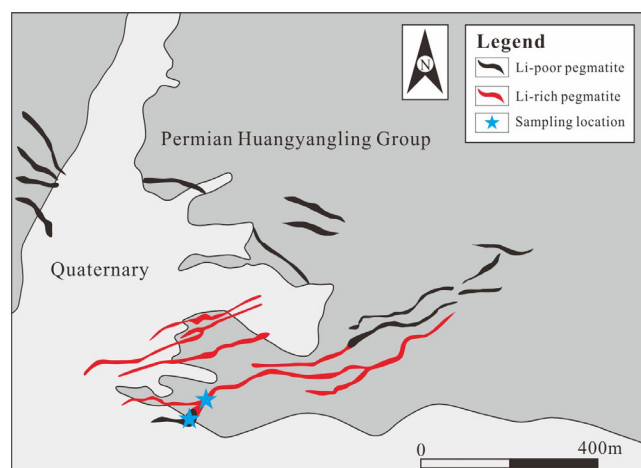


Figure 2. Geological sketch map of the Dahongliutandong Li deposit [30].

2.2. Deposit Geology

The newly discovered Dahongliutandong Li deposit ($35^{\circ}56'50''$ N, $79^{\circ}17'16''$ E; West Kunlun, NW China) is one of the few pegmatite-type Li deposits hosted within Permian strata (Figure 2). The geological characteristics of the Dahongliutandong deposit have been well documented in previous studies [8] and are briefly summarized as follows.

Mineralized pegmatite veins occur in the lower section of the Permian Huangyangling Group, which consists of weakly metamorphosed fine-clastic rocks that have reached greenschist-facies conditions (Figure 3a,b). The dominant lithology includes metamorphic feldspathic quartz siltstone, with minor slate and leptynite.

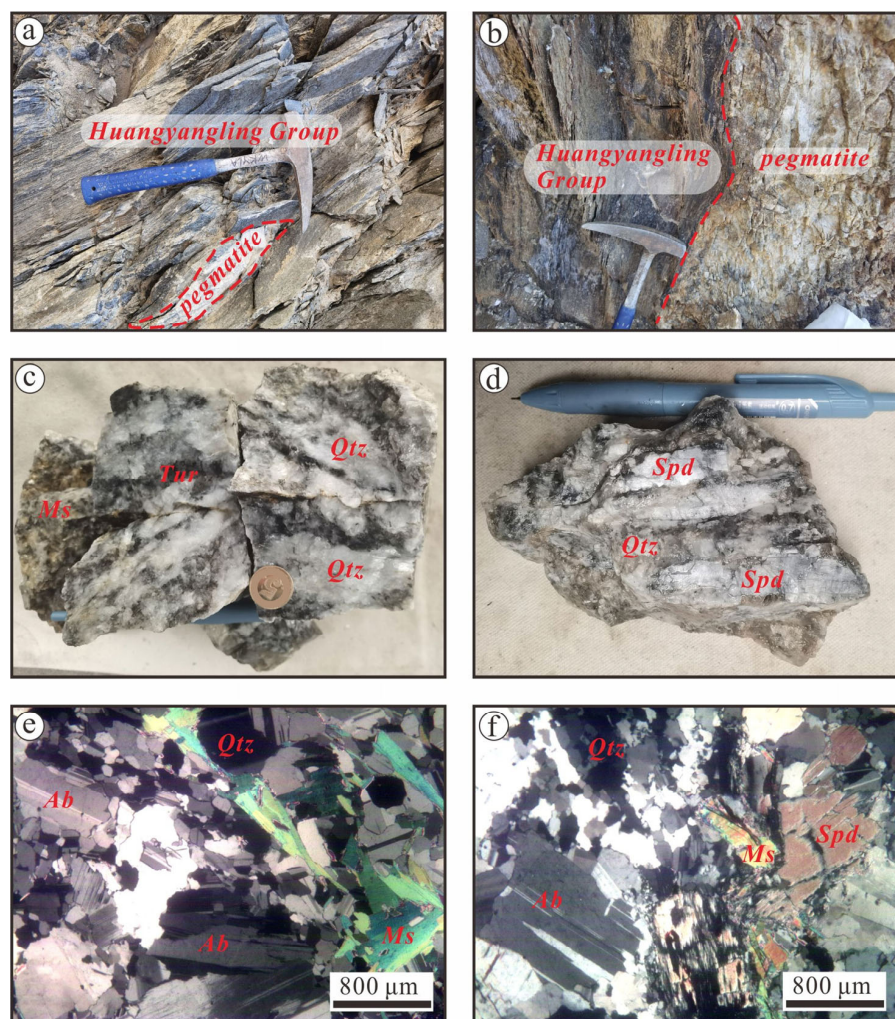


Figure 3. (a,b) Field photographs showing the contact relationships between the Huangyangling Group and pegmatites at the Dahongliutandong Li deposit; (c,d) hand specimens of Li-poor and Li-rich pegmatites from the Dahongliutandong Li deposit; (e,f) photomicrographs of Li-poor and Li-rich pegmatites from the Dahongliutandong Li deposit. Mineral abbreviations: Qtz, quartz; Spd, spodumene; Ms, muscovite; Tur, tourmaline; Ab, albite.

