

Subduction between the Jiamusi and Songliao blocks: Geochronological and geochemical constraints from granitoids within the Zhangguangcailing orogen, northeastern China

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ABSTRACT

Bulk-rock major and trace element, Sr-Nd isotopic, and zircon U-Pb-Hf isotopic data are reported for Jurassic igneous rocks from a north-south traverse through the Zhangguangcailing orogen, which formed by the subduction of an ocean and final collision between the Jiamusi and Songliao blocks in northeastern China. These results provide new insights into tectonic processes involving the subduction and collision to form the Zhangguangcailing orogen and final amalgamation of the Jiamusi and Songliao blocks. Our new results, together with data from the literature, indicate that the Jurassic granitoid rocks in the Zhangguangcailing orogen were emplaced in the period from ca. 191 to 163 Ma, with a magmatic flare-up ca. 180 Ma accompanied by mafic magmatism. These granitoid rocks are metaluminous and I-type in composition, and enriched in K, Rb, Th, and U, and depleted in Ba, Nb, Ta, Sr, P, and Ti, with constant initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.704338–0.705349), and positive $\epsilon_{\text{Nd}}(t)$ (+1.6 to +3.1) and zircon $\epsilon_{\text{Hf}}(t)$ (+0.83 to +10.51) values. These geochemical features indicate that the Jurassic I-type granitoid rocks were probably generated as a consequence of variable degrees of interaction between continental crust and mantle-derived melts, which resulted from the subduction of oceanic lithosphere (Heilongjiang ocean), and led to an active continental margin during Early to Middle Jurassic time.

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INTRODUCTION

Granitoids occur widely in continental regions and largely originate from heat transfer from the mantle to the crust in various tectonic settings (Chappell and White, 1992; Moyen et al., 2001; Pearce et al., 1984; Sylvester, 1989). Thus, the formation of granitoids is crucial to understanding the lithospheric evolution and the geodynamic processes operating during Earth history (Condie and Kröner, 2013; Pearce et al., 1984). Granitic intrusions are widespread in northeastern China, mostly emplaced during Paleozoic–Mesozoic time, as a consequence of the interaction of diverse tectonic processes (Jahn et al., 2001; Wu et al., 2000, 2001, 2003b, 2005, 2011). However, the tectonic mechanisms responsible for the formation of these granitoids are still debated, especially for those in the Zhangguangcailing orogen, which is considered to have developed from the subduction of a paleo-ocean (herein the Heilongjiang ocean), the closure of which led to the final collision of the Jiamusi and Songliao blocks (Wang et al., 2012a, 2012b, 2014; Wu et al., 2011; Xu et al., 2013; Zhu et al., 2015, 2016). In the past few years researchers have carried out extensive investigations on the Zhangguangcailing orogen, in particular the blueschist-bearing Heilongjiang complex, which is the major component of the Zhangguangcailing orogen, and have produced large amounts

of new data and interpretations. However, a number of unresolved issues still remain regarding the formation and evolution of the Zhangguangcailing orogen. One such issue concerns the origin and lifespan of the ocean between the Jiamusi and Songliao blocks separated by the Zhangguangcailing orogen; different models have been proposed (Wang et al., 2012b; Xu et al., 2009, 2013; Zhou et al., 2009, 2010a, 2010b; Zhu et al., 2015, 2016). One model suggests that oceanic subduction between the two blocks took place in the Late Ordovician, followed by mid-Silurian collision (Wang et al., 2012a, 2012b, 2014; Xu et al., 2009, 2013). However, this model has been challenged by the identification of a Mesozoic high-pressure metamorphic belt (Heilongjiang complex) between the Jiamusi and Songliao blocks (Wu et al., 2011; Zhou et al., 2010a, 2010b; Zhu et al., 2015, 2016). Another model argues that the ocean between the Jiamusi and Songliao blocks developed by intracontinental rifting and was finally closed most probably in the Early Jurassic, based on the fact that mafic lithologies (blueschists, greenschists, and amphibolites) of the Heilongjiang complex display both enriched mid-oceanic ridge basalt (E-MORB) or ocean island basalt (OIB) geochemical affinities and their formation ages range from the Permian to Triassic (Wu et al., 2011; Zhou et al., 2009, 2010b; Zhu et al., 2015, 2016). However, this model is inconsistent with a recent study that has demonstrated that the subduction-related metamorphism happened during Early to Middle Jurassic time.

In addition to large amounts of mafic lithologies from the Heilongjiang complex, there are also abundant granitoids in the Zhangguangcailing

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orogen, and their rock-forming ages and geochemical features can provide new constraints on the issues.

Few detailed geochronological and geochemical studies have been carried out on the granitoids in the Zhangguangcailing orogen (Sun et al., 2005; Wu et al., 2000). It is notable that these granitoid rocks were previously considered to be related to the orogenic collapse of the Central Asian orogenic belt (Wu et al., 2002). However, Wu et al. (2011) suggested that the granitoids were associated with the subduction of the Heilongjiang ocean between the Jiamusi and Songliao blocks. Thus, these granites are of great significance in reconstructing the relationship of the Jiamusi and Songliao blocks, as well as the evolution of the intervening Heilongjiang ocean. In this contribution we present whole-rock geochemical Sr-Nd isotopic compositions and zircon U-Pb dating and Lu-Hf isotope results for the granites in the Zhangguangcailing orogen. These new data not only elucidate the petrogenesis of these granitoids, but also place important constraints on tectonic processes related to the subduction of the Heilongjiang ocean to form the Zhangguangcailing orogen between the Jiamusi and Songliao blocks.

REGIONAL GEOLOGY

Northeastern China is composed of a collage of several microcontinental blocks, including, from southeast to northwest, the Khanka, Jiamusi, Songliao, Xing'an, and Erguna, all of which are separated from one another by major faults (Figs. 1 and 2A). It has been suggested that the Zhangguangcailing orogen belongs to the eastern Central Asian orogenic belt, and that it formed during two stages of evolution at different times and by different processes (Jahn et al., 2001; Natal'in, 1991, 1993; Sengör et al., 1993; Sengör and Natalin, 1996; Wang et al., 2015; Wang et al., 2002; Wu et al., 2000, 2001, 2003b, 2005, 2011; Xu et al., 2009, 2013; Yu et al., 2012). In the Paleozoic, its tectonic development was controlled by the evolution of Paleo-Asian Ocean between the Siberia and North China cratons, whereas since the Jurassic it formed as a result of subduction of the paleo-Pacific plate (Wu et al., 2011; Xu et al., 2009; Zhang et al., 2010; Zhou and Wilde, 2013; Zhou et al., 2009, 2010a).

Occupying an extensive area in the central part of northeastern China, the Songliao block is composed of the Songliao basin in the central portion, the southern Great Xing'an range in the west, the Lesser Xing'an range in the northeast, and is bounded by the Zhangguangcailing orogen

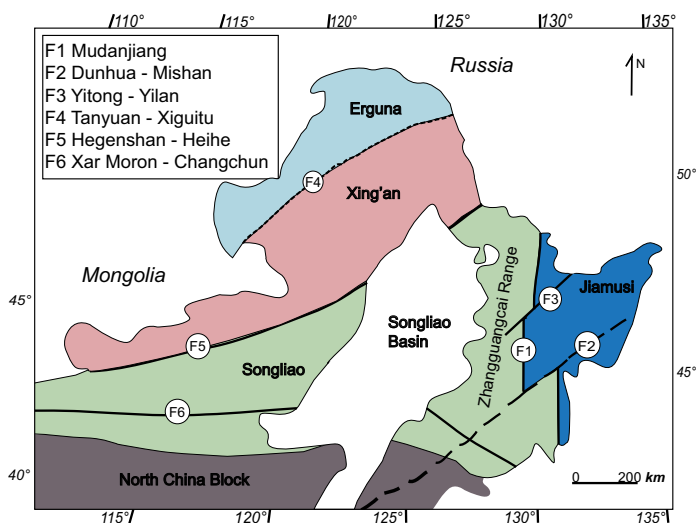


Figure 1. Tectonic subdivisions of northeastern China. F1–F6 are major faults.

in the east (Fig. 2B). The Songliao basin, serving as the most important base of the petroleum industry in China, has a basement mainly composed of granite, gneiss, and Paleozoic sediments, based on numerous exploration drill holes. However, others have suggested that the basement of the Songliao basin is Phanerozoic, identical to the surrounding orogenic belts, such as the Great Xing'an range and elsewhere (Gao et al., 2007; Pei et al., 2007; Wu et al., 2011).

