

Article

Late Cambrian N-MORB-Type Amphibolite in Central Jilin Province, NE China: Implications for Subduction Initiation in the Paleo-Asian Ocean

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Abstract

The Shitoukoumen area in central Jilin Province, NE China, preserves a Permian blocks-in-matrix assemblage containing pre-Permian mafic and sedimentary blocks that provides an important record of the Paleozoic evolution of the eastern Paleo-Asian Ocean. We present petrographic, zircon U-Pb geochronological and Lu-Hf isotopic, and whole-rock geochemical and Sr-Nd isotopic data for newly discovered amphibolites. Zircons from the amphibolites show metamorphic characteristics, and zircon U-Pb dating yielded an age of 503 ± 4 Ma, recording Late Cambrian metamorphism. The amphibolite is tholeiitic, with low SiO₂ (48.46–52.22 wt.%) and K₂O (0.07–0.17 wt.%) and relatively high MgO (4.48–6.31 wt.%), Fe₂O₃^T (11.01–15.48 wt.%), and CaO (9.07–12.55 wt.%). It has low total REE abundances and slightly LREE-depleted patterns, with no negative Nb-Ta anomalies. Its $\epsilon_{\text{Hf}}(t)$ and $\epsilon_{\text{Nd}}(t)$ values are +14.9 to +20.4 and +7.2 to +8.4, respectively, while the initial ⁸⁷Sr/⁸⁶Sr ratios are slightly elevated, consistent with seawater alteration. These geochemical and isotopic characteristics are consistent with an N-MORB-like oceanic crustal protolith derived from partial melting of a depleted spinel-facies mantle source. Together with the spatial association with the Zhangjiatun–Toudaogou–Xiaosuihe SSZ ophiolite, the amphibolite may represent a component of a metamorphic sole related to Late Cambrian intra-oceanic subduction initiation of the Paleo-Asian Ocean, although this interpretation remains tentative.

Keywords: Bainaimiao arc; late Cambrian; amphibolite; subduction initiation; Paleo-Asian Ocean



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1. Introduction

The Paleo-Asian Ocean (PAO) tectonic domain preserves one of the most prolonged and intricate records of Phanerozoic continental crustal accretion and reworking, documenting key geological processes that shaped the Paleozoic global paleogeographic framework [1–9]. The Bainaimiao Arc Belt (BAB), situated along the southern margin of the PAO tectonic domain, is an approximately E-W-trending Early Paleozoic arc belt extending across Inner Mongolia, Liaoning, and Jilin provinces in Northeast (NE) China [10–18]. It hosts abundant Early Paleozoic metavolcanic-sedimentary and intrusive rocks with arc or adakitic affinities, making the BAB a critical natural laboratory for investigating the

subduction-accretion processes of the PAO and the Early Paleozoic paleogeographic configuration. Detailed studies of various Early Paleozoic units have provided important constraints on the tectonic affinity of the BAB and the Early Paleozoic evolution of the PAO [9–42]. However, considerable uncertainty remains, and proposed models interpret the BAB as a Japan-type island arc [19,20], an Andean-type magmatic arc [9,21], an Alaskan-type magmatic arc [18,22,23] or an exotic accreted terrane/microcontinent [10,12–17,24–35]. These contrasting interpretations have resulted in different tectonic reconstruction scenarios for the Early Paleozoic evolution of the PAO and, more broadly, the southeastern Central Asian Orogenic Belt (CAOB) [9–42].

In recent decades, arc magmatic rocks identified in the BAB have provided substantial evidence for Early Paleozoic subduction of the Paleo-Asian oceanic plate (PAOP) [10,11,13–15,17,18,21,23–28,30,36,38–42]. Previous studies have primarily focused on the development of arc magmatism, slab subduction, and ocean closure, whereas the initiation of subduction has received comparatively less attention. Although several studies have investigated SSZ-type ophiolites in the Tulinkai area of Inner Mongolia and the Zhangjiatun–Toudaogou–Xiaosuihe (ZTX) area of Jilin Province [30,40], the timing and mechanisms of Early Paleozoic subduction initiation of the PAOP remain debated. Identifying and characterizing geological units that record the early stages of subduction are therefore essential for constraining the timing, tectonic context, and geodynamic mechanisms of subduction initiation. Such investigations can provide new constraints on the Early Paleozoic tectonic evolution of the southeastern CAOB.

The Shitoukoumen–Bonihe area in Jilin Province, located in the eastern BAB, exposes a distinctive assemblage of diabase dikes, mafic volcanic lavas, mafic-ultramafic complexes, and radiolarian-bearing pelagic siliceous rocks [42–44]. The assemblage commonly exhibits a “blocks-in-matrix” texture and has previously been compared with dismembered ophiolitic assemblages [41–44]. It therefore provides an important target for investigating the evolution of oceanic lithosphere and subduction initiation in the eastern PAO. Published geological, paleontological, petrographic, geochronological, and geochemical studies have established several important characteristics of the Shitoukoumen blocks-in-matrix assemblage. In particular, the matrix has been interpreted to have formed during the Early Permian [41–43], whereas Early Carboniferous metamorphosed oceanic crustal fragments and Late Carboniferous carbonate blocks have also been identified within the *mélange* [44]. These published data provide important constraints on the Paleozoic evolution of the *mélange*; however, they do not clearly establish whether the *mélange* also preserves geological records of the Early Paleozoic evolution of the PAO.

Isotopic geochronology and radiogenic isotope geochemistry are widely used to constrain the age, protolith, and petrogenesis of metamorphosed igneous rocks. Zircon U–Pb dating provides constraints on magmatic crystallization and metamorphic recrystallization, whereas zircon Lu–Hf isotopes can help evaluate magma sources and crustal evolution [45–47]. Whole-rock Sr–Nd isotopic compositions are widely used to constrain the characteristics of magma sources and crust–mantle evolution [48,49]. Together, these methods can help identify the protolith and tectonic significance of metamorphosed igneous rocks, particularly in complex accretionary belts [50].

During our field investigations in the Shitoukoumen area, amphibolite was observed within the blocks-in-matrix assemblage and selected for detailed study. We therefore present petrographic, zircon U–Pb geochronological and Lu–Hf isotopic, and whole-rock geochemical and Sr–Nd isotopic data for the amphibolite to constrain its protolith, metamorphic history, and tectonic significance. Our results provide new constraints on the nature and tectonic significance of the amphibolite and its relationship to the pre-Permian mafic assemblages in the Shitoukoumen area.

2. Geological Setting and Sample Descriptions

The BAB is located in the composite zone between the southeastern CAOB and the northern margin of the North China Craton (NCC) (Figure 1). From south to north, this composite zone comprises the northern NCC margin, the BAB, the Ondor Sum subduction-accretion complex, the Erdaojing subduction complex, the Baolidao arc accretionary complex, the Hegenshan back-arc basin, and the Uliastai active continental margin. The BAB lies south of the Solonker–Xar Moron–Changchun Suture Zone and north of the Bayan Obo–Duolun–Chifeng–Kaiyuan Fault and extends nearly E–W for approximately 1300 km [10]. The Solonker–Xar Moron–Changchun Suture Zone is generally regarded as an important tectonic boundary associated with the evolution of the PAO, but its exact position, age, and tectonic significance remain debated [9,51,52]. In particular, the nature and age of the mafic and so-called ophiolitic rocks exposed along the suture have been interpreted differently in different studies [53,54].

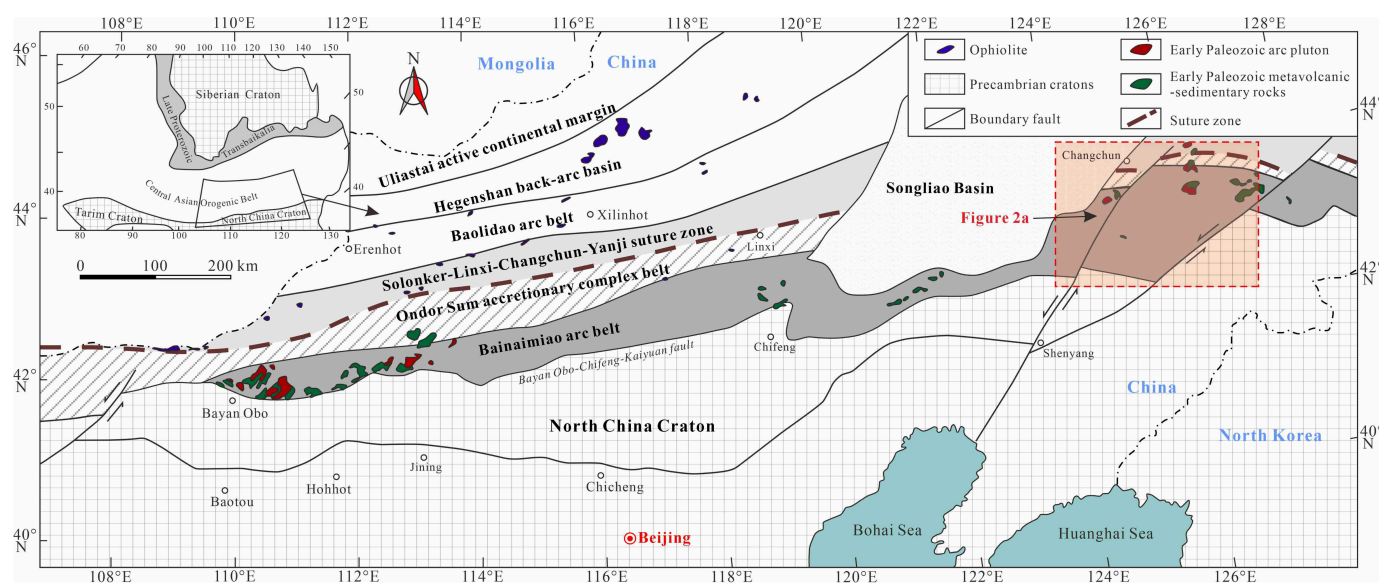


Figure 1. Tectonic location of CAOB and sketch tectonic map of the northern margin of the NCC, modified from [10].

The BAB hosts Early Paleozoic metasedimentary rocks of greenschist to lower amphibolite facies (e.g., the Baoerhantu and Bainaimiao groups), as well as Late Cambrian to Early Silurian calc-alkaline volcanic rocks and intermediate–felsic intrusions. These magmatic rocks are attributed to subduction of the PAOP [10,11,13–15,17,18,21,23–28,30,35–40]. Locally, these rocks are unconformably overlain by Late Silurian to Early Devonian molasse deposits or intruded by Devonian syn-collisional granite. These relationships have been interpreted to indicate collision between the Bainaimiao Arc and the NCC during the Late Silurian to Early Devonian [15–18,23–30]. However, alternative models have proposed different configurations for Early Paleozoic convergence and collision in the southeastern CAOB [55,56]. Furthermore, a series of Precambrian basement fragments have recently been identified in the BAB. These include Mesoproterozoic metamorphic strata in the Damao area (western segment) [15], Neoproterozoic diabase within the Xiaowulanhua mélange [14], Neoproterozoic to Mesoproterozoic metamorphic and magmatic rocks in the Shaolanghe, Jiefangyingzi, Shuangsheng, and Reshui areas (middle segment) [57,58]; and the Paleo- to Mesoproterozoic Chenjiatun metamorphic complex and Mesoproterozoic granites near Yitong and Gongzhuling (eastern segment) [22,34,59].