The pegmatite veins in the area can be classified into two distinct types: Li-poor and Li-rich varieties, which differ notably in their geological features. The Li-poor pegmatites are significantly smaller, with lengths of 1.5–65 m and widths of 0.5–0.8 m. These veins occur obliquely within the same Permian strata and consist predominantly of quartz, feldspar, muscovite, and tourmaline, lacking spodumene. They typically display a medium- to coarse-grained granitic pegmatitic texture and massive structure, with local limonitization observed. In contrast, the Li-rich pegmatites are relatively large, measuring 10–450 m in length and 1.5–21 m in width, and extend in a NW–SE direction, generally parallel to or slightly crosscutting the bedding of the Permian Huangyangling Group. Their contact zones exhibit strong schistosity, along with silicification and tourmalinization. Mineralogically, spodumene is the characteristic ore mineral, accompanied by feldspar, quartz, muscovite, and tourmaline. Structurally, both vein types are controlled by NW–SE-trending fractures.

The Li-poor pegmatites strike 320–340° and dip 50–70° NE, while the Li-rich pegmatites strike 315–335° with steeper dips of 60–80° NE.

3. Sampling and Analytical Methods

3.1. Sampling

This study focuses on analyzed samples from the No. 1 veins of both Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit (Figure 2; Table 1). No significant alteration is observed in these samples. The pegmatite veins at Dahongliutandong are generally homogeneous in hand specimens and lack well-developed internal zoning, although subtle variations in mineral assemblages and grain sizes are observed locally. The Li-poor pegmatites typically display a medium- to coarse-grained granitic pegmatitic texture and massive structure. The Li-poor pegmatites (samples DD-1-1 to DD-1-4) consist mainly of quartz (20%–25%), albite (20%–30%), muscovite (5%–10%), and minor tourmaline (~5%), with apatite and rare zircon as accessory minerals (Figure 3c,e); they exhibit relatively uniform mineral distribution throughout the veins. In contrast, the Li-rich pegmatites (samples DD-2-1 to DD-2-4) are primarily composed of albite (55%–60%), quartz (25%–30%), spodumene (15%–20%), and minor muscovite (~5%), with zircon, columbite-tantalite (coltan), cassiterite, and apatite as accessory minerals (Figure 3d,f). The Li-rich pegmatites typically display a coarse-grained pegmatitic texture and massive to weakly banded structure. The Li-rich pegmatites show heterogeneity, with spodumene concentrated in aggregates or bands (Figure 3d) and spodumene-rich zones occurring in the central parts of thicker veins. Accessory cassiterite and columbite-tantalite are also irregularly distributed and mainly associated with spodumene-rich areas.

Table 1. Summary of sample information for the No. 1 vein of the Dahongliutandong Li deposit.

Sample ID	Vein Type	Textural Characteristics	Mineral Assemblage
DD-1-1	Li-poor pegmatite	Medium- to coarse-grained, massive	Qtz (22%), Ab (28%), Ms (8%), Tur (4%); accessory Ap, Zrn
DD-1-2	Li-poor pegmatite	Medium- to coarse-grained, massive	Qtz (25%), Ab (25%), Ms (7%), Tur (3%); accessory Ap, Zrn
DD-1-3	Li-poor pegmatite	Medium- to coarse-grained, massive	Qtz (20%), Ab (30%), Ms (10%), Tur (5%); accessory Ap, Zrn
DD-1-4	Li-poor pegmatite	Medium- to coarse-grained, massive	Qtz (23%), Ab (27%), Ms (9%), Tur (4%); accessory Ap, Zrn
DD-2-1	Li-rich pegmatite	Coarse-grained, massive to weakly banded	Ab (58%), Qtz (28%), Spd (18%), Ms (4%); accessory Zrn, CGMs, Cst, Ap
DD-2-2	Li-rich pegmatite	Coarse-grained, massive to weakly banded	Ab (60%), Qtz (25%), Spd (20%), Ms (5%); accessory Zrn, CGMs, Cst, Ap
DD-2-3	Li-rich pegmatite	Coarse-grained, massive to weakly banded	Ab (55%), Qtz (30%), Spd (16%), Ms (5%); accessory Zrn, CGMs, Cst, Ap
DD-2-4	Li-rich pegmatite	Coarse-grained, massive to weakly banded	Ab (57%), Qtz (27%), Spd (19%), Ms (4%); accessory Zrn, CGMs, Cst, Ap

Mineral abbreviations: Qtz = quartz, Ab = albite, Ms = muscovite, Tur = tourmaline, Spd = spodumene, Ap = apatite, Zrn = zircon, CGMs = columbite-group minerals, Cst = cassiterite.

3.2. Analytical Methods

The detailed analytical procedures for whole-rock major and trace element compositions and cassiterite U–Pb isotope data from both Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit are described below.

3.2.1. Whole-Rock Major and Trace Element Analysis

Whole-rock major and trace element analyses were conducted at Wuhan Sample Solution Analytical Technology Co., Ltd. (Wuhan, China). Major element compositions

were determined by X-ray fluorescence (XRF) spectroscopy (Primus II, Rigaku Corporation, Tokyo, Japan) using fused glass beads. The international standards GSR-1, GSR-3, and GSR-9 were used for calibration, and analytical uncertainties were better than 5%. Trace element concentrations were measured using an Agilent 7700e inductively coupled plasma mass spectrometer (ICP-MS) (Agilent Technologies, Santa Clara, CA, USA). The international standards AGV-2, BCR-2, and RGM-2 were used for calibration, and the analytical precision was generally better than 5% for most trace elements. Powdered samples were completely dissolved in a mixed HF–HNO₃ solution in sealed Teflon bombs and heated for 48 h. The analytical procedures followed those described by Liu et al. (2008) [31].