Two separate stages of granitic magmatism are recognized in the southern Great Xing'an range, which extends into the western part of the Songliao block (Fig. 2B). Paleozoic granitoids with emplacement ages of 321 to 237 Ma that are composed of diorite, tonalite, and granodiorite, are mostly exposed in the western part (Wu et al., 2011), whereas Mesozoic plutons of granodioritic, monzogranitic, and syenogranitic composition have ages in the range 150–131 Ma (Li et al., 2004; Li et al., 1999; Liu et al., 2008; Wu et al., 2011).

Located between the Jiamusi and Songliao blocks, the Zhangguangcailing orogen is characterized by the Heilongjiang complex, rare Paleozoic and late Mesozoic volcanic and sedimentary rocks, and voluminous Phanerozoic granitoids (Fig. 2B). The Heilongjiang complex is composed of blueschist, serpentinite, greenschist, mica schist, quartzite, and locally granulite gneiss, which has undergone high-pressure metamorphism at temperatures of 320–450 °C and pressures of 8–11 kbar (Zhou et al., 2009). The blueschists are a significant component of the Heilongjiang complex and in places contain well-preserved pillows (Wu et al., 2007). The serpentinite is exposed locally in tectonic contact with other rocks; residual minerals indicate that the ultramafic protoliths include dunite, lherzolite, and harzburgite. The quartzite is associated with greenschist and Fe-Mn nodules (pyrolusite and psilomelane) containing spessartine, stilpnomelane, sodium amphibole, and piemontite. The fine-grained muscovite-albite schist is a metamorphosed shale or mudstone (Cao et al., 1992; Li et al., 1999). The mica schists have a penetrative mylonitic fabric, and some original bedding supporting a sedimentary origin (Cao et al., 1992; Li et al., 1999). All the rocks in the Heilongjiang complex are tectonically juxtaposed, indicating their possible association in a mélangé (Wu et al., 2007). The Mesozoic volcanic units are composed of hornblende, gabbro diabase, rhyolites, and basaltic andesites.

Large volumes of granitoids are a significant component of the Zhangguangcailing orogen. They consist of granodiorite, monzogranite, syenogranite, and alkali-feldspar granite, being genetically I- and A-type granites (Wu et al., 2000, 2002, 2003a, 2003b, 2005, 2011; Yang et al., 2012). In the A-type granites, quartz and perthitic feldspar are the principal phases, accompanied by minor plagioclase and the alkaline mafic minerals. The Heilongjiang Bureau of Geology and Mineral Resources (1993) supported the idea that most of these granites were emplaced in the early Paleozoic, and some in the Triassic, but recent precise geochronological U-Pb data by Wu et al. (2011) indicate two main phases of granitic magmatism, one from 508 to 447 Ma, and the second from 222 to 175 Ma. Thus, most of the A-type granitoids in the area were emplaced during the Late Triassic–Middle Jurassic, with a few in the early Paleozoic.

The I-type granitoids contain abundant miarolitic cavities and igneous layering formed by biotite bands, suggesting their derivations from deep sources and emplacement at shallow levels with extensive fractional crystallization (felsic I-type). Mafic microgranular enclaves are common within the plutons, but their spatial distribution is heterogeneous. They have ellipsoidal and flattened shapes, ranging from 1 mm to 1 m (Figs. 3A–3C). Their contacts with the host are sharp, rounded, or irregular, and large enclaves have diffusive contacts without deformation. New geochronological data indicate that some I-type granites (i.e., Xinhua-tun) were emplaced in the Jurassic (208–169 Ma), not in the Triassic,

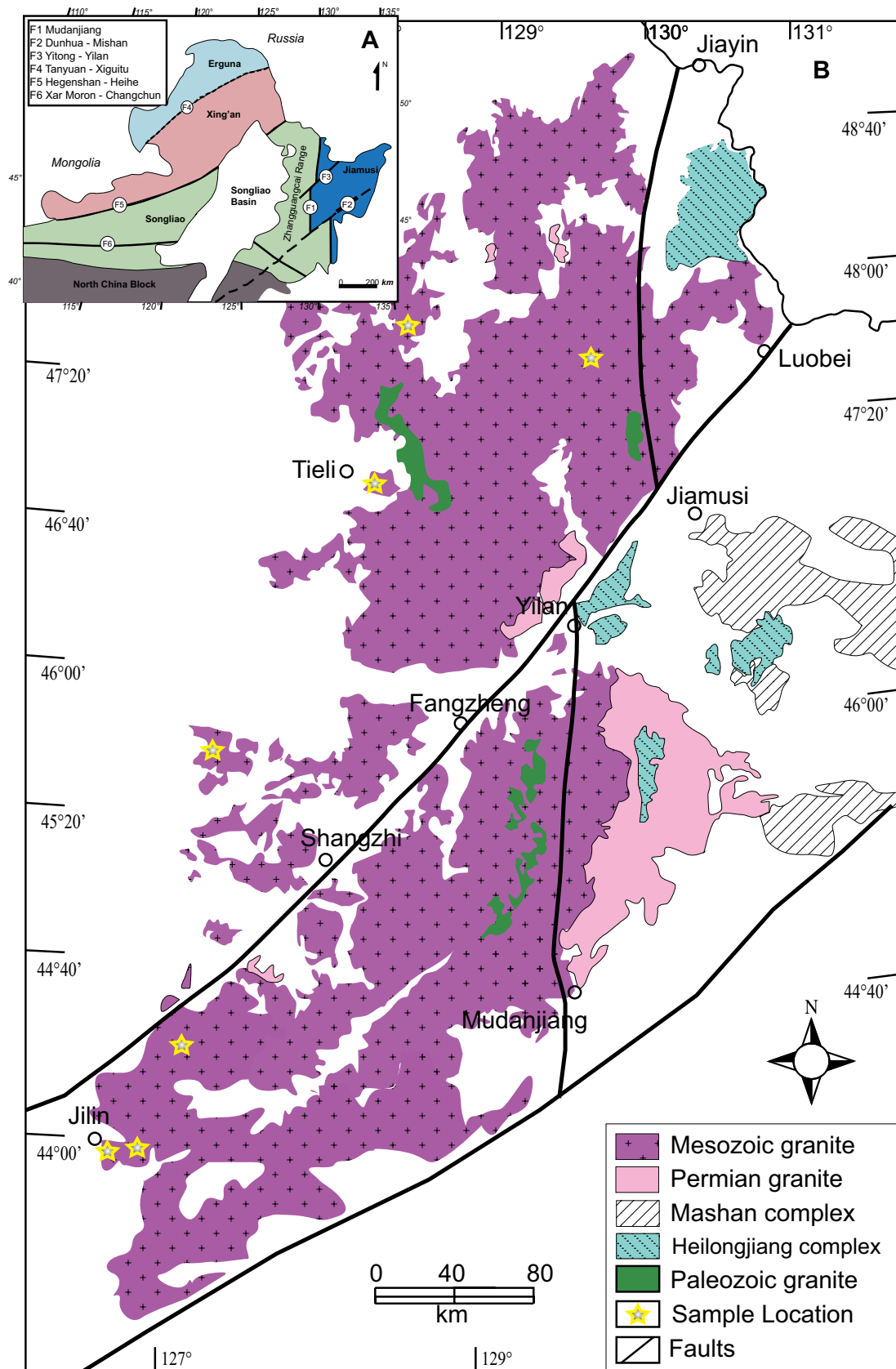


Figure 2. (A) Tectonic subdivisions of northeastern China. F1–F6 are major faults. (B) Geological sketch map of the Heilongjiang complex and adjacent areas in northeastern China, showing the spatial distribution of the complex.