The study area lies in the eastern segment of the BAB, where the tectonic setting is more complex than in the western segment. During the Paleozoic, the eastern BAB evolved

within the PAO tectonic domain; in the Mesozoic, however, the Paleo-Pacific tectonic regime strongly overprinted and modified it [1–8]. This transition triggered multiple episodes of dynamic metamorphism and extensive granite emplacement, which largely destroyed the original sedimentary structures and primary stratigraphic relationships of the Paleozoic rocks. Consequently, Early Paleozoic rocks occur only as isolated outcrops, lenses, or roof pendants and have generally undergone later metamorphism; most rock assemblages are highly incomplete (Figure 2a). These conditions hinder reconstruction of the Early Paleozoic tectonic evolution of the eastern BAB.

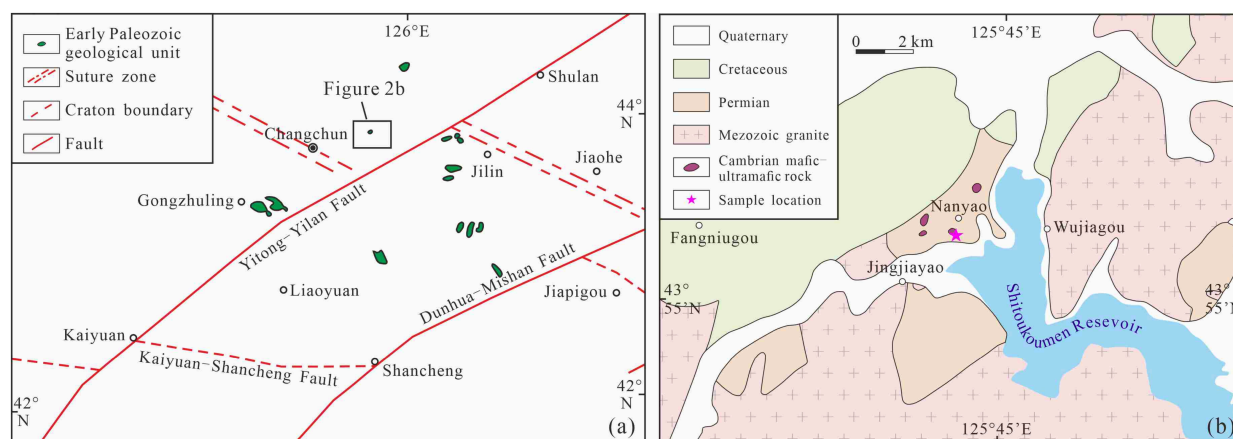


Figure 2. Tectonic sketch map of central Jilin Province (a) and geological map of the Shitoukoumen area (b), modified from [42].

Given this poor preservation, Permian and Cretaceous strata are the most widely exposed in the study area (Figure 2b). The Permian succession consists predominantly of marine sedimentary rocks, including crystalline limestone, siliceous mudstone, graywacke, siltstone, polymictic conglomerate, and minor calc-alkaline volcanic rocks. Although this sequence has been assigned various stratigraphic names in the literature (e.g., the Fanjiatun, Yangjiagou, and Shitoukoumen formations), recent geochronological data consistently indicate an Early Permian age [41–43]. The area also contains scattered Carboniferous fragments, including Early Carboniferous metamorphosed oceanic crustal rocks consisting chiefly of basaltic andesite and basaltic trachyandesite, and Late Carboniferous fusulinid-bearing bioclastic limestone [42–44]. Together with the amphibolite we identified, these fragments occur as olistoliths enclosed within the Early Permian matrix. The Cretaceous Yingchengzi Formation unconformably overlies the Permian and consists mainly of felsic volcanic rocks, sandstone, and mudstone. Intrusive rocks were emplaced mainly during the Triassic to Jurassic and consist of quartz diorite, monzogranite, alkali feldspar granite, syenite, and granite porphyry. The structural framework is dominated by ductile shear zones and faults. The ductile shear zones trend roughly NW, are widespread in the Late Paleozoic strata, and are mainly related to the closure of the PAO. Regional strike-slip deformation occurred episodically from the Permian to the Cretaceous [60,61]. Faults in the study area strike predominantly NE, with subordinate NW and nearly N-S trends; most fault planes dip steeply and display shear-related features.

Amphibolite samples for this study were collected from the northwestern shore of the Shitoukoumen Reservoir (GPS: 43°57′24″ N, 125°43′40″ E). The weathered surface is brown, and the fresh surface is grayish-green (Figure 3a,b). The amphibolite has a massive structure and a medium- to fine-grained granoblastic to prismatic texture. The major constituent minerals are amphibole (50–70 vol.%) and plagioclase (25–40 vol.%), with minor quartz (Figure 3c–e). Amphibole occurs mainly as subhedral to irregular prisms, 0.1 to

1.0 mm in size, and displays khaki to green pleochroism and one or two sets of cleavages. Plagioclase is unevenly distributed and occurs mostly as anhedral or irregular granular grains, 0.02 to 0.5 mm in size. Quartz occurs as anhedral grains or aggregates filling interstices between amphibole and plagioclase. Accessory minerals include zircon, titanite, apatite, and garnet.

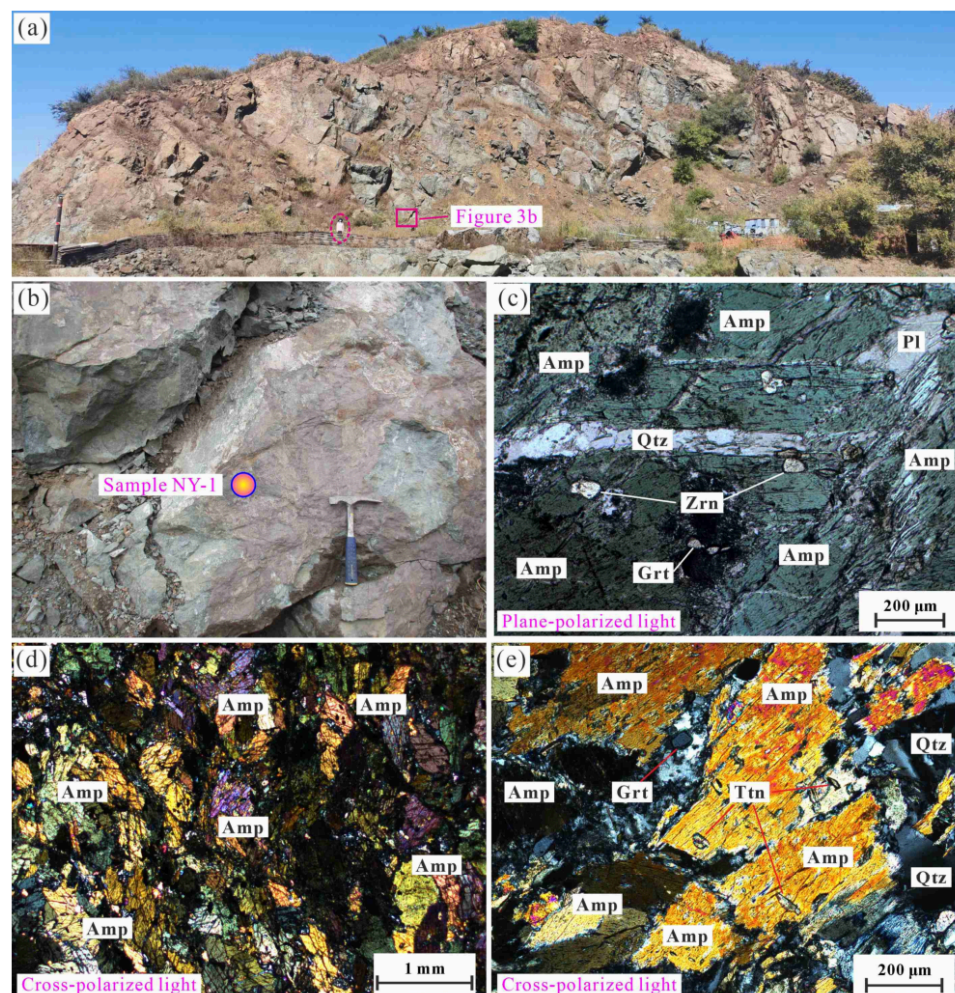


Figure 3. Field photographs (a,b) and photomicrograph (c–e) of the Shitoukoumen amphibolite. Mineral abbreviations: Amp—amphibole; Pl—plagioclase; Qtz—Quartz; Grt—garnet; Zrn—Zircon; Ttn—titanite. Abbreviations of mineral names are the same as in [62].

3. Analytical Methods

3.1. Zircon U-Pb Dating

Based on petrographic observations, we selected one fresh amphibolite sample (NY-1) for zircon separation and U-Pb dating. Zircon grains were separated using conventional magnetic and heavy liquid techniques at the Langfang Regional Geological Survey, Hebei Province, China. Approximately 200 grains were hand-picked under a binocular microscope and placed in an epoxy mount. The mount was then polished to approximately half the grain thickness to expose the interiors of the grains and cleaned in an ultrasonic cleaner prior to analysis. Cathodoluminescence (CL) images were obtained for all zircon grains using an FEI Quanta 400 FEG scanning electron microscope equipped with a Gatan MonoCL3+ spectrometer. U-Pb isotopic dating was performed by Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) at the State Key Laboratory of Continental Evolution and Early Life, Northwest University, Xi'an, China, following the

procedures of Yuan et al. [63]. The analyses used an Agilent 7500a quadrupole ICP-MS coupled with a GeoLas 200M laser-ablation system. A laser spot size of 32 μm , a repetition rate of 6 Hz, and an ablation depth of 20–40 μm were employed during the analyses. To monitor reproducibility and accuracy, reference materials (NIST 610, GJ-1 and 91500) were analyzed together with the samples as QA/QC measures. Raw data were reduced offline using GLITTER 4.0, and U-Pb concordia diagrams and weighted mean age calculations were produced using the Microsoft Excel macro Isoplot 3.00.