3.2.2. Cassiterite U–Pb Dating

Cassiterite U–Pb dating and trace element analyses were conducted at the State Key Laboratory of Critical Earth Material Cycling and Mineral Deposits, Nanjing University, China. Measurements were performed using an ASI Resolution S-155 193 nm ArF excimer laser ablation system (Applied Spectra, Inc., West Sacramento, CA, USA) coupled to a Thermo Scientific iCAP Qc quadrupole ICP–MS (Thermo Fisher Scientific, Waltham, MA, USA). Analytical procedures generally followed those described by Li et al. (2016) [32] and Zhang et al. (2017) [33,34]. A laser beam diameter of 74 µm, an energy density of 4 J/cm², and a repetition rate of 5 Hz were typically used. For samples zz50-1 and zz57-1, which contain smaller cassiterite grains, the beam diameter was reduced to 43 µm with an increased energy density of 6 J/cm². NIST SRM 614 glass served as the primary external standard for correcting ²⁰⁶Pb/²⁰⁷Pb ratios and trace element concentrations. The Cligga Head (CLGH) cassiterite from Cornwall, UK, with an ID-TIMS U–Pb age of 285.14 ± 0.25 Ma [35], was used to calibrate ²⁰⁶Pb/²³⁸U ratios. Cassiterite XHL from the Xianghualing deposit (South China), with a reference age of 156 ± 4 Ma (ID-TIMS age) [36], was employed as a secondary monitoring standard. Standard analyses were interspersed at regular intervals: NIST SRM 614 was measured twice after every 12 unknowns, CLGH twice after every 6 unknowns, and XHL once after every 6 unknowns. Each analysis comprised 20 s of background acquisition, 50 s of ablation signal collection, and up to 20 s of gas-blank measurement. Dwell times were set to 8 ms for ²⁰⁴Pb, 15 ms for ²⁰⁶Pb and ²⁰⁸Pb, 20 ms for ²³⁸U, ²³²Th, and ²⁰⁷Pb, and 8 ms for other elements. Raw data were processed offline using ICPMSDataCal 9.9 [37]. Cassiterite typically has extremely low Th/U ratios (<0.01), making ²⁰⁸Pb predominantly common Pb. To correct for common Pb, we applied the Tera–Wasserburg diagram lower-intercept approach. U–Pb ages were calculated, and Tera–Wasserburg concordia diagrams were generated using Isoplot 4.15 [38]. Data reduction accounted for variable common Pb contents following the methods of Chew et al. (2014) [39] and Zhang et al. (2022) [40].

4. Results

4.1. Whole–Rock Major and Trace Element Compositions

The whole-rock major and trace element compositions from both Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit are presented in Table A1.

The studied samples show high and variable SiO₂ contents ranging from 70.57 wt% to 78.50 wt% and low loss on ignition (LOI) varying between 0.01 wt% and 0.06 wt%. All the samples exhibit extremely low contents (<0.2 wt%) of TiO₂, MnO, and MgO. The Li-poor pegmatites contain 70.57–72.37 wt% SiO₂, 16.76–18.24 wt% Al₂O₃, 0.01–0.08 wt% TFe₂O₃, 8.65–9.29 wt% Na₂O, 0.08–0.49 wt% K₂O, and 0.17–0.21 wt% CaO. All the Li-poor pegmatites in this study plot in the granite field of the TAS diagram (Figure 4a) [41]. The molar [Al₂O₃/(CaO + Na₂O + K₂O)] (i.e., A/CNK) values range from 1.47 to 1.61, suggesting a strongly peraluminous affinity (Figure 4b) [42]. Compared to Li-poor pegmatites, the Li-rich varieties are characterized by higher contents of SiO₂ (74.46–78.50 wt%), K₂O

(0.41–0.55 wt%), and CaO (0.11–0.33 wt%) but lower contents of Al_2O_3 (14.98–16.93 wt%) and Na_2O (6.32–7.55 wt%). In the SiO_2 versus $\text{Na}_2\text{O} + \text{K}_2\text{O}$ diagram (Figure 4a) [41], all samples plot within the granite field. Their A/CNK and A/NK values range from 1.45 to 1.95 and 1.52 to 1.99, respectively, indicating a strongly peraluminous affinity (Figure 4b) [42].

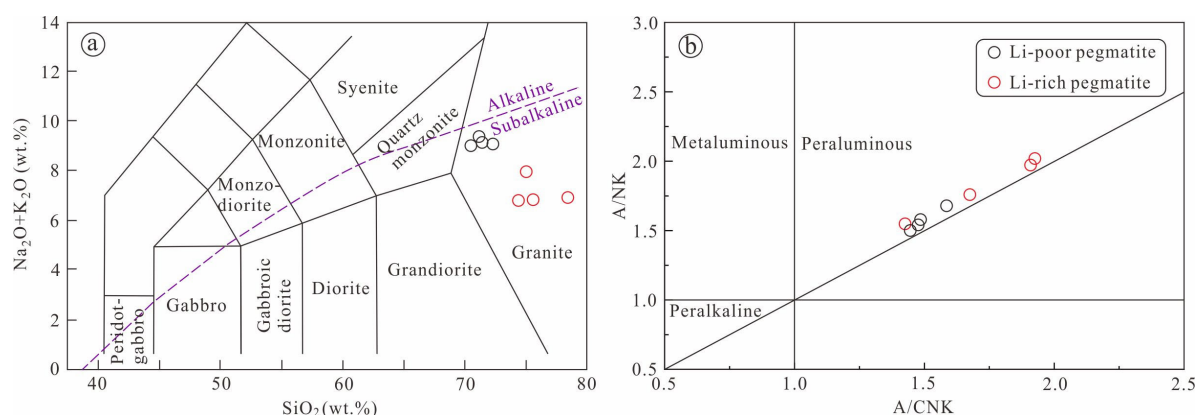


Figure 4. Chemical classification diagrams for both Li-poor and Li-rich pegmatites in the Dahongliutandong Li deposit. (a) TAS (total alkali silica) diagram [41]; (b) A/NK versus A/CNK diagram [42].