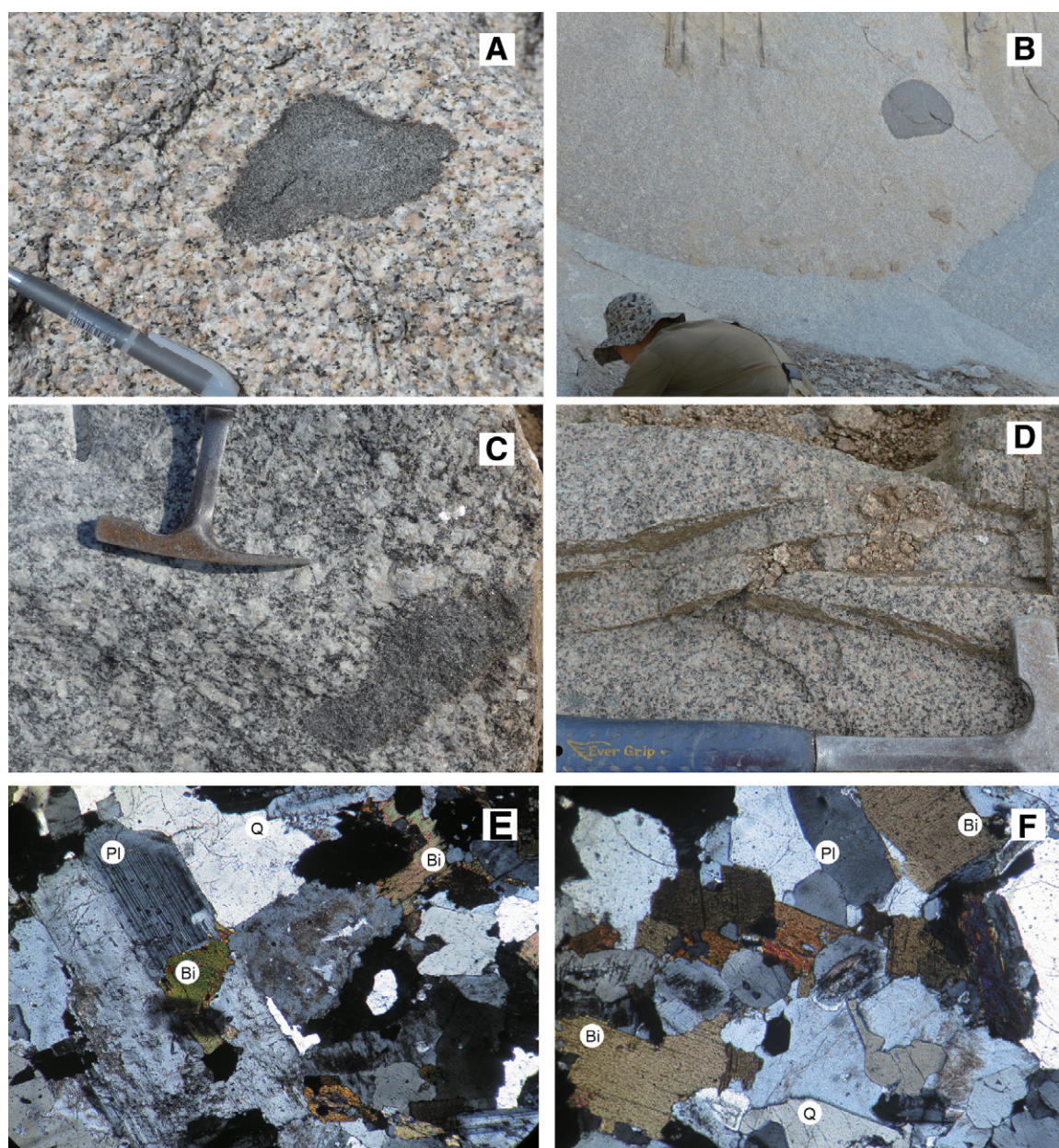


Figure 3. (A–D) Field photos of granitoids in the Zhangguangcailing orogen. (E, F) Microphotographs showing textural features of the granitoid samples (15YL18–4, 15YL40–2) from the Zhangguangcailing orogen (Pl—plagioclase, Q—quartz, Kf—K-feldspar, Bi—biotite).

as previously suggested (Wu et al., 2003b; Yang et al., 2012). However, little effort has been made to combine the tectonic and petrological data in order to contribute to the understanding of the geodynamic evolution of the large volumes of I-type granites in the Zhangguangcailing orogen.

The Jiamusi block, located to the east of the Zhangguangcailing orogen, is made up of three components, the Mashan supracrustal rocks and two granitoids of different ages. The Mashan supracrustal rocks are characterized by sedimentary and minor volcanic rocks metamorphosed to upper amphibolite to granulite facies. They comprise pelitic granulites and/or gneisses, calc-silicate rocks, marbles, and minor amphibolites and mafic granulites, referred to as the khondalite series in Chinese literature (Wilde et al., 2000). Previous studies suggested that the Mashan

supracrustal rocks formed in the Neoarchean, but recent precise age data indicate that their protoliths have Mesoproterozoic–Neoproterozoic ages and underwent granulite facies metamorphism ca. 500 Ma (Wilde et al., 1997, 1999, 2000, 2003). There are two stages of granitoids in the Jiamusi block: (1) deformed early Paleozoic granitic rocks that are associated with the Mashan supracrustal rocks. Wilde et al. (1997, 1999, 2003) suggested that these were coeval with granitic rocks in South Australia and accordingly that the Jiamusi block was connected with Gondwana in the early Paleozoic and later drifted northward. (2) Permian granitoids that have a locally preserved magmatic fabric or foliation with no sign of metamorphism or deformation, except for some granites exposed along the Mudanjiang fault (Wilde et al., 1997; Wu et al., 2000, 2011).

METHODOLOGY

We collected 67 samples from the Zhangguangcailing orogen (Appendix 1; Fig. 3), 15 of which were selected for geochemical analysis, and 8 for zircon U-Pb-Hf analyses.

Zircon U-Pb Dating

Zircon grains were separated from mafic samples using standard density and magnetic separation techniques. Cathodoluminescence (CL) images (Fig. 4) with a scanning electron microscope (Leo 1450VP, Germany) were followed by in situ U-Pb analyses.

The U-Pb analyses were performed using a multicollector laser ablation–inductively coupled plasma–mass spectrometer (MC-LA-ICP-MS) at the Department of Earth Sciences in the University of Hong Kong. A Nu Instruments MC-ICP-MS is attached to a Resonetics Resolution M-50-HR excimer laser ablation system. Analyses were made with a beam diameter of 30 mm and 6 Hz repetition rate, which yielded a signal intensity of 0.03 V at ^{238}U for the standard 91500. Typical ablation time was 40 s for each measurement, resulting in pits 30–40 mm deep. Raw data were performed with an ICPDataCal_ver8.0.

Hf Isotope Analyses

In situ zircon Hf isotope analyses were carried out using a Finnigan Neptune MC-ICP-MS with a NewWave UP213 nm laser ablation microprobe at the State Key Lab for Mineral Deposit Research, Nanjing University, China. The analyses were made with a laser beam diameter of 32 μm , a repetition rate of 10 Hz, a laser power of 100 mJ/pulse, and an ablation time of 30 s. The GJ-1 zircon standard was analyzed to check instrument reliability and stability. Helium was used as the carrier gas to transport the ablated sample from the laser ablation cell to the ICP-MS torch via a mixing chamber mixed with argon. The typical ablation time was 80–120 s, resulting in pits 50–60 μm in diameter and 40–50 μm deep. The analytical conditions and procedures are as described by Griffin et al. (2000). The ^{176}Lu decay constant of 1.865×10^{-11} (Scherer et al., 2001) was used for calculation of initial $^{176}\text{Hf}/^{177}\text{Hf}$ values, and the Hf model ages were based on the depleted-mantle model and a mean crustal composition ($^{176}\text{Lu}/^{177}\text{Hf} = 0.015$; Griffin et al., 2000, 2004).