3.2. Zircon Lu-Hf Isotopic Analyses

Zircon Lu-Hf isotopic analyses were conducted at Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China, using a Thermo Fisher Neptune Plus MC-ICP-MS coupled to a Geolas HD excimer ArF laser ablation system (Coherent, Göttingen, Germany). All analyses were performed on zircon grains in single spot ablation mode with a spot size of 44 μm and an energy density of $\sim 7.0 \text{ J cm}^{-2}$. Isobaric interferences of ^{176}Lu and ^{176}Yb were corrected using the interference-free isotopes ^{175}Lu and ^{173}Yb and the recommended ratios $^{176}\text{Lu}/^{175}\text{Lu} = 0.02656$ and $^{176}\text{Yb}/^{173}\text{Yb} = 0.79639$. Instrumental mass bias was corrected by normalizing Yb isotope ratios to $^{172}\text{Yb}/^{173}\text{Yb} = 1.35274$ and Hf isotope ratios to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ using an exponential mass fractionation law [64]. To assess data quality, three international zircon reference materials (Plešovice, 91500, and GJ-1) were analyzed together with the unknown samples. Plešovice served as the primary external standard for calibration, whereas 91500 and GJ-1 were used as secondary standards to monitor accuracy and reproducibility. In addition, the high-Yb/Hf zircon standard Temora 2 was analyzed to evaluate the accuracy of Hf isotope measurements for zircons with high Yb/Hf ratios. Repeated analyses yielded the following $^{176}\text{Hf}/^{177}\text{Hf}$ ratios: Plešovice = 0.282478 ± 0.000006 (1σ , $n = 6$); 91500 = 0.282295 ± 0.000011 (1σ , $n = 4$); GJ-1 = 0.282003 ± 0.000010 (1σ , $n = 4$). These results demonstrate the accuracy and external reproducibility of the Lu-Hf isotopic analyses.

3.3. Whole-Rock Major and Trace Element Analyses

Whole-rock major and trace element analyses were performed at Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Six fresh amphibolite samples were collected from different parts of the outcrop. Weathered surfaces were removed, and the samples were crushed and powdered to 200 mesh in an agate mortar. For major element analysis, the powdered samples were fused into glass disks. Major oxides were determined by wavelength-dispersive X-ray fluorescence (XRF) using a Rigaku ZSX Primus II spectrometer. Analytical quality was monitored by analyzing reference materials (GBW07103, GBW07105, GBW07111, and GBW07112) and duplicate samples along with the unknowns. Loss on ignition (LOI) was determined by ignition at 1000 °C. FeO concentrations were determined using the potassium dichromate volumetric method. For trace element analysis, approximately 50 mg of dried sample powder was digested in Teflon bombs using an HNO_3 + HF mixture. Trace element concentrations were then measured using an Agilent 7700e ICP-MS. Standard reference materials of AGV-2, BCR-2, and RGM-2 were incorporated as QA/QC measures. Analytical precision was better than 5% for major elements and better than 10% for trace elements.

3.4. Whole-Rock Sr-Nd Isotopic Analyses

Sr and Nd isotopic analyses were performed at Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Sample powders were digested in Teflon bombs using a mixture of HNO_3 , HF, and HCl. Sr and Nd were then separated by conventional ion-exchange chromatography. Isotope ratios were measured using Thermo Fisher Neptune Plus multicollector inductively coupled plasma mass spectrometer (MC-ICP-

MS). Mass fractionation was corrected using the exponential law and the reference ratios $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. During the analytical sessions, the measured isotope ratios of the monitoring standards were NIST 987 $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.710240 (2SD = 0.000010) and GSB 04-3258-2015 $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.512438 (2SD = 0.000008).

4. Analytical Results

4.1. Zircon U-Pb Geochronology

Zircons from amphibolite sample NY-1 are mostly subhedral to anhedral, predominantly short-prismatic to equant, and 50–120 μm in size. In CL images, they exhibit weakly zoned, unzoned, or fir-tree sector-zoned internal structures (Figure 4a), resembling zircons that formed or recrystallized during high-temperature metamorphism [50,65–67]. Some grains also display thin, bright white overgrowth rims.

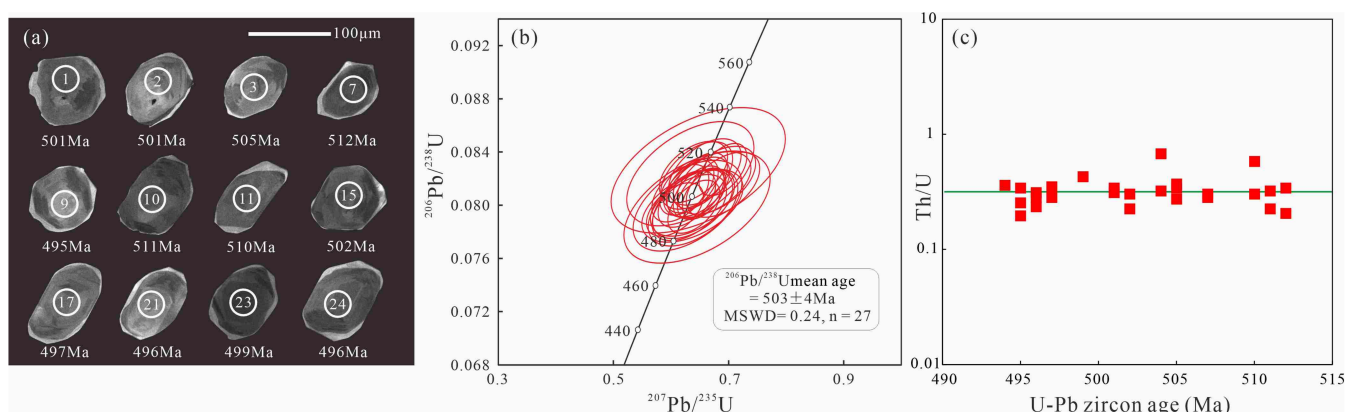


Figure 4. Representative CL images (a), zircon U-Pb concordia diagram (b) and Th/U versus U-Pb ages diagram (c) of the Shitoukoumen amphibolite. The green line indicates the empirical Th/U = 0.3 boundary between magmatic and metamorphic zircons [50]. The red squares represent the analytical spots of sample NY-1.

U-Pb dating was performed on 30 zircon grains from sample NY-1; the results are presented in Table 1. Three analyses (spots 16, 26, and 30) were excluded because they were discordant or had large uncertainties. The remaining 27 analyses plot on or near the concordia curve (Figure 4b). These zircons have relatively low Th and U concentrations of 2.32–32.39 ppm and 10.94–54.11 ppm, respectively, and Th/U ratios of 0.20–0.70. Most of the Th/U ratios are below or close to the empirical boundary of 0.3 between metamorphic and magmatic zircons (Figure 4c) [50]. Their $^{206}\text{Pb}/^{238}\text{U}$ ages range from 512 to 494 Ma, yielding a weighted mean of 503 ± 4 Ma (n = 27, MSWD = 0.24).

4.2. Zircon Lu-Hf Isotopes

From the dated zircon population, fifteen grains with concordant U-Pb ages were selected for Lu-Hf isotopic analysis (Table 2). They have $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of 0.00002–0.00054, $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.28288–0.28304, and $f_{\text{Lu}/\text{Hf}}$ values from −0.98 to −1.00. Their $\varepsilon_{\text{Hf}}(t)$ values range from +14.9 to +20.4 and plot close to the depleted mantle evolution line in the $\varepsilon_{\text{Hf}}(t)$ versus U-Pb age diagram (Figure 5).

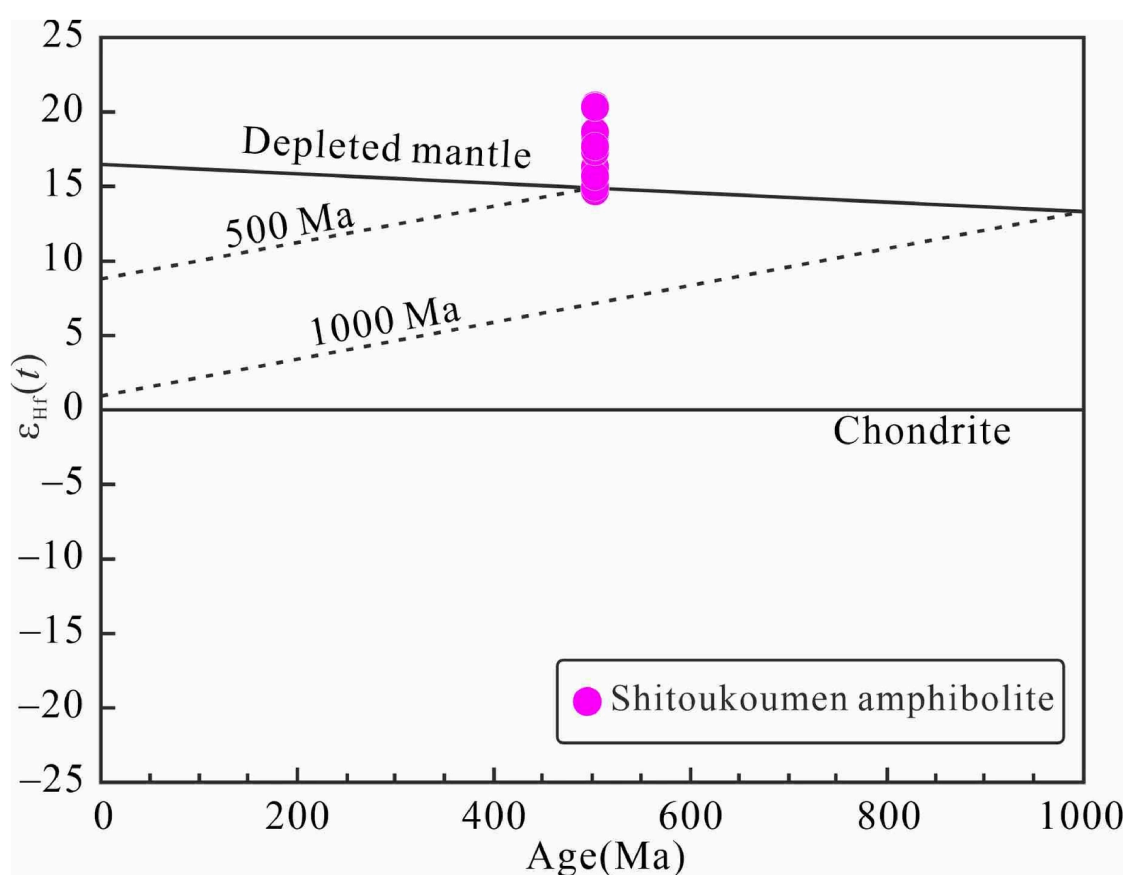
Table 1. LA-ICP-MS zircon U-Pb data for the Shitoukoumen amphibolite.