In terms of trace elements, both the Li-poor and Li-rich pegmatites in this study exhibit similar patterns of incompatible element enrichment and depletion. Their chondrite-normalized rare earth element (REE) patterns are coherent (Figure 5a) [43], characterized by light REE (LREE) enrichment and a gradual decrease in heavy REEs (HREEs), with $(\text{La}/\text{Yb})_N$ ratios ranging from 3.99 to 8.02 in the Li-poor group and from 2.51 to 3.90 in the Li-rich group. The Li-poor pegmatites generally have higher total REE concentrations than the Li-rich pegmatites. Except for a few samples, both groups display predominantly negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.03\text{--}0.77$), consistent with significant plagioclase fractionation under relatively oxidizing conditions. The primitive mantle-normalized trace element spider diagram (Figure 5b) [43] shows consistent enrichment in large-ion lithophile elements (LILEs; e.g., Rb, U, K, and Pb) and depletion in high-field-strength elements (HFSEs; e.g., Nb and Ti). Negative Ba and Ce anomalies, together with positive Ta and Hf anomalies, are also observed in both groups of pegmatites. These geochemical features suggest that although the Li-poor and Li-rich pegmatites differ in Li and rare earth element (REE) concentrations, they likely originated from a similar source or underwent common early magmatic evolution.

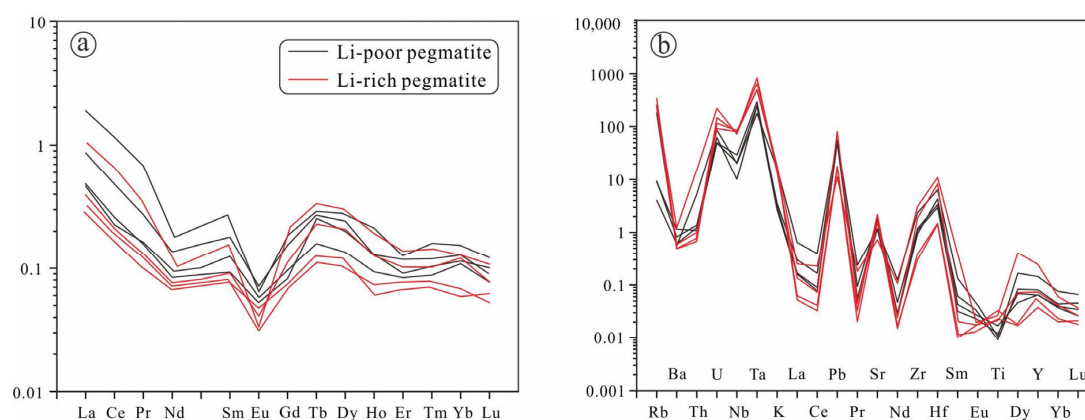


Figure 5. (a) Chondrite-normalized rare earth element (REE) patterns and (b) primitive mantle-normalized multi-element diagrams for both Li-poor and Li-rich pegmatites in the Dahongliutandong Li deposit. The chondrite and primitive mantle normalization values are from [43].

4.2. Cassiterite U–Pb Age

The cassiterite U–Pb isotope dating results for both Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit are provided in Table A2.

Cathodoluminescence (CL) images reveal that cassiterite grains from both Li-poor and Li-rich pegmatites are predominantly gray in color, exhibit euhedral to subhedral shapes, range from 100 to 200 μm in length and 50–100 μm in width, and show no zoning (Figure 6a,b). Clean grain boundaries with minimal fractures or alteration and intergrowth relationships with albite and quartz indicate primary magmatic crystallization. U–Pb dating of cassiterite from the Li-poor and Li-rich pegmatites yields consistent Tera–Wasserburg lower-intercept ages of 208 ± 11 Ma (MSWD = 0.86; $n = 21$) and 206 ± 5 Ma (MSWD = 1.7; $n = 22$), respectively (Figure 6a,b).