Whole-Rock Major and Trace Element Analyses

The major element contents of the rocks were analyzed with an Axios mAX X-ray fluorescence spectrometer. Uncertainties for the major elements are generally <2%. Trace element contents of the rocks were analyzed with a Quadrupole ICP-MS at the State Key Laboratory of Ore Deposit Geochemistry (Institute of Geochemistry, Chinese Academy of Sciences, Guiyang) using international standards AGV-2 (andesite), BCR-1 (basalt), G-2 (granite), OU-6 (slate), AMH-1 (andesite), and GBPG-1 (plagiogneiss) for analytical quality control (Potts et al., 2000, 2001). The analytical precision of most trace elements is generally better than 5%. Detailed analytical procedures are described in Liang et al. (2000).

Whole-Rock Sr-Nd Isotopes

The samples were dissolved in a mixture of HF and HNO_3 in sealed Teflon bombs, and separated using a combination of ion exchange and extraction chromatography (at Nanjing Focums Technology Co. Ltd). After cooling, the capsule was opened and evaporated. The residue was dissolved in 3M HCl. Sr, Nd, and Hf were then separated by the following

procedure: Rb-Sr were loaded into a mixed ion-exchange column that contained a Dowex 50W X8 cation exchange resin (100–200 mesh) and an Eichrom Sr specific resin (100–200 mesh) to separate Rb, Sr, rare earth elements (REEs), and Pb. The REEs were separated by an Ln specific resin. Sr and Nd isotopic ratios were measured with a Nu Plasma II MC-ICP-MS. The mass fractionation corrections for Sr and Nd isotopic ratios are based on $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of Sr standard NBS987 was determined to be 0.710248 ± 0.000010 (1σ , $n = 7$), agreeing well with 0.710250 ± 0.000030 (Höppe, 1999) within analytical error. A $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of JNdi standard solutions yielded an average value of 0.512104 ± 0.000010 (1σ , $n = 7$), similar to the suggested average ratio of 0.512115 ± 0.000007 (Tanaka and Toda, 2000). Total procedural blanks were 50 pg for Nd and 400 pg for Sr.

For calculation of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, $\epsilon_{\text{Hf}}(t)$ values, and Nd model ages, the adopted parameters were: decay constant for ^{87}Rb and $^{147}\text{Sm} = 1.42 \times 10^{-11} \text{ yr}^{-1}$ (Steiger and Jäger, 1977) and $6.54 \times 10^{-12} \text{ yr}^{-1}$ (Lugmair and Marti, 1978), respectively; $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of CHUR (chondrite uniform reservoir) = 0.1967 (Jacobsen and Wasserburg, 1980); $^{143}\text{Nd}/^{147}\text{Nd}$ ratio of CHUR = 0.512638 (Goldstein et al., 1984); $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{147}\text{Nd}$ ratios for depleted mantle (DM) = 0.2136 and 0.513151 (Liew and Hofmann, 1988), respectively, and a $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.12 was used for the average continental crust (Liew and Hofmann, 1988).

RESULTS

Petrography

Given that the petrographic characteristics of the granitoids are similar, we describe them together. They are generally fine to medium grained or porphyric in texture. Plagioclase (30%–35%), K-feldspar (25%–30%), quartz (10%–15%), and biotite (3%–10%) are major mineral phases in all rock types. Plagioclase forms subhedral, prismatic, and lath-shaped crystals (Figs. 3E, 3F). Some show oscillatory zoning, prismatic cellular growth, and albite twinning. K-feldspar forms anhedral, rarely subhedral crystals of perthitic orthoclase (Figs. 3E, 3F). Quartz is anhedral with irregular cracks and is interstitial to other minerals. Biotite is euhedral and subhedral reddish-brown and forms prismatic crystals and lamellas (Figs. 3E, 3F).

Zircon U-Pb and Lu-Hf Results

The results of zircon U-Pb dating of eight samples are listed in Table 1, zircon U-Pb concordia diagrams are in Figure 4, and zircon Lu-Hf results of five samples are given in Table 2 and Figure 5.

Zircons from all samples are generally equant to prismatic, colorless, and transparent. Crystal lengths range from 100 to 400 μm , with length/width ratios between 1.5:1 and 4:1. In CL images, most zircons display clear oscillatory zoning. There are no metamorphic overgrowths or erosions in the zircons (Fig. 3). All the analyzed zircons have variable uranium (24–2590 ppm) and thorium (67–1872 ppm) contents with the Th/U ratio ranging from 0.17 to 3.32 (Table 1), consistent with a magmatic origin (Hoskin and Schaltegger, 2003). Thus, the interpretation of the zircon U-Pb isotopic data (see following) is straightforward and the ages are interpreted to represent the time of zircon crystallization, and thus the timing of the host-rock emplacement.

The 21 analyzed zircons from granite sample (15YL14–1) collected near Yichun gave a weighted mean U-Pb age of $182.8 \pm 1.3 \text{ Ma}$ (Fig. 4C) and $\epsilon_{\text{Hf}}(t)$ values ranging from 1.06 to 3.43. Zircons from another granitic sample (15YL28–1) near Jiamusi yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $185 \pm 0.62 \text{ Ma}$ with $\epsilon_{\text{Hf}}(t)$ values of 4.27–6.09 (Figs. 4E and 5; Table 2). To the south of Yichun near Tieli, a quartz diorite (15YL18–4)

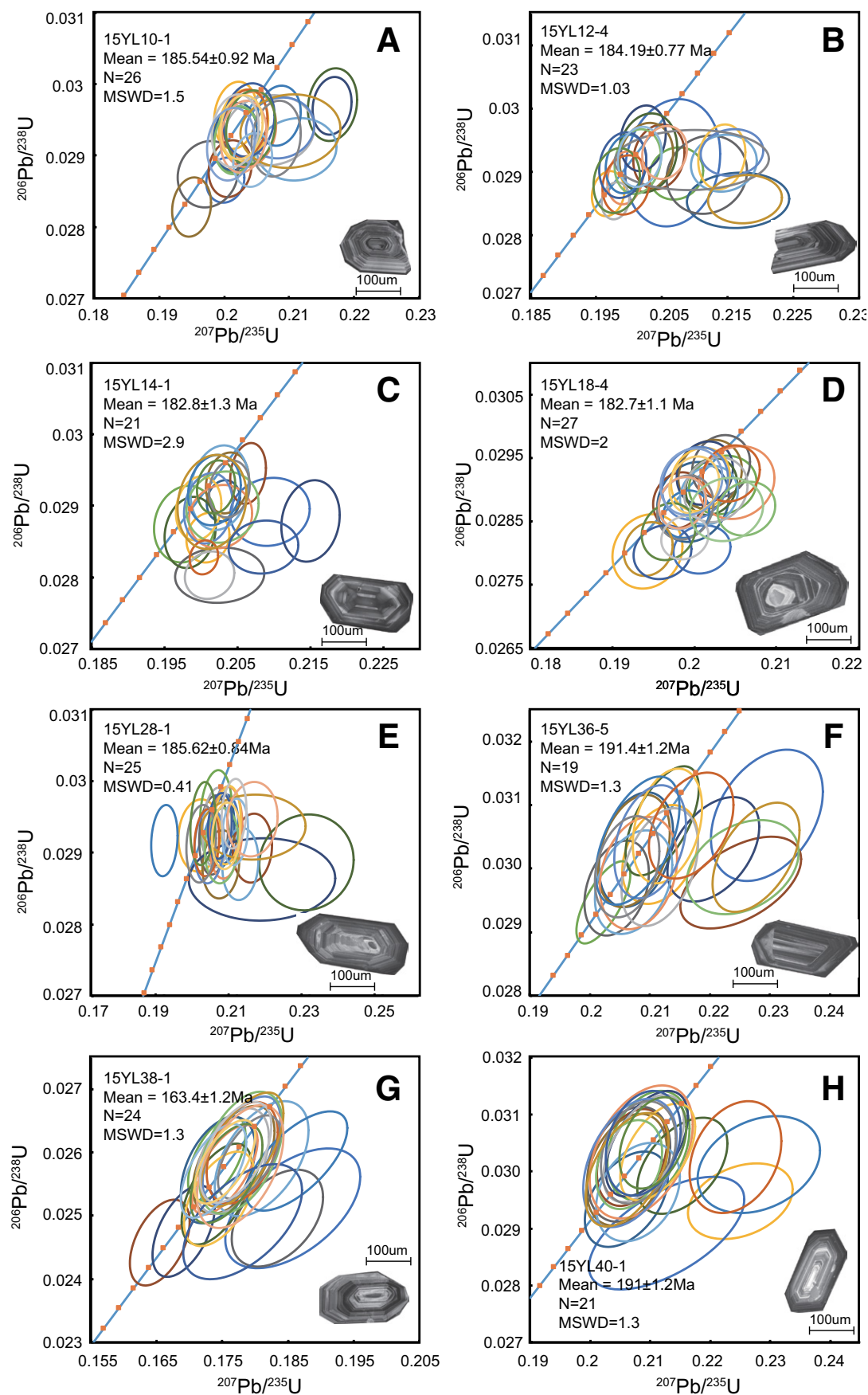


Figure 4. U-Pb concordia diagrams of zircon data and representative cathodoluminescence images of zircons from granitic samples in the Zhangguangcailing orogen. MSWD—mean square of weighted deviates.