Spots	Th/U Ratio	Concentration (ppm)		Isotopic Ratios						Age (Ma)					
		Th	U	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ
NY-1-01	0.35	17	49	0.05890	0.00314	0.65639	0.03004	0.08081	0.00149	564	112	512	18	501	9
NY-1-02	0.32	12	38	0.05858	0.00348	0.65322	0.03433	0.08086	0.00158	552	125	511	21	501	9
NY-1-03	0.35	17	49	0.05668	0.00366	0.63670	0.03710	0.08147	0.00167	478	138	500	23	505	10
NY-1-04	0.24	10	43	0.05805	0.00372	0.63956	0.03683	0.07989	0.00163	531	135	502	23	496	10
NY-1-05	0.29	10	36	0.06013	0.00525	0.67890	0.05561	0.08188	0.00208	608	178	526	34	507	12
NY-1-06	0.38	11	29	0.06138	0.00498	0.69018	0.05219	0.08154	0.00200	653	165	533	31	505	12
NY-1-07	0.35	15	44	0.06054	0.00341	0.69017	0.03394	0.08268	0.00160	623	117	533	20	512	10
NY-1-08	0.37	11	30	0.05522	0.00399	0.60674	0.04038	0.07968	0.00164	421	154	482	26	494	10
NY-1-09	0.35	16	46	0.05798	0.00607	0.63823	0.06365	0.07983	0.00237	529	215	501	39	495	14
NY-1-10	0.33	7	21	0.05617	0.00455	0.63899	0.04839	0.08250	0.00188	459	171	502	30	511	11
NY-1-11	0.60	32	54	0.05684	0.00481	0.64461	0.05100	0.08224	0.00207	485	177	505	31	510	12
NY-1-12	0.70	23	33	0.05594	0.00377	0.62757	0.03842	0.08135	0.00171	450	144	495	24	504	10
NY-1-13	0.29	5	18	0.05761	0.00568	0.63717	0.05973	0.08020	0.00207	515	203	501	37	497	12
NY-1-14	0.26	8	30	0.05859	0.00970	0.64523	0.10382	0.07986	0.00344	552	326	506	64	495	21
NY-1-15	0.31	12	40	0.05524	0.00395	0.61629	0.04045	0.08090	0.00176	422	152	488	25	502	11
NY-1-16 *	0.02	0.01	1	0.05845	0.09133	0.71846	1.11922	0.08913	0.01263	547	1797	550	661	550	75
NY-1-17	0.36	13	36	0.05774	0.00545	0.63764	0.05691	0.08007	0.00211	520	195	501	35	497	13
NY-1-18	0.28	5	19	0.05895	0.00578	0.66296	0.06195	0.08155	0.00202	565	200	516	38	505	12
NY-1-19	0.20	6	28	0.05738	0.00510	0.63163	0.05288	0.07982	0.00203	506	185	497	33	495	12
NY-1-20	0.21	2	11	0.05680	0.01111	0.64725	0.12376	0.08263	0.00385	483	383	507	76	512	23
NY-1-21	0.29	4	14	0.05778	0.00677	0.63720	0.07191	0.07996	0.00224	521	238	501	45	496	13
NY-1-22	0.31	17	54	0.05767	0.00377	0.65091	0.03836	0.08184	0.00171	517	138	509	24	507	10
NY-1-23	0.44	17	37	0.05656	0.00402	0.62772	0.04086	0.08047	0.00174	474	151	495	25	499	10
NY-1-24	0.32	10	32	0.05699	0.00727	0.62858	0.07719	0.07997	0.00279	491	260	495	48	496	17
NY-1-25	0.33	14	44	0.05768	0.00429	0.64748	0.04440	0.08138	0.00183	518	156	507	27	504	11
NY-1-26 *	0.03	0.02	1	0.05841	0.11539	0.64988	1.27908	0.08067	0.01594	545	2049	508	787	500	95
NY-1-27	0.23	10	40	0.05802	0.00361	0.64800	0.03602	0.08097	0.00162	530	131	507	22	502	10
NY-1-28	0.23	9	37	0.05789	0.00484	0.65870	0.05149	0.08250	0.00204	525	174	514	32	511	12
NY-1-29	0.31	5	17	0.05577	0.00820	0.63362	0.09028	0.08237	0.00320	443	298	498	56	510	19
NY-1-30 *	0.16	0.03	0.16	0.28960	0.57374	1.63559	2.97798	0.04095	0.03354	3416	1615	984	1147	259	208

* Data marked with an asterisk were excluded.

Table 2. Zircon Lu-Hf isotope results for the Shitoukoumen amphibolite.

Spots	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$\pm 1\sigma$	$(^{176}\text{Hf}/^{177}\text{Hf})_t$	$\varepsilon_{\text{Hf}}(0)$	$\varepsilon_{\text{Hf}}(t)$	$f_{\text{Lu/Hf}}$
NY-1-01	503	0.01567	0.00046	0.28288	0.00002	0.282874	+3.8	+14.7	−0.99
NY-1-02	503	0.01650	0.00049	0.28304	0.00004	0.283036	+9.5	+20.4	−0.99
NY-1-03	503	0.01317	0.00043	0.28298	0.00003	0.282981	+7.5	+18.5	−0.99
NY-1-04	503	0.01313	0.00044	0.28295	0.00003	0.282949	+6.4	+17.4	−0.99
NY-1-05	503	0.01851	0.00050	0.28304	0.00003	0.283034	+9.4	+20.4	−0.99
NY-1-06	503	0.01254	0.00033	0.28299	0.00004	0.282985	+7.7	+18.6	−0.99
NY-1-07	503	0.01115	0.00037	0.28291	0.00003	0.282904	+4.8	+15.8	−0.99
NY-1-08	503	0.01501	0.00050	0.28304	0.00004	0.283033	+9.4	+20.3	−0.98
NY-1-09	503	0.00858	0.00035	0.28289	0.00002	0.282888	+4.2	+15.2	−0.99
NY-1-10	503	0.01642	0.00047	0.28292	0.00003	0.282920	+5.4	+16.3	−0.99
NY-1-11	503	0.00085	0.00002	0.28288	0.00002	0.282882	+3.9	+15.0	−1.00
NY-1-12	503	0.01190	0.00039	0.28295	0.00003	0.282948	+6.3	+17.3	−0.99
NY-1-13	503	0.00889	0.00025	0.28290	0.00005	0.282902	+4.7	+15.7	−0.99
NY-1-14	503	0.01779	0.00054	0.28295	0.00003	0.282949	+6.4	+17.4	−0.98
NY-1-15	503	0.00923	0.00028	0.28296	0.00003	0.282958	+6.7	+17.7	−0.99

**Figure 5.** Zircon $\varepsilon_{\text{Hf}}(t)$ versus U-Pb ages diagram of the Shitoukoumen amphibolite.

4.3. Major and Trace Element Geochemistry

A total of six amphibolite samples were selected for whole-rock geochemical analysis; the results are presented in Table 3. These samples have low SiO_2 (48.46–52.22 wt.%), moderate TiO_2 (1.17–2.25 wt.%), and relatively high MgO (4.48–6.31 wt.%), $\text{Fe}_2\text{O}_3^{\text{T}}$ (11.01–15.48 wt.%), and CaO (9.07–12.55 wt.%) contents, indicating a mafic composition. Their Na_2O and K_2O contents range from 3.35 to 3.84 wt.% and 0.07 to 0.17 wt.%, respectively, corresponding to $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of 22.59–54.43 and reflecting strong Na enrichment and K depletion.

Table 3. Whole-rock major (wt.%) and trace element (ppm) concentrations of the Shitoukoumen amphibolite.

Sample No.	NY-1	NY-2	NY-3	NY-4	NY-5	NY-6
SiO ₂	52.22	48.88	51.16	50.45	49.23	48.46
TiO ₂	1.25	1.99	2.13	1.17	1.58	2.25
Al ₂ O ₃	12.71	13.04	12.44	12.63	14.27	12.52
Fe ₂ O ₃ ^T	11.01	14.85	13.04	11.85	13.53	15.48
CaO	11.65	9.65	9.07	12.55	9.48	10.07
MgO	4.48	6.31	4.89	4.75	5.82	5.37
K ₂ O	0.07	0.09	0.10	0.12	0.17	0.12
Na ₂ O	3.81	3.57	3.83	3.41	3.84	3.35
MnO	0.18	0.18	0.16	0.19	0.18	0.18
P ₂ O ₅	0.11	0.18	0.19	0.12	0.19	0.22
LOI	1.58	1.54	1.98	2.49	1.99	1.82
Total	99.06	100.28	98.98	99.73	100.28	99.84
Li	4.35	9.82	11.45	3.80	9.21	7.82
Be	1.00	0.72	0.94	0.96	0.70	0.79
Sc	27.80	52.60	38.96	30.46	39.32	40.05
V	289.50	419.14	359.92	314.81	359.62	407.85
Cr	30.02	203.23	78.38	108.88	60.6	30.74
Co	30.56	49.87	43.26	33.53	38.97	45.36
Ni	21.40	53.74	26.83	44.65	33.93	30.38
Cu	8.81	13.60	35.69	2.46	4.14	102.45
Zn	74.26	65.57	57.30	67.03	55.72	48.06
Ga	13.57	15.14	15.85	18.86	19.96	20.46
Rb	0.30	0.47	0.88	1.42	2.30	1.40
Sr	236.50	151.12	162.91	273.55	181.16	188.84
Y	38.19	73.62	82.05	27.71	47.73	50.44
Zr	64.53	82.42	98.71	62.43	78.79	102.92
Nb	2.52	4.29	5.06	2.16	3.19	4.45
Cs	0.23	0.33	0.78	0.29	0.42	0.69
Ba	30.63	19.11	31.84	50.40	39.74	28.79
La	3.46	6.17	6.07	3.19	7.05	5.54
Ce	10.24	17.83	17.91	9.51	21.10	17.13
Pr	1.83	3.26	3.24	1.61	3.31	2.85
Nd	9.67	17.13	17.97	8.93	17.25	15.21
Sm	3.20	5.96	6.20	3.02	5.67	5.35
Eu	1.16	1.94	1.87	1.10	1.98	1.79
Gd	3.80	6.89	7.44	3.72	7.22	7.10
Tb	0.87	1.65	1.79	0.74	1.35	1.30
Dy	6.81	12.13	13.45	4.61	8.29	8.47
Ho	1.43	2.78	2.90	0.99	1.72	1.83
Er	4.33	7.92	9.07	2.91	4.96	5.56
Tm	0.69	1.23	1.39	0.42	0.67	0.76
Yb	4.41	7.66	8.94	2.83	4.52	5.22
Lu	0.70	1.23	1.40	0.45	0.71	0.81
Hf	1.81	2.49	2.91	1.90	2.47	3.06
Ta	0.23	0.35	0.45	0.14	0.24	0.30
Pb	1.47	0.72	0.77	1.04	0.29	0.26
Th	0.15	0.15	0.12	0.13	0.18	0.14
U	0.07	0.08	0.07	0.05	0.09	0.08

Note: Fe₂O₃^T = total iron expressed as Fe₂O₃.

The amphibolites have relatively low total rare earth element (REE) abundances ($\Sigma\text{REE} = 44.03\text{--}99.64$ ppm), with light rare earth elements (LREEs) and heavy rare earth elements (HREEs) contents of 27.36–56.36 ppm and 16.67–46.38 ppm, respectively. Their LREE/HREE ratios range from 1.15 to 1.91. On the chondrite-normalized REE diagram, the samples exhibit relatively flat patterns (Figure 6a), with $(\text{La}/\text{Yb})_{\text{N}}$ values of 0.49–1.12, indicating limited LREE-HREE fractionation. In the primitive mantle-normalized trace element diagram (Figure 6d), they display enrichment in Ba, slight depletion in Zr and Hf, and no significant negative Nb-Ta anomalies.