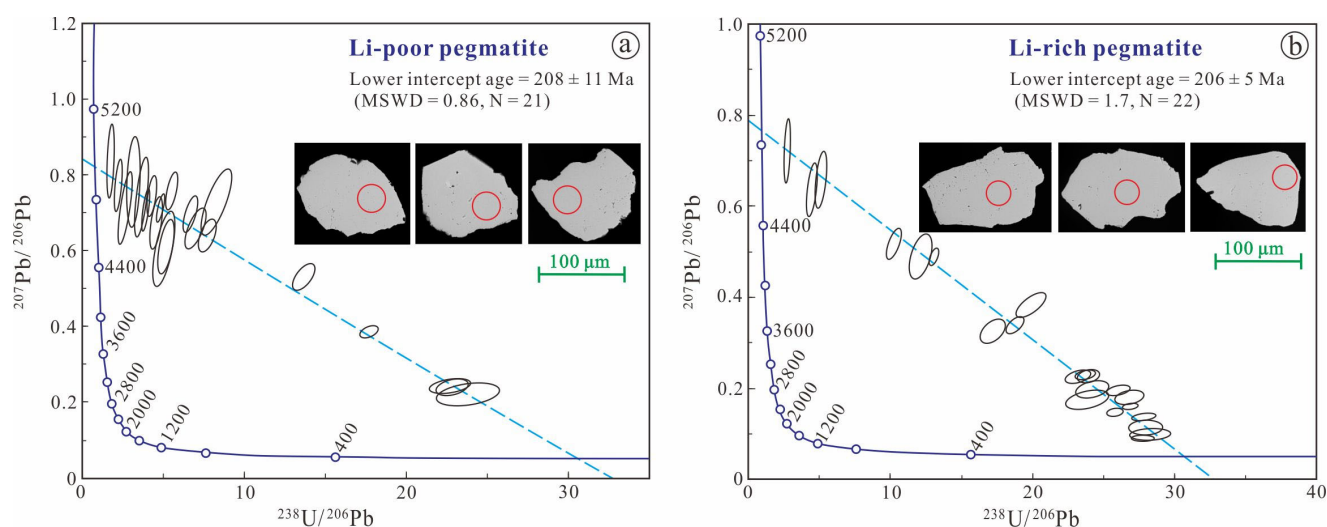


Figure 6. Representative cathodoluminescence (CL) images and cassiterite U–Pb Tera–Wasserburg lower-intercept ages for the pegmatites from the Dahongliutandong Li deposit. (a) Li-poor pegmatites; (b) Li-rich pegmatites. Red circles indicate the locations of U–Pb analyses.

5. Discussion

5.1. Age of the Dahongliutandong Li Deposit

Precise determination of mineralization age is fundamental for constraining the genesis of rare metal pegmatite deposits. Although zircon U–Pb dating is a commonly employed geochronological method, direct dating of ore-forming minerals such as cassiterite and columbite-group minerals (CGMs) provides more direct and robust constraints on the timing of rare metal mineralization [11,12,44]. Despite challenges associated with high common Pb and low U contents in cassiterite [45], methodological advances have demonstrated that Tera–Wasserburg lower-intercept ages are more reliable than conventional $^{206}\text{Pb}/^{207}\text{Pb}$ – $^{238}\text{U}/^{207}\text{Pb}$ isochron methods for high-common-Pb systems [32].

In this study, cassiterite grains from both Li-poor and Li-rich pegmatites at Dahongliutandong exhibit euhedral to subhedral morphology, an absence of internal zoning in cathodoluminescence (CL) images (Figure 6a,b), and magmatic intergrowths with albite and quartz, supporting a primary magmatic origin. U–Pb dating yields consistent Tera–Wasserburg lower-intercept ages of 208 ± 11 Ma (MSWD = 0.86; $n = 21$) for Li-poor pegmatites and 206 ± 5 Ma (MSWD = 1.7; $n = 22$) for Li-rich pegmatites. These cassiterite U–Pb ages are further corroborated by recent zircon U–Pb geochronology conducted on pegmatites from the same area. Kong et al. (2023) [8] reported LA–ICP–MS zircon U–Pb ages of 205.0 ± 2.6 Ma and 205.2 ± 1.4 Ma for Li-rich and Li-poor pegmatites, respectively, at Dahongliutandong. These ages overlap within analytical uncertainty, constraining

the Li mineralization at Dahongliutandong to a Late Triassic (~205–208 Ma) magmatic–hydrothermal event.

This metallogenic age framework is consistent with published geochronological data from West Kunlun and the adjacent Songpan–Ganzi rare metal metallogenic belts. For instance, within the same Dahongliutan ore field, Yan et al. (2018) [22] reported a columbite U–Pb age of 211.9 ± 2.4 Ma and a cassiterite U–Pb age of 218 ± 12 Ma. The nearby Bailongshan deposit yields a columbite U–Pb age of 208.1–213.9 Ma [6,46], which is coeval with the emplacement of the ca. 205–220 Ma Dahongliutan batholith [7,25–28]. Pegmatites in the West Kunlun rare metal metallogenic belt, such as those at Xiaorubulong, Huoshitashi, Mulinchang, and Xuefengling, also record concentrated mineralization ages of ~205–208 Ma [23,27]. Extending eastward to the Songpan–Ganzi rare metal metallogenic belt, major deposits such as Jiajika, Zhawulong, and Lijiaqou exhibit principal metallogenic epochs during the Late Triassic to Early Jurassic (~192–217 Ma) [46–49]. This extensive spectrum of mineralization ages (~200–220 Ma) across different tectonic units reveals a regional-scale rare metal mineralization event in the Late Triassic within the Tethyan tectonic domain of southwestern China.

In summary, geochronological evidence constrains the mineralization age of the Dahongliutandong Li deposit to ~205–208 Ma, which is coeval with regional Late Triassic rare metal events in the West Kunlun–Songpan–Ganzi orogenic belt.

5.2. Implications for Regional Mineralization

Based on the mineralization age (~205–208 Ma) of the Dahongliutandong Li deposit, integrated with published geochemical and geochronological data, this study provides important insights into the tectonic setting and Li metallogenic potential in this region. The Dahongliutandong pegmatites are characterized by enrichment in spodumene as the primary Li-rich mineral and are classified within the LCT (Li–Cs–Ta) family [50]. Pegmatites of this family are generally interpreted as resulting from extreme fractional crystallization of peraluminous granitic melts, typically derived from partial melting of metasedimentary crustal sources [51–53]. Consequently, most LCT pegmatites exhibit a strong compositional affinity and spatial–genetic relationship with S-type granites [54,55].