TABLE 1. U-Pb DATA FOR GRANITOIDS FROM THE ZHANGGUANGCAILING OROGEN

Sample	Th (ppm)	U (ppm)	Th/U	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ (1 σ)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (1 σ)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (1 σ)	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ (p)	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ age (Ma)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (1 σ)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ age (Ma)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (1 σ)	Age (Ma)	1 σ
15YL10-1-1	553.31	105.82	5.23	0.04951	0.00016	0.20179	0.00218	0.02956	0.00031	0.14	172.31	12.04	186.64	2.56	187.80	1.93
15YL10-1-2	423.27	50.29	8.42	0.05061	0.00024	0.20018	0.00193	0.02866	0.00021	0.11	233.40	11.11	185.28	1.75	182.13	1.33
15YL10-1-4	477.48	39.98	11.94	0.05008	0.00018	0.20184	0.00227	0.02922	0.00030	0.13	198.23	7.41	186.68	1.67	185.67	1.88
15YL10-1-6	522.33	45.44	11.50	0.05002	0.00017	0.20172	0.00219	0.02927	0.00031	0.14	194.53	12.03	186.58	1.75	185.96	1.94
15YL10-1-8	642.72	53.99	11.91	0.05053	0.00014	0.20092	0.00215	0.02881	0.00026	0.12	220.44	10.18	185.91	2.02	183.13	1.66
15YL10-1-9	537.09	39.35	13.65	0.04977	0.00043	0.19745	0.00307	0.02874	0.00031	0.10	183.42	23.14	182.96	2.55	182.66	1.92
15YL10-1-11	435.32	47.51	9.16	0.05003	0.00016	0.19498	0.00199	0.02828	0.00028	0.14	198.23	12.03	180.87	1.92	179.76	1.73
15YL10-1-13	475.19	53.00	8.97	0.05295	0.00024	0.21656	0.00198	0.02970	0.00027	0.13	327.84	13.89	199.04	1.46	188.67	1.66
15YL10-1-14	523.97	52.46	9.99	0.05303	0.00061	0.21667	0.00250	0.02971	0.00034	0.13	331.54	30.55	199.13	2.13	188.72	2.11
15YL10-1-15	365.06	37.82	9.65	0.04893	0.00109	0.21118	0.00403	0.02908	0.00029	0.07	142.68	47.22	194.55	2.62	184.80	1.81
15YL10-1-16	615.97	38.00	16.21	0.05038	0.00041	0.20383	0.00274	0.02937	0.00035	0.13	213.04	18.51	188.36	2.10	186.58	2.18
15YL10-1-17	403.65	42.99	9.39	0.05098	0.00071	0.20702	0.00450	0.02936	0.00032	0.07	238.96	33.33	191.05	2.63	186.51	2.02
15YL10-1-18	446.30	24.71	18.07	0.05000	0.00017	0.20299	0.00250	0.02942	0.00033	0.13	194.53	12.03	187.65	2.06	186.93	2.09
15YL10-1-19	586.59	43.88	13.37	0.05134	0.00053	0.20860	0.00345	0.02938	0.00028	0.08	257.47	24.07	192.38	2.21	186.68	1.77
15YL10-1-20	348.24	40.68	8.56	0.05013	0.00019	0.20192	0.00224	0.02922	0.00031	0.14	211.19	9.26	186.75	1.80	185.64	1.97
15YL10-1-21	421.73	35.70	11.81	0.05112	0.00027	0.20840	0.00221	0.02956	0.00027	0.12	255.62	11.11	192.21	1.59	187.79	1.72
15YL10-1-22	516.91	29.40	17.58	0.05006	0.00016	0.20329	0.00219	0.02945	0.00031	0.14	198.23	7.41	187.91	8.06	187.12	1.94
15YL10-1-23	440.03	36.26	12.13	0.05169	0.00034	0.20801	0.00251	0.02924	0.00035	0.14	272.29	14.82	191.88	3.18	185.79	2.19
15YL10-1-24	472.29	31.23	15.12	0.05172	0.00087	0.21018	0.00505	0.02935	0.00034	0.07	272.29	37.04	193.70	2.81	186.45	2.14
15YL10-1-25	523.40	29.75	17.59	0.05008	0.00017	0.20387	0.00259	0.02950	0.00034	0.13	198.23	7.41	188.40	1.81	187.40	2.13
15YL10-1-26	380.31	30.08	12.64	0.05035	0.00016	0.20410	0.00252	0.02939	0.00034	0.14	209.33	2.78	188.59	2.23	186.73	2.15
15YL10-1-29	544.12	43.30	12.57	0.05191	0.00180	0.20439	0.00198	0.02893	0.00025	0.12	250.07	7.41	188.83	5.63	183.88	1.55
15YL10-1-30	534.29	36.13	14.79	0.05120	0.00017	0.20299	0.00231	0.02927	0.00033	0.14	209.33	2.78	187.66	1.96	185.96	2.09
15YL10-1-31	519.94	37.64	13.82	0.05032	0.00015	0.20168	0.00236	0.02935	0.00034	0.14	187.12	2.78	186.54	1.84	186.45	2.11
15YL10-1-32	414.43	30.88	13.42	0.04985	0.00016	0.20266	0.00213	0.02940	0.00029	0.14	194.53	12.03	187.37	1.64	186.79	1.85
15YL10-1-33	524.96	34.08	15.40	0.04999	0.00016	0.20102	0.00242	0.02916	0.00034	0.14	194.53	12.03	185.99	1.89	185.29	2.11
15YL12-4-1	759.59	930.21	0.82	0.04999	0.00017	0.19683	0.00165	0.02866	0.00023	0.14	187.12	0.92	182.44	1.41	182.16	1.47
15YL12-4-11	181.96	504.01	0.36	0.05142	0.00023	0.20663	0.00479	0.02915	0.00066	0.14	261.18	41.66	190.72	4.03	185.20	4.15
15YL12-4-12	291.11	429.24	0.68	0.05171	0.00033	0.20720	0.00271	0.02897	0.00027	0.10	272.29	14.82	191.20	2.29	184.12	1.72
15YL12-4-14	844.12	966.35	0.87	0.05448	0.00078	0.21658	0.00513	0.02855	0.00029	0.06	390.79	33.33	199.06	4.29	181.46	1.80
15YL12-4-16	573.33	2020.68	0.28	0.05068	0.00015	0.20456	0.00258	0.02924	0.00034	0.13	233.40	7.41	188.98	2.18	185.78	2.11
15YL12-4-17	379.22	668.85	0.57	0.05273	0.00031	0.21190	0.00404	0.02896	0.00041	0.10	316.73	14.82	195.14	3.39	184.01	2.55
15YL12-4-19	775.08	1697.31	0.46	0.05022	0.00019	0.20266	0.00269	0.02924	0.00036	0.13	205.63	7.40	187.37	2.27	185.77	2.24
15YL12-4-2	496.27	492.39	1.01	0.04965	0.00012	0.20210	0.00230	0.02953	0.00034	0.15	188.97	5.56	186.90	1.95	187.61	2.12
15YL12-4-21	374.92	902.73	0.42	0.05020	0.00025	0.20286	0.00299	0.02930	0.00041	0.14	211.19	12.96	187.54	2.52	186.18	2.57
15YL12-4-23	650.69	1101.54	0.59	0.05304	0.00035	0.21446	0.00329	0.02914	0.00030	0.09	331.54	14.81	197.29	2.76	185.17	1.86
15YL12-4-24	820.22	1996.15	0.41	0.05007	0.00010	0.19944	0.00179	0.02891	0.00028	0.16	198.23	8.33	184.65	1.52	183.70	1.75
15YL12-4-26	748.59	766.59	0.98	0.05002	0.00014	0.20164	0.00218	0.02923	0.00031	0.14	194.53	10.18	186.52	1.85	185.76	1.95
15YL12-4-28	397.21	1036.29	0.38	0.05026	0.00010	0.19792	0.00142	0.02855	0.00019	0.14	205.63	0.92	183.37	1.21	181.44	1.21
15YL12-4-29	941.71	1161.83	0.81	0.05333	0.00053	0.21416	0.00238	0.02924	0.00034	0.14	342.65	22.22	197.04	2.00	185.80	2.11
15YL12-4-3	428.63	2435.55	0.18	0.05308	0.00039	0.21566	0.00311	0.02930	0.00024	0.08	331.54	16.67	198.29	2.60	186.17	1.53
15YL12-4-30	353.68	593.69	0.60	0.05015	0.00030	0.20132	0.00230	0.02916	0.00034	0.15	211.19	14.81	186.24	1.95	185.30	2.14
15YL12-4-31	1182.11	2422.01	0.49	0.04968	0.00007	0.19954	0.00207	0.02912	0.00030	0.15	188.97	3.70	184.73	1.76	185.06	1.90
15YL12-4-32	544.53	551.80	0.99	0.05023	0.00025	0.19950	0.00237	0.02879	0.00031	0.13	205.63	11.11	184.70	2.01	183.00	1.93
15YL12-4-33	449.52	552.77	0.81	0.05170	0.00137	0.20956	0.00776	0.02919	0.00031	0.04	272.29	61.11	193.18	6.52	185.45	1.95
15YL12-4-4	365.74	749.78	0.49	0.05481	0.00052	0.21764	0.00369	0.02857	0.00025	0.07	405.61	25.00	199.95	3.08	181.60	1.59
15YL12-4-6	804.36	1457.46	0.55	0.04959	0.00010	0.19908	0.00236	0.02911	0.00034	0.14	176.01	8.33	184.35	2.00	184.96	2.12
15YL12-4-7	415.53	664.02	0.63	0.04979	0.00015	0.19812	0.00230	0.02887	0.00034	0.15	183.42	0.92	183.53	1.95	183.45	2.12
15YL12-4-8	888.71	969.74	0.92	0.05075	0.00015	0.20540	0.00223	0.02931	0.00028	0.12	227.85	0.93	189.69	1.88	186.21	1.74
15YL14-1-1	165.85	200.33	0.83	0.05104	0.00030	0.20094	0.00195	0.00195	0.02855	0.00	0.83	242.66	14.81	1.81	185.92	2.01
15YL14-1-2	350.65	717.90	0.49	0.05233	0.00038	0.20946	0.00360	0.00360	0.02892	0.00	0.49	298.21	16.67	3.15	193.10	3.62
15YL14-1-3	466.02	510.95	0.91	0.05020	0.00026	0.19779	0.00279	0.00279	0.02874	0.00	0.91	211.19	12.96	3.73	183.26	2.81
15YL14-1-4	239.56	391.84	0.61	0.05064	0.00016	0.20303	0.00149	0.00149	0.02907	0.00	0.61	233.40	7.41	1.28	187.69	1.64
15YL14-1-5	415.82	705.21	0.59	0.05088	0.00024	0.20645	0.00160	0.00160	0.02945	0.00	0.59	235.25	11.11	2.67	190.57	1.95
15YL14-1-7	699.64	1121.32	0.62	0.05226	0.00073	0.20257	0.00405	0.00405	0.02803	0.00	0.62	298.21	31.48	3.66	187.30	3.72
15YL14-1-9	365.69	633.29	0.58	0.05037	0.00017	0.20360	0.00193	0.00193	0.02932	0.00	0.58	213.04	4.63	1.94	188.16	2.39
15YL14-1-10	133.60	212.36	0.63	0.05422	0.00036	0.21497	0.00264	0.00264	0.02879	0.00	0.63	388.94	14.81	2.94	197.71	2.66
15YL14-1-12	624.81	786.34	0.79	0.05046	0.00019	0.19852	0.00228	0.00228	0.02863	0.00	0.79	216.74	12.04	4.08	183.87	3.85
15YL14-1-13	580.29	933.06	0.62	0.05024	0.00014	0.20256	0.00267	0.00267	0.02925	0.00	0.62	205.63	7.40	2.10	187.29	3.06
15YL14-1-14	356.74	591.31	0.60	0.05099	0.00064	0.20267	0.00287	0.00287	0.02885	0.00	0.60	238.96	62.03	3.38	187.38	2.56
15YL14-1-18	234.99	432.89	0.54	0.05193	0.00025	0.20113	0.00223	0.00223	0.02803	0.00	0.54	283.40	13.89	3.37	186.08	2.75
15YL14-1-19	347.60	666.66	0.52	0.05000	0.00021											