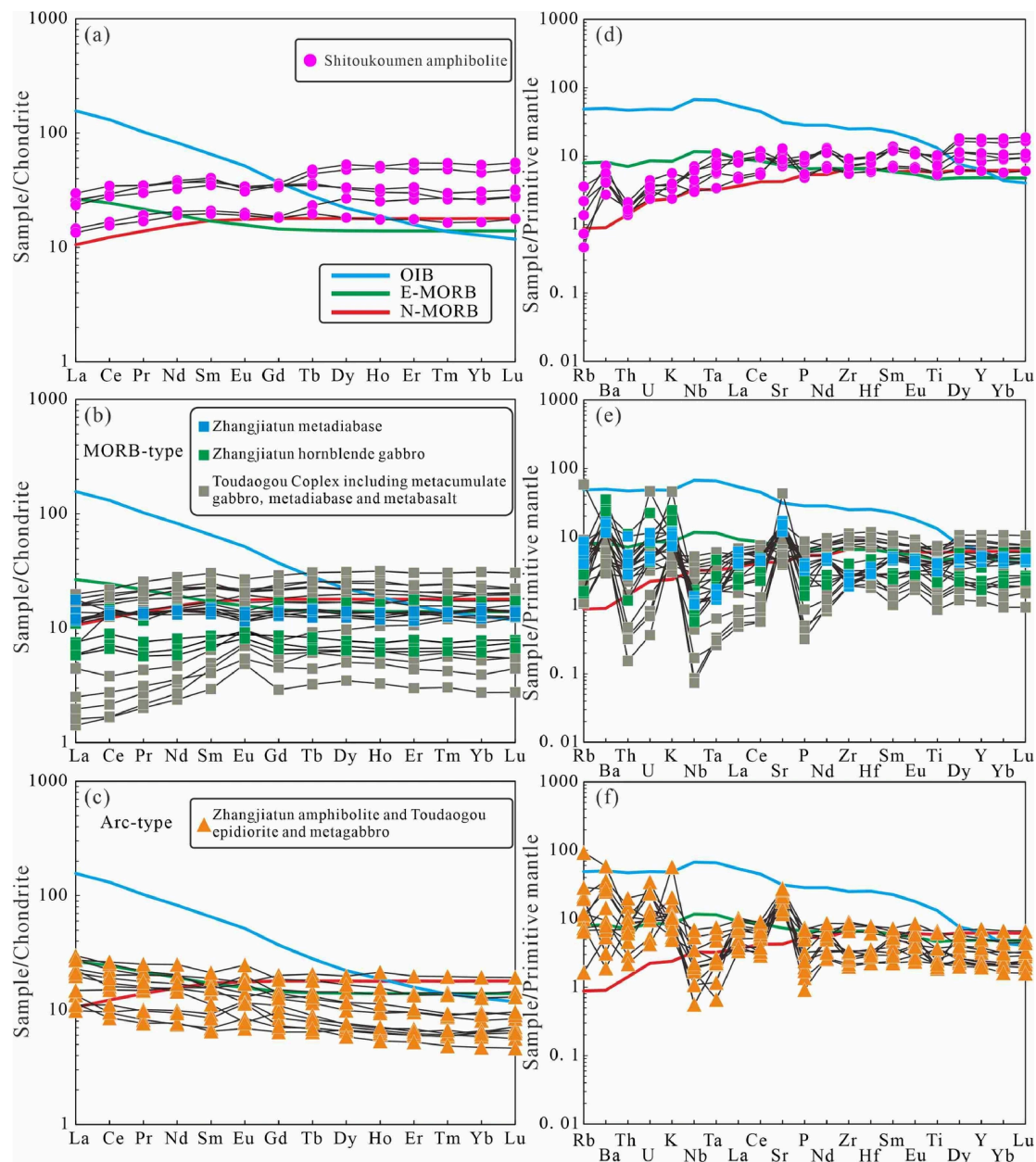


Figure 6. Chondrite-normalized REE patterns (a–c) and primitive mantle-normalized multi-element diagram (d–f) for Cambrian–Ordovician (meta-) basites of central Jilin Province. Reference data are from [24,26,30]. Reference data for the Zhangjiatun and Toudaogou complexes are from [24,26,30]. Chondrite- and primitive mantle-normalized values, as well as those for OIB, N-MORB, and E-MORB, are from [68]. OIB: Ocean Island Basalt, N-MORB: Normal Mid-Ocean Ridge Basalt, E-MORB: Enriched Mid-Ocean Ridge Basalt.

4.4. Whole-Rock Sr-Nd Isotopes

Whole-rock Sr-Nd isotopic results for the six amphibolite samples are presented in Table 4. Sr and Nd isotope ratios were back-calculated to 503 Ma, corresponding to the zircon U–Pb metamorphic age of the amphibolite. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (I_{Sr}) range from 0.703830 to 0.705561, and the initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (I_{Nd}) range from 0.512359 to 0.512418. The corresponding $\epsilon_{\text{Nd}}(t)$ values range from +7.2 to +8.4 and plot near the MORB field in the $\epsilon_{\text{Nd}}(t)$ versus I_{Sr} diagram (Figure 7).

Table 4. Whole-rock Sr-Nd isotopic compositions of the Shitoukoumen amphibolite.

Sample No.	Sm (ppm)	Nd (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	2 σ	I_{Sr}	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2 σ	I_{Nd}	$\epsilon_{\text{Nd}}(t)$
NY-1	3.20	9.67	0.704251	0.000008	0.704225	0.200311	0.513055	0.000005	0.512395	7.9
NY-2	5.96	17.1	0.705558	0.000009	0.705494	0.210378	0.513064	0.000006	0.512371	7.4
NY-3	6.20	18.0	0.703990	0.000010	0.703878	0.208417	0.513046	0.000004	0.512359	7.2
NY-4	3.02	8.93	0.705669	0.000007	0.705561	0.204454	0.513092	0.000005	0.512418	8.4
NY-5	5.67	17.3	0.704094	0.000009	0.703830	0.198142	0.513066	0.000005	0.512413	8.3
NY-6	5.35	15.2	0.704187	0.000005	0.704033	0.212789	0.513099	0.000004	0.512398	8.0

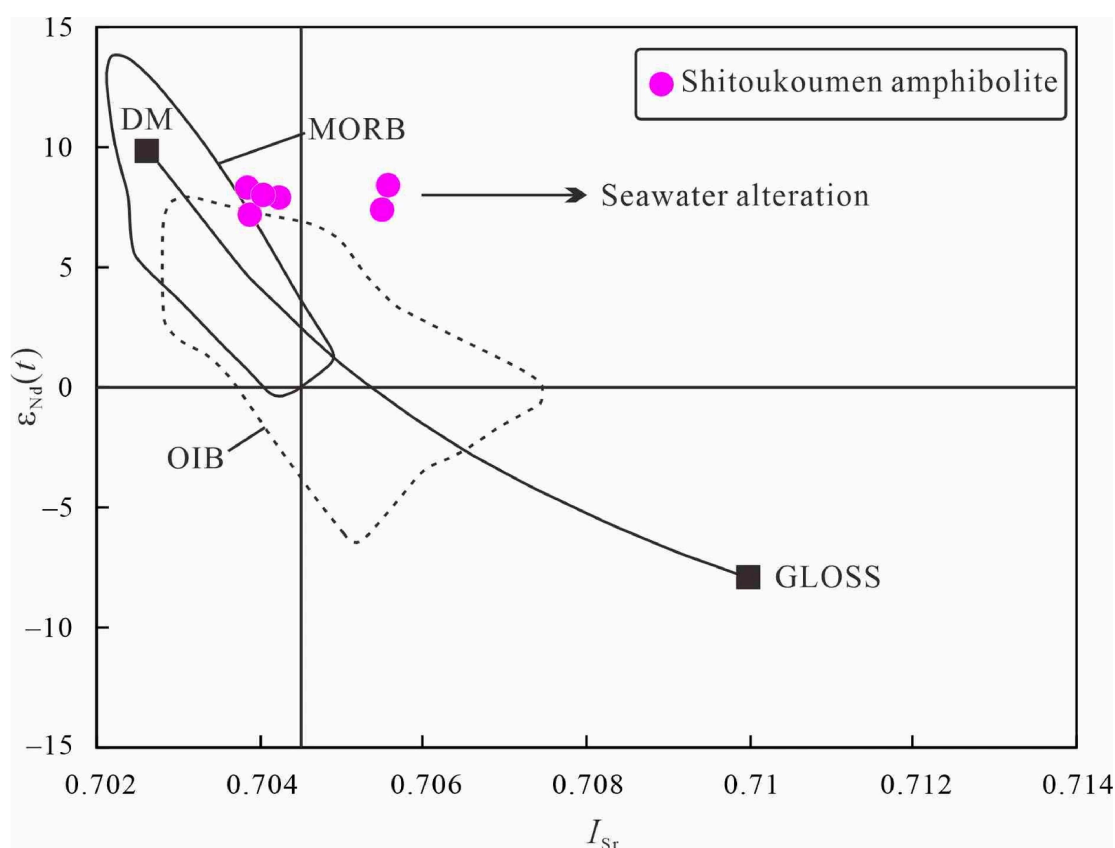


Figure 7. $\epsilon_{\text{Nd}}(t)$ versus I_{Sr} diagram of the Shitoukoumen amphibolite. DM: Depleted Mantle, MORB: Mid-Ocean Ridge Basalt, GLOSS: Global Subducting Sediments. DM data are from reference [69]; MORB and OIB data are from reference [70]; GLOSS data are from reference [71].

5. Discussion

5.1. Protolith Reconstruction

Amphibolite protoliths can be either mafic igneous rocks (gabbro, basalt, or mafic tuff) or sedimentary rocks (graywacke, calcareous shale, or ferruginous dolomitic argillaceous limestone). Because primary textures and structures are rarely preserved in the Shitoukoumen amphibolite, we use whole-rock geochemistry to constrain its protolith.

Several discrimination diagrams based on relatively immobile elements were applied. In the Zr/TiO₂-Ni and Zr-MgO diagrams [72,73], the samples plot in the igneous rock field and the ortho-amphibolite field, respectively (Figure 8a,b). In the La/Yb-ΣREE diagram [74], their low La/Yb ratios place the samples in the ortho-amphibolite field (Figure 8c). In the (al-alk)-c, ACFM, and ACF diagrams [75,76], all samples also plot in igneous rock fields (Figure 8d-f). Collectively, these results indicate that the protolith of the Shitoukoumen amphibolite was mafic igneous rock. In the Zr/TiO₂-Nb/Y diagram, all samples fall in the basalt field (Figure 9a), and in the TFeO/MgO versus SiO₂ diagram, they plot in the tholeiitic series field (Figure 9b).