In this context, the Dahongliutandong pegmatites are situated within the newly recognized >2000 km long rare metal metallogenic belt of the West Kunlun–Songpan–Ganzi orogenic belt, which hosts several world-class rare metal deposits, including Bailongshan, West 509-Daoban, Jiajika, and Zawulong [6,23,56–58]. Like other major deposits in this belt, the Dahongliutandong pegmatites are hosted by granites and low- to medium-grade metasedimentary rocks of the Tianshuihai–Songpan–Ganzi Terrane, reflecting a clear temporal, spatial, and paragenetic link to Late Triassic granites [6,7,23,28,56]. The Li-poor and Li-rich pegmatites in Dahongliutandong exhibit similar REE patterns, consistent trace element signatures, and strongly peraluminous compositions, suggesting derivation from a common magmatic source. Systematic geochemical trends—such as the enrichment of Li, Rb, Cs, Nb, and Ta from Li-poor to Li-rich pegmatites, decreasing K/Rb ratios, and negative Eu anomalies—further indicate progressive fractional crystallization as a key petrogenetic process. The contrasting geochemical signatures of the two pegmatite types reflect different stages of fractional crystallization. The Li-rich pegmatites are enriched in Li, Rb, Cs, Nb, Ta, and Sn, consistent with the progressive fractionation of feldspar and mica and the saturation of Nb–Ta oxides and cassiterite at the magmatic–hydrothermal transition [53,59]. In contrast, the Li-poor pegmatites are enriched in Be and Zr, suggesting control by early-crystallizing accessory minerals such as beryl and zircon. Their genetic link to the spatially associated two-mica granites is supported by consistent emplacement ages: 206–205 Ma for the West 509-Daoban two-mica granites [28] and 208–205 Ma for the

Dahongliutandong pegmatites. In addition, the West 509-Daoban and Bailongshan pegmatites display Sr–Nd isotopic compositions comparable to those of the West 509-Daoban two-mica granites, which are characterized by high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.71532–0.71661) and low $\epsilon\text{Nd}(t)$ values (−9.96 to −9.52) [7,60]. These lines of evidence collectively reinforce a cogenetic relationship between the pegmatites and the granitic magmatic system.

The formation of LCT pegmatites is closely linked to the fluid-magmatic differentiation of peraluminous granitic magmas [59,61]. As highly fractionated granitic melts evolve, they become enriched in fluxes (H_2O , F, B, P) and incompatible elements (Li, Rb, Cs, Nb, Ta), ultimately leading to the exsolution of a volatile-rich phase that promotes the crystallization of rare-metal minerals [62,63]. The Nb–Ta fractionation observed in peraluminous granites serves as a key marker of the magmatic–hydrothermal transition, with decreasing Nb/Ta ratios indicating progressive fluid exsolution and interaction [59]. Similar processes have been documented in rare-metal pegmatite provinces worldwide. In the Kalba region of Eastern Kazakhstan, Khromykh et al. (2020) [64] demonstrated that Li–Ta–Nb mineralization resulted from extreme fractional crystallization of rare-metal granite melts, with fluid saturation playing a critical role in ore formation. The Koktokay No. 3 pegmatite in the Chinese Altai is another classic example, where Shen et al. (2022) [65] showed that the parental highly fractionated leucogranite underwent extensive magmatic–hydrothermal evolution, leading to world-class rare-metal mineralization. More recently, Fanka and Tadthai (2023) [66] documented Li-bearing pegmatites in southern Thailand that formed through progressive fractionation of peraluminous granitic magmas, with fluid-magmatic processes controlling the distribution of rare elements. Oitseva et al. (2025) [67] further emphasized the importance of fluid saturation and volatile transfer in the formation of Li–Ta–Nb mineralization in the Kvartsevoye pegmatite deposit, Eastern Kazakhstan. These geochemical features are also consistent with fluid-magmatic differentiation of the parental granitic magma, a process widely recognized in the formation of LCT pegmatites [57,59]. The presence of tourmaline in Li-poor pegmatite types further supports the involvement of a boron-rich fluid phase during magmatic evolution, highlighting the role of volatile components in promoting rare metal enrichment. These lines of evidence collectively suggest that the Dahongliutandong Li pegmatites formed through advanced fluid-magmatic differentiation of peraluminous granitic melts, analogous to other major LCT pegmatite systems worldwide that are typically associated with post-collisional extensional environments following crustal thickening [51,68,69]. The mineralization is interpreted as the result of extreme fractional crystallization from a highly evolved, volatile-rich residual melt derived from the parental Dahongliutan pluton. This pluton constitutes a NW-trending, Late Triassic post-collisional complex extending for over 150 km along strike, represents the dominant intrusive unit in the Tianshuihai terrane, and was emplaced ca. 205–220 Ma [7,22,25–28,70]. The spatial proximity, overlapping ages, consistent compositions, and comparable isotopic signatures further support a cogenetic relationship between the Dahongliutan granites and the Dahongliutandong pegmatites, both of which formed in a post-collisional extensional setting following Paleo-Tethys closure.

During the Late Triassic, the gradual closure of the Paleo-Tethys Ocean from northwest to southeast in the WKOB led to intense collisional orogeny, crustal thickening, and syn-collisional magmatism, followed by a tectonic transition from compression to extension that triggered decompression melting of the thickened crust and widespread post-collisional magmatism [27,71–74]. The emplacement of the Dahongliutan pluton and the crystallization of its associated pegmatites represent a key response to this post-collisional extensional phase, with their formation age precisely recording the timing of the tectonic transition. This genetic linkage is supported by their spatial association and similar Late Triassic ages, consistent with regional magmatic and metallogenic events during the post-collisional stage

of the Paleo-Tethys closure in the WKOB [6,22–24,28,71]. Notably, this tectonic setting is not only analogous to that of other major global pegmatite deposits (e.g., Koktokay in China and Kenticha in Ethiopia) but also establishes a clear genetic and spatial linkage between rare metal mineralization in West Kunlun and that in the Songpan–Ganzi metallogenic belt, highlighting the significant exploration potential in this region.