TABLE 1. U-Pb DATA FOR GRANITOIDS FROM THE ZHANGGUANGCAILING OROGEN (*continued*)

Sample	Th (ppm)	U (ppm)	Th/U	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ (1 σ)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (1 σ)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (1 σ)	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ (p)	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ age (Ma)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (1 σ)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ age (Ma)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (1 σ)	Age (Ma)	1 σ
15YL14-1-24	589.60	1622.69	0.36	0.05137	0.00015	0.20038	0.00128	0.00128	0.02828	0.00	0.36	257.47	7.41	1.49	185.45	2.35
15YL14-1-26	816.56	1029.10	0.79	0.05057	0.00011	0.20389	0.00186	0.00186	0.02924	0.00	0.79	220.44	8.33	2.17	188.42	2.46
15YL14-1-27	247.43	373.31	0.66	0.05030	0.00021	0.20153	0.00310	0.00310	0.02906	0.00	0.66	209.33	9.26	3.45	186.42	3.04
15YL14-1-29	430.67	884.97	0.49	0.05303	0.00042	0.20852	0.00315	0.00315	0.02843	0.00	0.49	331.54	12.04	3.53	192.31	3.34
15YL14-1-30	499.60	1079.11	0.46	0.05006	0.00012	0.20205	0.00174	0.00174	0.02926	0.00	0.46	198.23	10.18	1.28	186.86	1.92
15YL18-4-1	1871.89	2222.27	0.84	0.05025	0.00009	0.19430	0.00280	0.00280	0.00039	0.14	205.63	(0.93)	180.29	2.39	178.17	2.44
15YL18-4-2	241.78	493.34	0.49	0.05185	0.00026	0.20092	0.00230	0.00230	0.00025	0.11	279.69	(16.67)	185.91	1.95	178.38	1.58
15YL18-4-3	326.62	384.85	0.85	0.04782	0.00157	0.18588	0.00338	0.00338	0.00031	0.09	100.09	77.77	173.11	2.90	180.86	1.97
15YL18-4-4	243.56	526.98	0.46	0.05068	0.00054	0.20346	0.00270	0.00270	0.00030	0.11	233.40	19.44	188.05	2.28	184.76	1.90
15YL18-4-5	85.19	147.48	0.58	0.05038	0.00028	0.19985	0.00289	0.00289	0.00041	0.14	213.04	17.59	185.00	2.45	183.04	2.60
15YL18-4-6	446.49	808.88	0.55	0.04982	0.00010	0.19812	0.00206	0.00206	0.00029	0.14	187.12	0.92	183.53	1.75	183.23	1.85
15YL18-4-7	239.40	391.08	0.61	0.05017	0.00014	0.20325	0.00233	0.00233	0.00032	0.14	211.19	7.40	187.87	1.97	186.60	2.04
15YL18-4-8	785.30	1728.39	0.45	0.05004	0.00008	0.20194	0.00257	0.00257	0.00036	0.14	198.23	8.33	186.76	2.17	185.79	2.25
15YL18-4-9	196.82	366.74	0.54	0.04991	0.00014	0.20130	0.00225	0.00225	0.00033	0.15	190.82	7.41	186.23	1.90	185.92	2.06
15YL18-4-10	272.73	580.70	0.47	0.05045	0.00012	0.20208	0.00209	0.00209	0.00030	0.14	216.74	5.56	186.88	1.77	184.58	1.86
15YL18-4-11	352.42	724.85	0.49	0.05053	0.00012	0.20174	0.00232	0.00232	0.00031	0.13	220.44	10.18	186.60	1.96	183.75	1.92
15YL18-4-12	124.25	201.77	0.62	0.05102	0.00024	0.20516	0.00303	0.00303	0.00038	0.13	242.66	11.11	189.48	2.56	184.99	2.38
15YL18-4-13	83.36	188.50	0.44	0.05061	0.00018	0.20261	0.00253	0.00253	0.00034	0.13	233.40	9.26	187.33	2.14	184.30	2.11
15YL18-4-14	305.55	572.19	0.53	0.04989	0.00010	0.20077	0.00236	0.00236	0.00033	0.14	190.82	5.55	185.77	2.00	185.27	2.05
15YL18-4-15	419.02	737.58	0.57	0.04986	0.00012	0.20009	0.00262	0.00262	0.00038	0.15	187.12	5.55	185.21	2.22	184.89	2.38
15YL18-4-16	345.24	581.86	0.59	0.05203	0.00017	0.20634	0.00234	0.00234	0.00028	0.12	287.10	7.41	190.48	1.97	182.39	1.76
15YL18-4-17	93.17	301.05	0.31	0.05041	0.00016	0.19901	0.00184	0.00184	0.00024	0.13	213.04	7.41	184.29	1.56	181.85	1.53
15YL18-4-18	415.66	770.90	0.54	0.05062	0.00017	0.20447	0.00228	0.00228	0.00029	0.13	233.40	7.41	188.90	1.93	185.89	1.85
15YL18-4-19	310.63	541.52	0.57	0.05024	0.00013	0.19887	0.00226	0.00226	0.00033	0.15	205.63	7.40	184.17	1.92	182.49	2.08
15YL18-4-21	120.95	246.58	0.49	0.05025	0.00017	0.19440	0.00198	0.00198	0.00028	0.14	205.63	7.40	180.38	1.69	178.39	1.77
15YL18-4-22	220.88	408.83	0.54	0.05079	0.00037	0.19616	0.00232	0.00232	0.00028	0.12	231.55	21.29	181.87	1.97	178.09	1.74
15YL18-4-23	252.19	419.93	0.60	0.05034	0.00014	0.19689	0.00218	0.00218	0.00030	0.14	209.33	2.78	182.49	1.85	180.14	1.85
15YL18-4-24	378.25	688.50	0.55	0.05000	0.00013	0.19847	0.00186	0.00186	0.00027	0.15	194.53	12.03	183.83	1.58	182.94	1.71