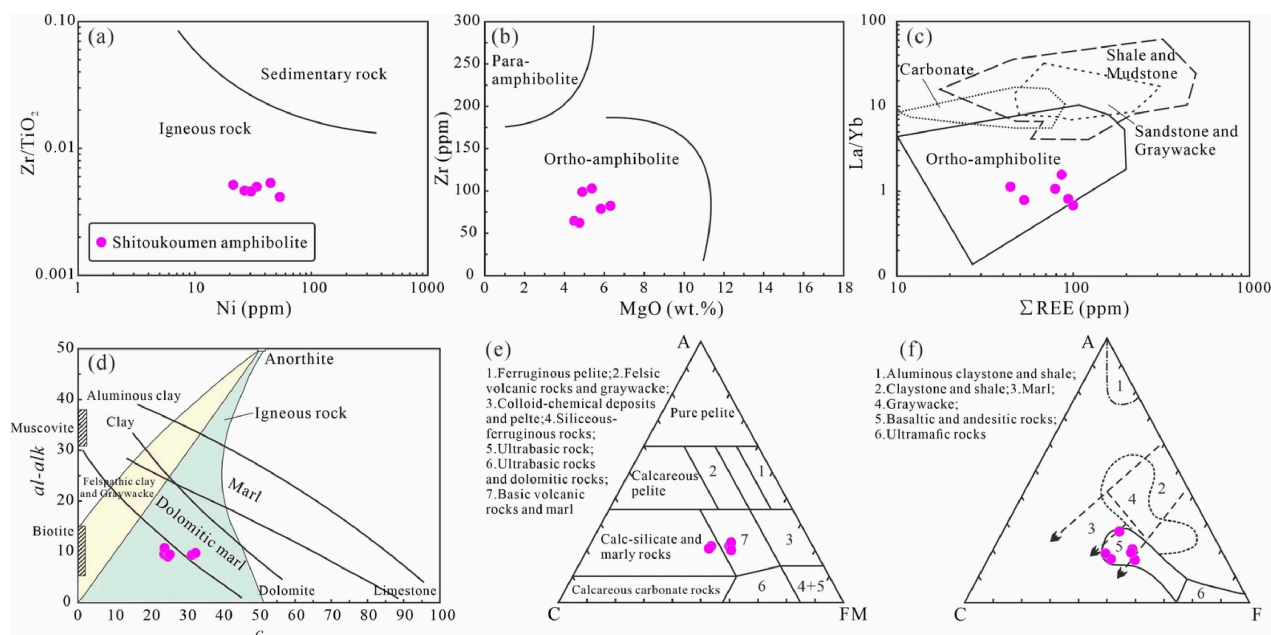


Figure 8. Protolith reconstruction diagrams for the Shitoukoumen amphibolite. (a) Zr/TiO₂ vs. Ni diagram [72]; (b) Zr vs. MgO diagram [73]; (c) La/Yb vs. ΣREE diagram [74]; (d) al-alk vs. C diagram [75]; (e) ACFM diagram [76]; (f) ACFM diagram [76].

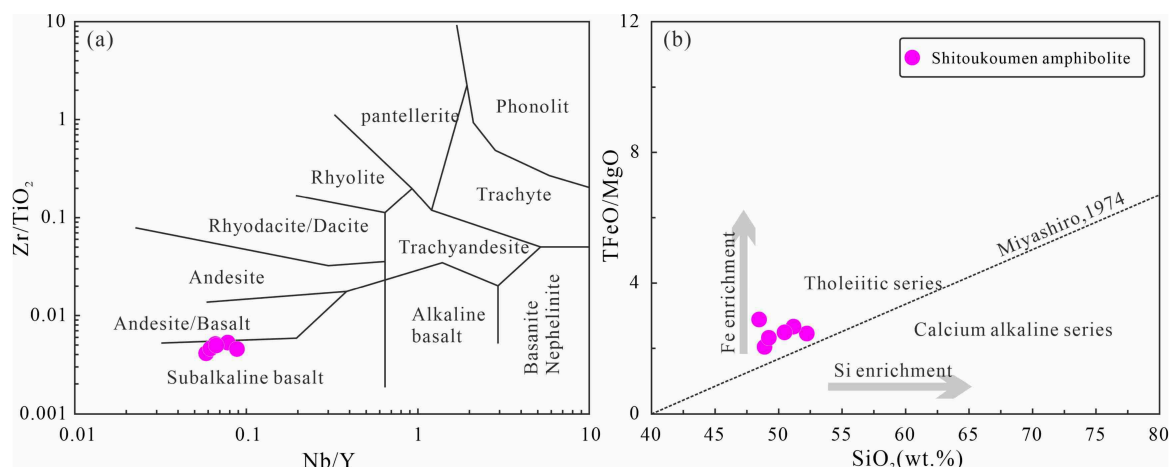


Figure 9. Discrimination diagram of rock types and rock series for the Shitoukoumen amphibolite. (a) Zr/TiO₂ vs. Nb/Y diagram [77]; (b) TFeO/MgO vs. SiO₂ diagram [78].

5.2. Effects of Alteration, Crustal Contamination and Fractional Crystallization

Prior to utilizing geochemical data for tracing petrogenesis and magma source characteristics, it is essential to assess the effects of metamorphism or alteration on element mobility. The Shitoukoumen amphibolite samples have low LOI values of

1.58–2.49 wt.%, with only one sample exceeding 2 wt.%, indicating weak alteration. Given the generally immobile behavior of Zr during secondary processes, element mobility can be assessed from correlations with Zr [79]. The amphibolites show positive correlations of REEs (e.g., La, Ce, Nd), high-field-strength elements (HFSEs, e.g., Nb, Ta), Hf, Sr, Ba, and TiO_2 with Zr, whereas Rb and K_2O show no such correlation. Therefore, the following discussion relies mainly on relatively immobile elements, including HFSEs, REEs, and some transition metals.

The geochemical results indicate that the protoliths of the Shitoukoumen amphibolites were mafic and likely derived from mantle melting. Mantle-derived magmas can assimilate crustal material during ascent, emplacement, or eruption [80,81]. However, several lines of evidence argue against significant crustal contamination: (1) Continental crust is typically depleted in Nb and Ta and enriched in Zr, Hf, and large ion lithophile elements (LILEs) [82]. The studied samples lack positive Th-U anomalies and negative Nb-Ta anomalies; instead, they show slight negative Zr-Hf anomalies, which is inconsistent with significant crustal involvement. (2) Crustal materials generally have low Nb/U ratios (~ 6.15) and elevated $(\text{La}/\text{Nb})_{\text{PM}}$ and $(\text{Th}/\text{Nb})_{\text{PM}}$ ratios [82–84], whereas the studied samples plot near MORB in the Nb/U-Nb and $(\text{Th}/\text{Nb})_{\text{PM}}-(\text{La}/\text{Nb})_{\text{PM}}$ diagrams (Figure 10a,b). (3) The absence of inherited zircons further argues against crustal contamination.

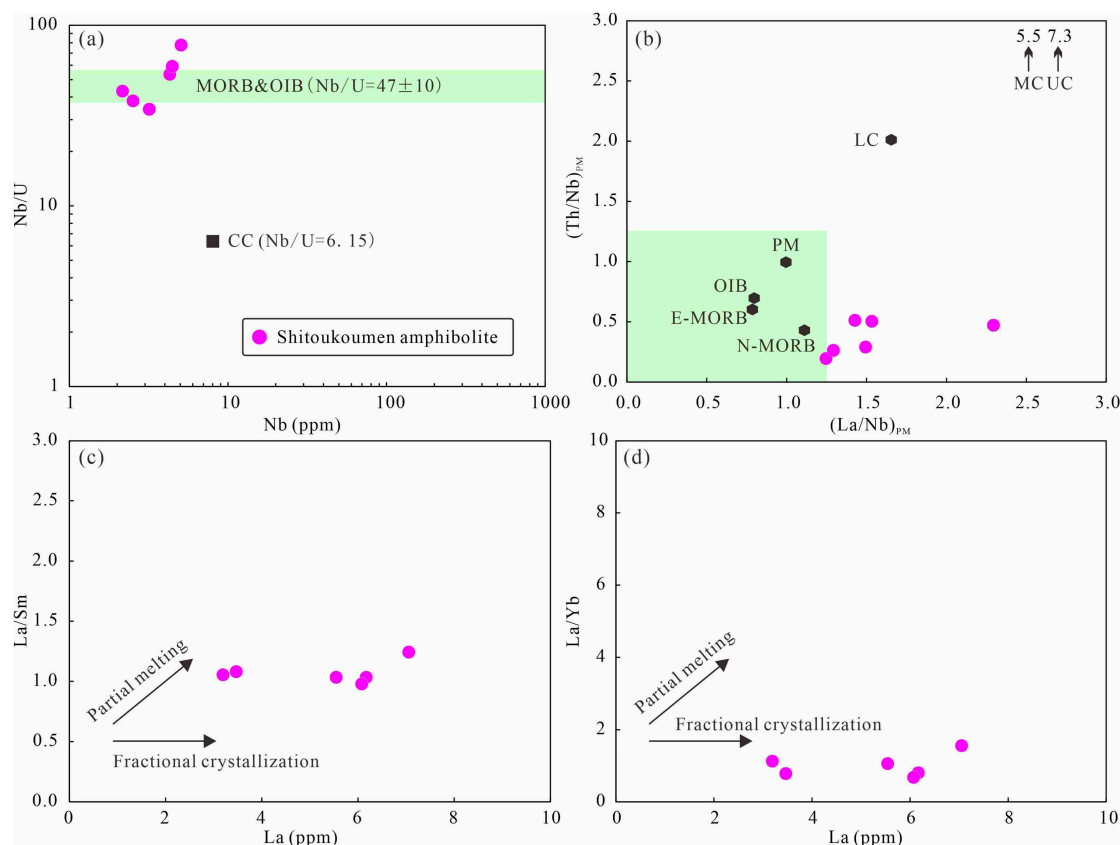


Figure 10. Discrimination diagrams for crustal contamination (a,b) and for fractional crystallization versus partial melting (c,d) for the protoliths of the Shitoukoumen amphibolites. (a) Nb/U vs. Nb diagram [83]; (b) $(\text{Th}/\text{Nb})_{\text{PM}}$ vs. $(\text{La}/\text{Nb})_{\text{PM}}$ diagram [84]; (c) La/Sm vs. La diagram; (d) La/Yb vs. La diagram. The data for continental crust (CC), upper crust (UC), middle crust (MC), and lower crust (LC) are from [82]. The subscript PM denotes primitive mantle normalization, and the normalization values, as well as the data for OIB, E-MORB and N-MORB, are from [68].

The samples have MgO contents of 4.48–6.31 wt.% and Cr and Ni concentrations of 30.0–203 ppm and 21.4–53.7 ppm (Table 3), respectively, which are lower than those of typi-

cal primary basaltic magmas (Cr = 300–500 ppm; Ni = 300–400 ppm) [85]. This is consistent with fractional crystallization of the parental magmas. During equilibrium melting, La/Sm and La/Yb ratios increase with La, whereas these ratios remain nearly constant during fractional crystallization. In the La/Sm-La and La/Yb-La diagrams, the samples follow fractional crystallization trends (Figure 10c,d). In Harker diagrams (Figure 11), Cr, Co, Ni, and Sc correlate positively with MgO, indicating fractionation of mafic minerals such as olivine and pyroxene. TiO_2 and Fe_2O_3^T also correlate positively with MgO, consistent with Fe-Ti oxide fractionation. However, the samples lack significant Eu anomalies, indicating that plagioclase fractionation was limited.