6. Conclusions

1. Cassiterite U–Pb dating indicates that the mineralization of the Dahongliutandong Li deposit occurred during the Late Triassic (~206–208 Ma), contemporaneous with a post-collisional extensional setting following the closure of the Paleo-Tethys Ocean.
2. Geochemical analyses reveal that both Li-poor and Li-rich pegmatites exhibit strongly peraluminous signatures, consistent trace-element patterns, and negative Eu anomalies, suggesting a common magmatic source.
3. As the first Li deposit discovered within the Permian Huangyangling Group, this finding extends the metallogenic framework of the West Kunlun orogenic belt and offers new guidance for regional rare metal exploration.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Whole-rock major and trace element compositions of the Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit.

Sample	DD-1-1	DD-1-2	DD-1-3	DD-1-4	DD-2-1	DD-2-2	DD-2-3	DD-2-4
Lithology	Li-poor pegmatites				Li-rich pegmatites			
Major oxides (wt.%)								
SiO ₂	72.37	70.57	71.24	71.49	75.66	78.50	75.10	74.46
TiO ₂	0.004	0.001	0.003	0.002	0.007	0.005	0.003	0.004
Al ₂ O ₃	16.76	18.24	17.49	17.60	16.87	14.98	15.05	16.93
TFe ₂ O ₃	0.02	0.01	0.01	0.09	0.25	0.22	0.23	0.22
MnO	0.006	0.005	0.004	0.006	0.051	0.044	0.100	0.033
MgO	0.010	0.002	0.010	0.003	0.005	0.011	0.012	0.020
CaO	0.19	0.21	0.17	0.20	0.11	0.11	0.33	0.13
Na ₂ O	9.00	8.90	9.29	8.65	6.32	6.39	7.55	6.25

Table A1. Cont.

Sample	DD-1-1	DD-1-2	DD-1-3	DD-1-4	DD-2-1	DD-2-2	DD-2-3	DD-2-4
K ₂ O	0.08	0.11	0.09	0.49	0.51	0.53	0.41	0.55
P ₂ O ₅	0.20	0.24	0.20	0.22	0.13	0.11	0.44	0.09
LOI	0.30	0.28	0.31	0.44	0.53	0.57	0.51	0.51
SUM	98.93	98.56	98.82	99.18	100.43	101.47	99.73	99.19
Trace elements (ppm)								
Li	67.14	77.52	118.53	62.85	14,579.06	12,200.25	1615.02	17,914.35
Be	89.90	234.16	862.84	110.38	89.45	44.65	5.45	2.43
Sc	0.16	0.18	0.07	0.04	0.19	0.34	0.36	0.13
V	0.40	0.77	1.80	1.15	0.91	0.85	0.89	1.10
Cr	0.39	0.27	0.28	0.31	0.34	0.30	0.30	0.30
Co	0.02	0.03	0.02	0.05	0.04	0.03	0.05	0.03
Ni	0.51	0.60	0.41	0.37	0.05	0.03	0.07	0.21
Cu	0.53	1.14	0.75	1.71	0.11	0.25	0.43	0.39
Zn	2.23	2.13	3.39	6.92	23.13	21.20	29.77	33.60
Ga	13.80	15.07	14.31	17.92	25.82	25.10	16.45	31.29
Rb	2.58	5.95	5.72	112.90	144.29	154.60	159.46	209.51
Sr	24.96	36.66	35.61	24.69	46.06	33.76	44.93	15.43
Y	0.30	0.37	0.29	0.66	0.11	0.11	0.33	1.11
Zr	10.59	13.31	12.25	26.41	3.37	4.37	20.96	34.84
Nb	15.10	7.19	20.99	14.54	55.12	59.45	51.84	57.08
Sn	0.92	61.74	1.04	19.40	48.66	46.83	25.89	176.28
Cs	2.15	5.39	20.57	6.78	7.44	6.12	13.27	7.20
Ba	4.29	5.78	8.11	3.93	3.48	3.43	8.57	4.18
La	0.11	0.21	0.11	0.45	0.04	0.04	0.09	0.17
Ce	0.14	0.30	0.16	0.71	0.07	0.06	0.13	0.40
Pr	0.02	0.03	0.01	0.07	0.01	0.01	0.01	0.05
Nd	0.04	0.06	0.04	0.17	0.02	0.02	0.03	0.14
Sm	0.019	0.027	0.014	0.059	0.004	0.009	0.014	0.172
Eu	0.005	0.014	0.005	0.007	0.003	0.001	0.002	0.002
Gd	0.02	0.03	0.02	0.07	0.01	0.00	0.02	0.24
Tb	0.006	0.009	0.009	0.022	0.001	0.002	0.009	0.076
Dy	0.03	0.06	0.05	0.12	0.01	0.01	0.05	0.30
Ho	0.005	0.007	0.007	0.014	0.003	0.002	0.007	0.020
Er	0.02	0.02	0.02	0.03	0.01	0.01	0.02	0.04
Tm	0.002	0.003	0.003	0.006	0.001	0.001	0.003	0.005
Yb	0.02	0.02	0.02	0.04	0.01	0.01	0.02	0.03
Lu	0.002	0.003	0.003	0.005	0.001	0.002	0.002	0.003
Hf	1.33	1.03	0.92	1.96	0.44	0.46	2.54	3.37
Ta	9.92	9.90	11.78	7.15	19.56	19.95	34.20	26.84
Tl	0.02	0.04	0.05	0.64	0.81	0.88	1.01	1.15
Pb	9.34	10.36	10.26	10.11	3.21	3.32	14.90	2.06
Th	0.11	0.12	0.09	0.45	0.05	0.04	1.31	0.09
U	1.04	1.32	1.05	1.81	3.04	2.41	4.53	1.92
ΣREE	0.43	0.79	0.47	1.76	0.20	0.17	0.42	1.65
ΣLREE	0.32	0.63	0.35	1.45	0.16	0.13	0.28	0.94
ΣHREE	0.10	0.16	0.12	0.31	0.05	0.04	0.13	0.71
LREE/HREE	3.11	3.93	2.81	4.70	3.46	3.15	2.13	1.33
(La/Yb)N	4.03	6.39	3.99	8.02	2.51	2.43	3.07	3.90
Eu/Eu*	0.77	1.40	1.08	0.33	1.58	0.59	0.40	0.03

Table A2. In situ LA–MC–ICP–MS U–Pb dates of cassiterite from the Li-poor and Li-rich pegmatites in the newly discovered Dahongliutandong Li deposit.