15YL18-4-25	542.44	842.07	0.64	0.04999	0.00009	0.19857	0.00188	0.00188	0.00027	0.14	194.53	3.71	183.92	1.60	182.99	1.68
15YL18-4-26	202.68	321.45	0.63	0.05100	0.00020	0.19885	0.00189	0.00189	0.00023	0.12	238.96	9.26	184.15	1.60	179.55	1.43
15YL18-4-28	312.44	660.96	0.47	0.04989	0.00011	0.20000	0.00198	0.00198	0.00029	0.15	190.82	5.55	185.13	1.68	184.75	1.84
15YL18-4-29	67.03	142.51	0.47	0.04970	0.00020	0.19962	0.00249	0.00249	0.00035	0.14	188.97	9.26	184.81	2.11	185.07	2.17
15YL18-4-30	148.67	292.25	0.51	0.05137	0.00022	0.20388	0.00294	0.00294	0.00033	0.11	257.47	38.89	188.40	2.48	182.30	2.08
15YL28-1-1	168.77	421.40	0.40	0.04971	0.00140	0.19991	0.00382	0.00382	0.00033	0.09	188.97	66.66	185.05	3.43	185.80	2.06
15YL28-1-2	140.66	336.38	0.42	0.05105	0.00015	0.20669	0.00246	0.00246	0.00032	0.13	242.66	7.41	190.77	2.06	186.36	1.99
15YL28-1-3	199.78	461.18	0.43	0.05023	0.00014	0.20435	0.00286	0.00286	0.00042	0.15	205.63	7.40	188.80	2.32	187.51	2.64
15YL28-1-4	146.12	327.97	0.45	0.05098	0.00016	0.20590	0.00236	0.00236	0.00034	0.14	238.96	12.04	190.11	2.06	186.24	2.14
15YL28-1-5	84.80	199.75	0.42	0.05323	0.00049	0.21435	0.00356	0.00356	0.00032	0.09	338.95	25.00	197.20	2.10	184.70	1.99
15YL28-1-6	119.16	267.34	0.45	0.05052	0.00014	0.20370	0.00255	0.00255	0.00037	0.14	220.44	10.18	188.25	1.93	185.83	2.30
15YL28-1-7	77.94	186.12	0.42	0.05166	0.00058	0.20566	0.00339	0.00339	0.00031	0.09	333.39	25.92	189.91	2.59	183.25	1.97
15YL28-1-8	117.54	260.79	0.45	0.05381	0.00193	0.21699	0.01329	0.01329	0.00038	0.03	364.87	81.48	199.40	10.69	181.97	2.38
15YL28-1-9	92.76	195.74	0.47	0.05654	0.00146	0.22910	0.00853	0.00853	0.00044	0.05	472.27	57.40	209.45	3.10	183.44	2.76
15YL28-1-12	298.39	1070.29	0.28	0.05290	0.00042	0.21098	0.00326	0.00326	0.00033	0.10	324.13	18.52	194.38	2.79	183.31	2.06
15YL28-1-13	115.16	317.76	0.36	0.05146	0.00053	0.20700	0.00302	0.00302	0.00042	0.14	261.18	22.22	191.04	1.86	186.02	2.65
15YL28-1-14	110.02	250.98	0.44	0.05053	0.00017	0.20453	0.00261	0.00261	0.00037	0.14	220.44	7.41	188.95	2.38	186.52	2.30
15YL28-1-15	326.71	942.89	0.35	0.05120	0.00010	0.20738	0.00249	0.00249	0.00036	0.15	250.07	(0.93)	191.35	1.79	186.72	2.26
15YL28-1-16	243.72	494.76	0.49	0.05053	0.00067	0.20244	0.00266	0.00266	0.00035	0.13	220.44	31.47	187.19	3.16	184.91	2.19
15YL28-1-17	148.66	333.76	0.45	0.05125	0.00028	0.20591	0.00306	0.00306	0.00035	0.11	250.07	12.96	190.12	1.97	184.90	2.19
15YL28-1-18	70.29	130.90	0.54	0.04725	0.00162	0.19027	0.00239	0.00239	0.00033	0.14	61.21	81.48	176.86	2.06	185.38	2.06
15YL28-1-19	71.41	167.39	0.43	0.05026	0.00024	0.20184	0.00227	0.00227	0.00031	0.14	205.63	11.11	186.68	1.86	185.16	1.95
15YL28-1-21	120.75	278.79	0.43	0.05135	0.00014	0.20027	0.00263	0.00263	0.00036	0.14	187.12	17.59	185.36	1.95	185.08	2.24
15YL28-1-23	151.04	245.33	0.62	0.04987	0.00028	0.21463	0.00944	0.00944	0.00030	0.03	322.28	77.77	197.43	4.94	186.52	1.88
15YL28-1-24	117.74	205.42	0.57	0.05266	0.00179	0.20554	0.00217	0.00217	0.00030	0.14	187.12	26.85	189.80	11.48	186.63	1.90
15YL28-1-25	105.31	236.79	0.44	0.04987	0.00064	0.20066	0.00225	0.00225	0.00038	0.17	190.82	27.77	185.68	15.46	186.85	2.41
15YL28-1-27	151.95	373.13	0.41	0.04988	0.00060	0.20957	0.00231	0.00231	0.00031	0.13	279.69	7.41	193.20	1.61	186.13	1.93
15YL28-1-28	122.38	282.69	0.43	0.05188	0.00018	0.21431	0.00462	0.00462	0.00034	0.07	309.32	33.33	197.17	6.52	187.21	2.16
15YL28-1-29	161.04	277.43	0.58	0.05256	0.00078	0.20934	0.00227	0.00227	0.00032	0.14	261.18	41.66	193.00	1.77	187.70	2.01
15YL28-1-30	81.12	202.02	0.40	0.05143	0.00023	0.20709	0.00259	0.00259	0.00031	0.12	257.47	45.37	191.10	1.84	185.77	1.92
15YL36-5-1	267.36	812.08	0.33	0.05069	0.00015	0.21171	0.00257	0.00257	0.00032	2.67	227.85	7.41	194.99	2.15	191.96	1.99
15YL36-5-10	525.66	1469.87	0.36	0.05383	0.00034	0.22953	0.00379	0.00379	0.00042	9.83	364.87	19.44	209.81	3.13	195.81	2.65
15YL36-5-11	447.57	647.69	0.69	0.04976	0.00011	0.20229	0.00185	0.00185	0.00026	1.26	183.42	0.92	187.06	1.57	187.26	1.66
15YL36-5-12	345.05	1118.81	0.31	0.04969	0.00											