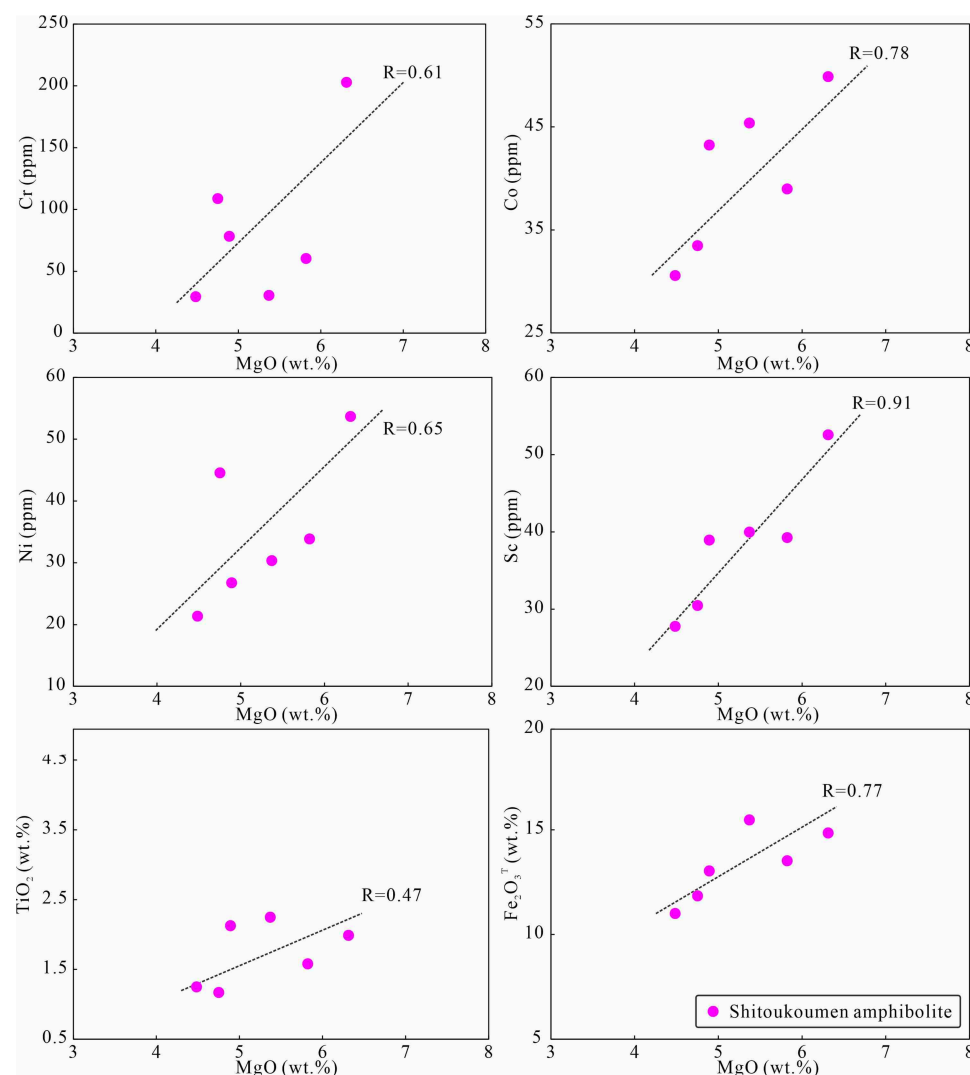


Figure 11. Harker diagrams showing variations in selected major and trace elements versus MgO for the Shitoukoumen amphibolites.

5.3. Petrogenesis and Source Characteristics

The protoliths of the Shitoukoumen amphibolites are tholeiitic mafic rocks, and their REE and trace element patterns display N-MORB affinity (Figure 6), suggesting derivation from an N-MORB-like mantle source. Although fractional crystallization may have modified the concentrations of some trace elements, radiogenic isotope ratios and ratios of highly incompatible elements (e.g., REEs and HFSEs) are largely insensitive to this process. Moreover, selected trace element ratios vary systematically among mantle reservoirs and can therefore trace the mantle source of mafic rocks [86–88]. The Shitoukoumen amphibolites have positive $\epsilon_{\text{Hf}}(t)$ (+14.9 to +20.4) and $\epsilon_{\text{Nd}}(t)$ (+7.2 to +8.4) values (Figures 5 and 7), consis-

tent with derivation from a depleted mantle source. Furthermore, their Th/Yb (0.013–0.046), Nb/Yb (0.56–0.85), La/Nb (1.20–2.21), Nb/Zr (0.039–0.052), and Th/Zr (0.001–0.002) ratios are close to those of N-MORB. In the Th/Yb–Nb/Yb, TiO_2/Yb –Nb/Yb, Nb/Th–La/Nb, and Nb/Zr–Th/Zr diagrams, all samples plot near the N-MORB field (Figure 12), further supporting a depleted mantle source.

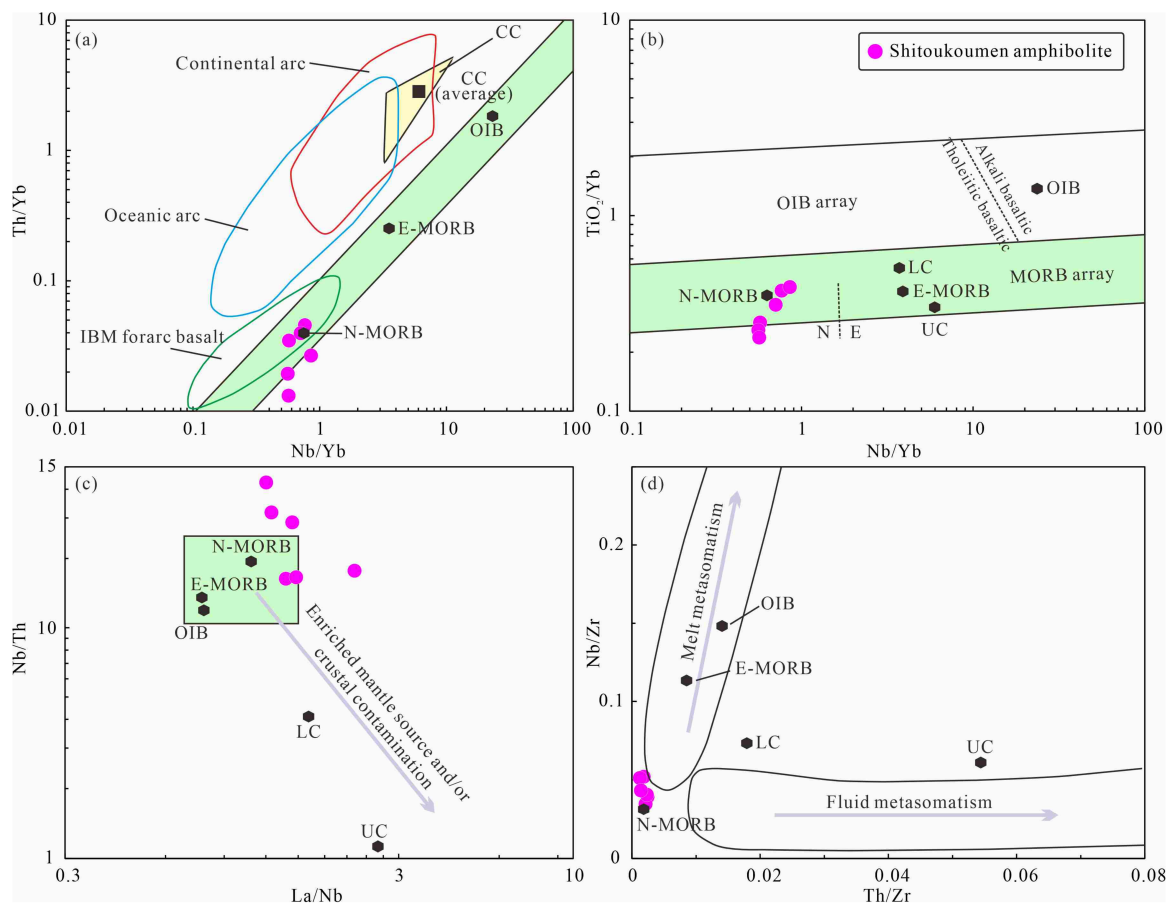


Figure 12. Mantle source discrimination diagrams for the Shitoukoumen amphibolites. (a) Th/Yb vs. Nb/Yb diagram [89]; (b) TiO_2/Yb vs. Nb/Yb diagram [90]; (c) Nb/Th vs. La/Nb diagram; (d) Nb/Zr vs. Th/Zr diagram [91].

The trace element compositions of mafic magmas are sensitive to the depth of mantle melting since garnet- and spinel-facies residues have contrasting partition coefficients. Magmas derived from garnet-facies sources are typically HREE-depleted and have high Sm/Yb and Dy/Yb ratios, whereas those from spinel-facies sources generally have N-MORB-like, LREE-depleted patterns and low Sm/Yb and Dy/Yb ratios [87]. The Shitoukoumen amphibolites have low ΣREE abundances and LREE-depleted patterns subparallel to N-MORB (Figure 6a), as well as low Sm/Yb and Dy/Yb ratios. In the Sm/Yb–La/Sm and Dy/Yb–La/Yb diagrams, they plot close to the spinel-facies lherzolite melting trend (Figure 13). These features suggest that the parental magmas of the protoliths were generated by approximately 5–10% partial melting of spinel lherzolite.

In summary, we conclude that the parental magmas of the Shitoukoumen amphibolite protoliths were derived from depleted mantle and produced by partial melting of spinel lherzolite. During magma evolution, they experienced fractional crystallization of mafic minerals such as olivine and pyroxene, as well as Fe–Ti oxides.

5.4. Tectonic Affinity and Constraints on the Early Paleozoic Subduction Initiation of the PAOP

The Paleozoic tectonic evolution of the southeastern CAOB was governed by subduction, accretion, and collision during closure of the PAO. However, the Early Paleozoic geological record in this region is poorly preserved because of long-lived accretion, post-collisional extension, and complex Mesozoic overprinting by the Okhotsk and Paleo-Pacific tectonic regimes [1–8]. In recent years, an increasing number of Early Paleozoic geological bodies have been identified in the BAB, and detailed petrological, geochemical, and geochronological studies of these rocks have provided abundant data for reconstructing the Early Paleozoic tectonic evolution of the PAO [10–40].