Concentrations (ppm)			Isotopic Ratios		Isotopic Ages (Ma)				
No.	Th	U	$^{207}\text{Pb}/^{235}\text{U}$ 1 σ (%)	$^{206}\text{Pb}/^{238}\text{U}$ 1 σ (%)	$^{207}\text{Pb}/^{235}\text{U}$	2 σ	$^{206}\text{Pb}/^{238}\text{U}$	2 σ	
Sample: DD-3 Li-poor pegmatites 208 $\pm$ 11 Ma (MSWD = 0.86; n = 21)									
DD-3-1	0.00	0.19	28.3864	7.5	0.2774	8.5	3031	256	1478
DD-3-2	0.00	0.14	34.7551	8.7	0.3236	9.0	2971	318	1662
DD-3-4	0.00	0.39	16.1926	6.7	0.1924	6.5	2609	198	1100
DD-3-5	0.01	0.31	46.7261	4.4	0.4380	5.4	3833	97	2285
DD-3-6	0.01	2.95	14.4894	3.6	0.1506	3.7	2735	68	907
DD-3-7	0.00	4.22	5.3585	3.8	0.0731	3.2	1825	67	454
DD-3-8	0.00	1.05	13.0219	4.7	0.1433	4.6	2610	90	853
DD-3-9	0.00	1.32	23.7882	4.0	0.2323	4.0	3194	86	1328
DD-3-11	0.01	1.38	11.4870	3.8	0.1303	3.7	2516	78	784
DD-3-12	0.01	5.28	1.4787	5.3	0.0442	3.6	876	68	278
DD-3-13	0.00	2.86	3.0077	2.7	0.0565	2.0	1387	43	354
DD-3-14	0.05	0.90	24.7446	4.0	0.2525	3.7	3238	89	1434
DD-3-15	0.00	6.62	1.4420	5.4	0.0437	3.1	865	67	275
DD-3-16	0.01	1.39	18.9265	3.7	0.1814	3.7	2997	73	1064
DD-3-17	0.00	0.24	16.5274	9.4	0.1979	8.9	2693	301	1099
DD-3-18	0.00	0.29	65.4868	6.2	0.5674	6.8	4152	126	2812
DD-3-19	0.01	2.63	1.2779	9.0	0.0421	5.5	699	108	264
DD-3-20	0.02	0.51	12.1274	6.5	0.1210	6.7	2329	186	735
DD-3-21	0.00	0.18	36.2619	6.9	0.3702	7.9	3339	237	1946
DD-3-24	0.02	0.43	20.1216	6.3	0.2170	5.3	2952	128	1238
DD-3-25	0.02	1.78	20.1528	2.7	0.2051	3.0	3080	56	1194
Sample: DD-4 Li-rich pegmatites 206 $\pm$ 5 Ma (MSWD = 1.7; n = 22)									
DD-4-2	0.00	6.39	0.7918	3.8	0.0388	1.5	582	36	245
DD-4-3	0.00	4.22	1.0094	7.4	0.0419	4.1	660	81	264
DD-4-5	0.00	5.65	2.6461	3.5	0.0503	3.3	1286	54	315
DD-4-6	0.01	5.54	1.3059	4.1	0.0417	2.0	821	47	263
DD-4-8	0.00	6.44	0.4844	8.1	0.0353	3.4	366	54	223
DD-4-9	0.01	4.26	0.6812	4.0	0.0359	2.0	514	33	227
DD-4-10	0.01	3.86	0.4515	4.9	0.0361	1.8	367	31	228
DD-4-11	0.01	9.38	2.4892	3.2	0.0533	2.2	1242	48	334
DD-4-12	0.02	0.69	17.7113	4.5	0.1952	4.7	2868	97	1130
DD-4-13	0.00	3.36	5.1463	2.1	0.0764	1.8	1828	36	474
DD-4-14	0.01	0.87	19.6059	4.6	0.2237	4.6	2980	101	1295
DD-4-15	0.01	9.55	0.9253	5.5	0.0373	2.6	646	59	236
DD-4-16	0.04	6.99	1.1333	5.6	0.0414	3.1	729	67	261
DD-4-17	0.01	4.11	1.3401	4.2	0.0431	2.5	847	52	272
DD-4-18	0.01	2.86	6.9707	3.2	0.0977	3.4	2075	61	598
DD-4-19	0.00	1.70	5.5656	5.6	0.0824	4.4	1832	97	507
DD-4-20	0.02	2.85	1.0339	3.5	0.0384	2.1	716	36	243
DD-4-21	0.01	0.45	36.4593	5.3	0.3673	4.7	3545	116	1966
DD-4-22	0.00	5.43	2.6090	4.8	0.0582	3.3	1252	72	363
DD-4-23	0.07	3.24	0.8249	2.7	0.0372	1.3	606	26	236
DD-4-24	0.01	5.59	1.3381	3.1	0.0422	1.9	852	37	266
DD-4-25	0.01	4.54	0.5654	9.5	0.0357	2.8	425	51	226

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