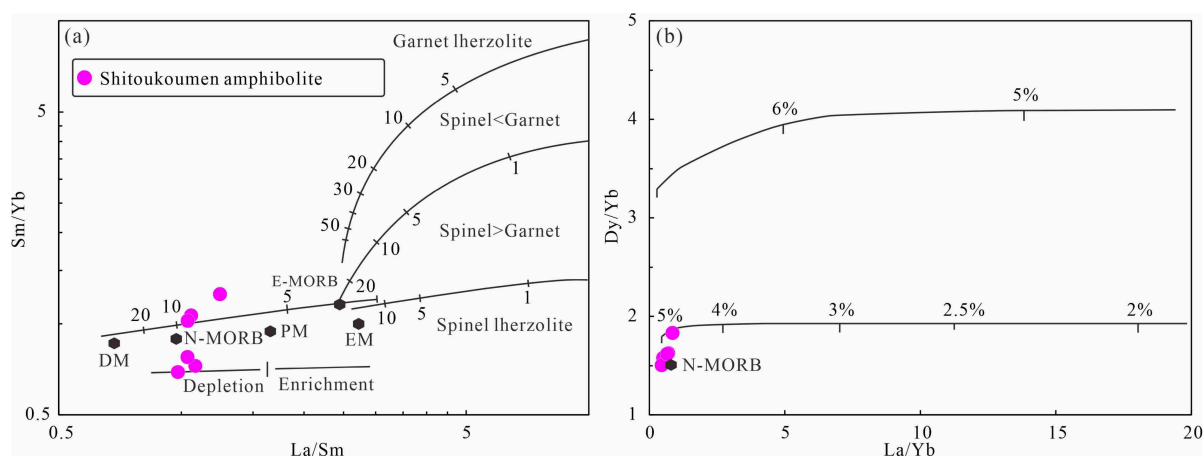


Figure 13. Sm/Yb vs. La/Sm (a) and Dy/Yb vs. La/Yb (b) diagrams for the Shitoukoumen amphibolites (modified after [87,92]).

The widespread recognition of Cambrian–Silurian arc magmatic rocks with subduction-related geochemical signatures and lithological associations in the BAB has led to broad acceptance that the region experienced Early Paleozoic subduction and accretion related to the evolution of the PAO [10,11,13–15,17,18,21,23–28,30,35–40]. However, the timing and mechanism of subduction initiation—a critical stage of the Wilson Cycle—remain a key unresolved issue in this tectonic evolution. Recent studies have yielded new constraints. The Tulinkai SSZ-type ophiolite, which is geochemically similar to the Troodos ophiolite, contains tonalite and metagabbro dated at 497–477 Ma, suggesting subduction initiation by ca. 500 Ma [38]; this interpretation has been widely adopted in subsequent studies [12,13,16,17,37,40]. Alternative views, however, place the initiation earlier. Early Cambrian dacite (518 ± 3 Ma) in the Baoerhantu Group has been interpreted as subduction-related lower-crustal melts and used to argue for subduction initiation at ca. 520 Ma [10]. Oceanic crustal fragments and forearc assemblages within the Ondor Sum subduction-accretion complex have been proposed to indicate initiation at ca. 510–501 Ma [25]. Inherited zircons (530–450 Ma) in Early Paleozoic diorite from the Damao Banner area have led to the inference that subduction may have begun as early as ca. 530 Ma [11].

Compared with the western BAB, evidence for Early Paleozoic subduction initiation in the central Jilin area of the eastern BAB is scarce and less well constrained. The earliest record, represented by Late Cambrian MORB-type metadiabase and serpentinite at Zhangjiatun and Xiaosuihe, resembles SSZ-type ophiolites and suggests subduction initiation before ca. 493 Ma [24]. These rocks have been further interpreted as an SSZ-type ophiolite formed in a forearc setting, with an initiation age broadly comparable to that in the Tulinkai area [30]. However, several arc magmatic rocks older than the SSZ ophiolites (e.g., ca. 518 Ma dacite, ca. 510 Ma mafic-rhyolite assemblage, and ca. 516 Ma tonalite) have

also been recognized in the BAB [10,30]; therefore, the possibility of two Early Paleozoic subduction systems cannot be ruled out [13,26,30].

In summary, although existing studies provide a basis for understanding subduction initiation of the PAOP, the spatiotemporal relationships between the two proposed subduction systems and the dynamic mechanisms of intra-oceanic subduction initiation remain poorly constrained, largely owing to the scarcity of preserved records. The Shitoukoumen N-MORB-type amphibolite provides new constraints on this process. Geochemically, it is classified as low-K tholeiitic, with REE and trace element patterns resembling those of N-MORB, and all samples plot within or near the N-MORB field in discrimination diagrams (Figures 10, 12 and 13). Its positive $\varepsilon_{\text{Hf}}(t)$ (+14.9 to +20.4) and $\varepsilon_{\text{Nd}}(t)$ (+7.2 to +8.4) values indicate a depleted mantle source, whereas the relatively wide range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.703830–0.705561) suggests some influence of seafloor alteration (Figure 7). Collectively, these features identify the amphibolite as a fragment of PAO crust.

Although the N-MORB affinity of the amphibolite could imply an ophiolitic origin, MORB-type rocks are not unique to mid-ocean ridges and also occur in oceanic plateaus and ocean islands [93–95]. Therefore, a direct link to the nearby ZTX SSZ ophiolite requires evaluation. Both the Shitoukoumen amphibolite and the mafic rocks of that ophiolite have low $(\text{La}/\text{Yb})_{\text{N}}$ ratios and are classified as MORB-type rather than arc-type [30,94]. However, the Zhangjiatun–Toudaogou rocks show weak Nb-Ta-Ti depletion and a subduction-related forearc affinity [24,26,30], whereas the Shitoukoumen amphibolite lacks such depletion and has N-MORB-like incompatible element ratios (Figures 10, 12 and 13). Furthermore, the formation age of the ZTX ophiolite (502–476 Ma) is slightly younger than the metamorphic age of the amphibolite (ca. 503 Ma). These differences suggest that the amphibolite and the exposed mafic rocks of the ZTX ophiolite may not have formed in identical magmatic environments.

Recent geochronological and geochemical studies have provided new insights into the tectonic affinity of the Shitoukoumen amphibolite [42–44]. Lithologically, the amphibolite and adjacent serpentinite lenses [42] occur together with Early Carboniferous OIB- and N-MORB-type oceanic basalts and Late Carboniferous neritic carbonate rocks as blocks within a Lower Permian volcanic-sedimentary succession [44]. The Permian sedimentary rocks, characterized by deep-water gravity-flow deposits [42,43], together with these pre-Permian blocks, form a “blocks-in-matrix” assemblage. This assemblage is comparable to Permian olistostromal and block-in-matrix deposits documented in extensional basins elsewhere in the CAO [95,96]. Together with the ZTX SSZ ophiolite and other ophiolitic fragments in central-eastern Jilin Province, these occurrences document the preservation of older oceanic and tectonic materials within the eastern BAB.

What, then, is the relationship between the Late Cambrian N-MORB-type amphibolite at Shitoukoumen and the onset of Early Paleozoic subduction of the PAO? Zircon morphology and U-Pb ages from the Shitoukoumen amphibolite provide further constraints. Zircons lack magmatic oscillatory zoning and instead display unzoned or fir-tree sector-zoned internal structures typical of high-temperature metamorphic zircons (Figure 4a) [50,65–67]. Although their Th/U ratios are variable (0.20–0.70), most values are at or close to the empirical boundary of 0.3 between metamorphic and magmatic zircons [65]. The ca. 503 Ma age therefore likely records metamorphism rather than magmatic crystallization. Although ca. 500 Ma metamorphism is widely documented in the Erguna, Xing’an, and Jiamusi–Khanka blocks of NE China and has been linked to a Late Pan-African event [97], the Shitoukoumen amphibolite lies far from these regions, arguing against such a correlation. Recent regional work reported a 502 ± 3 Ma gabbro from the Shitoukoumen area and a 502 ± 1 Ma SSZ-type metagabbro from the Qindaogou area, approximately 70 km to the southeast [98]. Although the field relationship between the Shitoukoumen gabbro and amphibolite is not

well established, the close similarity in age raises the possibility that the gabbro represents the protolith of the amphibolite.

In recent years, metamorphic soles—high-temperature metamorphic suites formed during the initial stage of intra-oceanic subduction by heating and friction of the down-going oceanic crust beneath the mantle wedge—have gained attention as key records of subduction initiation [99–104]. Metamorphic soles typically exhibit amphibolite- to granulite-facies metamorphism, occur directly beneath SSZ ophiolites, and show inverted metamorphic gradients [105,106]. Their metamorphic ages are generally close to those of the overlying SSZ ophiolites, as documented in Oman, Quebec, and Tibet [99–104]. The Shitoukoumen amphibolite shares several of these characteristics: it has N-MORB affinity, records amphibolite-facies metamorphism with metamorphic zircon textures and garnet, and is in direct contact with serpentinitized peridotite. Its ca. 503 Ma metamorphic age is also closely comparable to the ca. 502 Ma age of the SSZ-type metagabbro in Shitoukoumen and Qincagou areas [98]. Although a direct structural relationship between the amphibolite and the ZTX SSZ ophiolite has not yet been established, the close age relationship is compatible with a possible metamorphic-sole origin.

Current evidence broadly supports Late Cambrian intra-oceanic subduction initiation in the eastern PAO [10,11,13,23,24,26,30,38], although the geological record has been strongly overprinted by later tectonism. The Shitoukoumen amphibolite is spatially associated with the ZTX SSZ ophiolite (Figure 2a), and its metamorphic age is consistent with the Late Cambrian timing proposed for subduction initiation [24,26,30]. Taken together, its N-MORB affinity, high-temperature metamorphic characteristics, close spatial association with the ZTX SSZ ophiolite, and the close age relationship between the amphibolite metamorphism and nearby SSZ-type magmatism support a possible link to Late Cambrian intra-oceanic subduction initiation. We therefore interpret the amphibolite as a possible component of a metamorphic sole formed during Late Cambrian intra-oceanic subduction initiation of the PAO. This interpretation remains preliminary because quantitative P-T constraints, detailed structural relationships, and field evidence for an inverted metamorphic gradient are not yet available to independently test a metamorphic-sole origin. The amphibolite could alternatively represent an older oceanic crustal fragment associated with an intra-oceanic subduction event distinct from the one recorded by the ZTX ophiolite. The absence of a well-documented regional metamorphic event of this age in the BAB does not exclude the possibility of localized metamorphism related to an earlier intra-oceanic subduction system. Regardless of its precise relationship to the ZTX ophiolite, the Shitoukoumen amphibolite provides important evidence for Early Paleozoic oceanic and subduction-related processes in the eastern PAO. Further field, structural, petrochronological, and metamorphic investigations are needed to refine the early subduction history of the eastern PAO.

6. Conclusions

(1) Zircon U-Pb dating of the Shitoukoumen amphibolite yields a metamorphic age of 503 ± 4 Ma, recording Late Cambrian metamorphism.

(2) The amphibolite exhibits N-MORB-like geochemical and isotopic signatures, consistent with an oceanic crustal protolith derived from partial melting of a depleted spinel-facies mantle source. The positive $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values further support a depleted, juvenile mantle source.

(3) The combination of N-MORB affinity, high-temperature metamorphic characteristics, spatial association with the ZTX SSZ ophiolite, and the close age relationship between the amphibolite metamorphism and nearby SSZ-type magmatism is consistent with a pos-

sible metamorphic-sole origin related to Late Cambrian intra-oceanic subduction initiation of the PAO.

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