TABLE 1. U-Pb DATA FOR GRANITOIDS FROM THE ZHANGGUANGCAILING OROGEN (*continued*)

Sample	Th (ppm)	U (ppm)	Th/U	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ (1 σ)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (1 σ)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (1 σ)	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ (p)	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$ age (Ma)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (1 σ)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ age (Ma)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (1 σ)	Age (Ma)	1 σ
15YL36-5-17	170.58	396.46	0.43	0.05260	0.00028	0.22058	0.00312	0.03031	0.00034	2.73	322.28	12.96	202.39	2.60	192.48	2.11
15YL36-5-20	524.44	877.96	0.60	0.04999	0.00009	0.21205	0.00248	0.03075	0.00035	1.60	194.53	3.71	195.27	2.08	195.23	2.19
15YL36-5-21	407.58	1248.17	0.33	0.05038	0.00014	0.20732	0.00262	0.02979	0.00033	2.69	213.04	7.41	191.30	2.21	189.23	2.10
15YL36-5-22	382.51	1493.29	0.26	0.05036	0.00009	0.20811	0.00264	0.02993	0.00036	3.88	213.04	3.71	191.97	2.23	190.12	2.27
15YL36-5-23	620.65	1613.59	0.38	0.05117	0.00010	0.21166	0.00259	0.03002	0.00038	5.28	255.62	5.55	194.94	2.17	190.69	2.38
15YL36-5-24	436.20	1369.95	0.32	0.05042	0.00011	0.21291	0.00236	0.03067	0.00037	3.31	213.04	5.56	195.99	1.98	194.75	2.32
15YL36-5-3	811.63	2590.39	0.31	0.05008	0.00006	0.21004	0.00246	0.03042	0.00036	3.57	198.23	8.33	193.59	2.07	193.18	2.28
15YL36-5-4	399.86	1258.78	0.32	0.05408	0.00049	0.22544	0.00381	0.03003	0.00030	6.34	375.98	20.37	206.43	3.16	190.71	1.90
15YL36-5-5	227.28	431.70	0.53	0.04954	0.00014	0.20796	0.00284	0.03044	0.00041	2.43	172.31	10.19	191.84	2.39	193.32	2.58
15YL36-5-6	203.37	526.33	0.39	0.05112	0.00019	0.21689	0.00288	0.03068	0.00034	2.73	255.62	7.41	199.32	2.41	194.82	2.14
15YL36-5-8	367.70	1218.03	0.30	0.04981	0.00009	0.20622	0.00217	0.03003	0.00033	2.32	187.12	0.92	190.38	1.84	190.75	2.04
15YL36-5-9	292.67	596.90	0.49	0.05463	0.00018	0.22773	0.00296	0.03018	0.00035	4.55	398.20	7.41	208.32	2.45	191.69	2.20
15YL38-1-1	437.76	833.44	0.53	0.05328	0.00047	0.18576	0.00420	0.02512	0.00039	6.85	338.95	20.37	173.00	3.60	159.90	2.43
15YL38-1-10	598.85	1054.46	0.57	0.04869	0.00010	0.17415	0.00181	0.02591	0.00027	2.76	131.57	36.11	163.01	1.57	164.88	1.71
15YL38-1-11	325.27	754.32	0.43	0.04912	0.00011	0.17433	0.00230	0.02572	0.00034	3.20	153.79	10.19	163.17	1.99	163.71	2.16
15YL38-1-12	442.29	918.75	0.48	0.04878	0.00012	0.16545	0.00184	0.02458	0.00028	2.28	200.08	5.56	155.46	1.61	156.55	1.74
15YL38-1-13	322.81	751.31	0.43	0.05308	0.00032	0.18343	0.00285	0.02496	0.00031	6.20	331.54	14.81	171.01	2.45	158.94	1.98
15YL38-1-14	528.91	998.29	0.53	0.04937	0.00014	0.17673	0.00256	0.02589	0.00035	3.03	164.90	2.78	165.24	2.21	164.76	2.18
15YL38-1-15	540.03	1029.00	0.52	0.04951	0.00011	0.16908	0.00194	0.02475	0.00030	2.90	172.31	3.71	158.62	1.69	157.63	1.86
15YL38-1-16	583.83	1056.44	0.55	0.04980	0.00010	0.17415	0.00220	0.02534	0.00033	2.99	187.12	0.92	163.02	1.90	161.32	2.05
15YL38-1-17	544.46	1116.16	0.49	0.05049	0.00017	0.18100	0.00292	0.02590	0.00037	4.68	216.74	12.04	168.92	2.51	164.86	2.33
15YL38-1-18	789.94	1224.86	0.64	0.04935	0.00009	0.17534	0.00203	0.02573	0.00029	2.21	164.90	0.92	164.04	1.76	163.75	1.83
15YL38-1-19	437.26	982.22	0.45	0.04942	0.00010	0.17647	0.00231	0.02587	0.00034	2.24	168.60	3.70	165.02	1.99	164.64	2.14
15YL38-1-2	508.52	974.32	0.52	0.05000	0.00011	0.17449	0.00219	0.02526	0.00030	2.75	194.53	10.18	163.31	1.89	160.84	1.91
15YL38-1-20	668.16	1126.42	0.59	0.04951	0.00010	0.17795	0.00241	0.02603	0.00035	2.17	172.31	3.71	166.30	2.08	165.68	2.20
15YL38-1-21	487.02	1046.09	0.47	0.04961	0.00012	0.17786	0.00259	0.02600	0.00039	2.10	176.01	8.33	166.22	2.23	165.44	2.46
15YL38-1-22	652.01	984.42	0.66	0.05195	0.00026	0.18633	0.00314	0.02586	0.00032	3.99	283.40	11.11	173.49	2.69	164.62	2.02
15YL38-1-23	303.72	767.40	0.40	0.04964	0.00012	0.17803	0.00224	0.02600	0.00033	1.69	188.97	5.56	166.36	1.93	165.45	2.06
15YL38-1-24	1028.87	1787.50	0.58	0.05004	0.00010	0.17906	0.00194	0.02593	0.00027	2.00	198.23	10.18	167.26	1.68	165.03	1.69
15YL38-1-25	637.71	1011.69	0.63	0.04956	0.00012	0.17806	0.00255	0.02605	0.00037	1.50	176.01	10.19	166.39	2.20	165.76	2.31
15YL38-1-3	623.01	1142.25	0.55	0.05152	0.00038	0.17809	0.00371	0.02491	0.00037	4.49	264.88	12.04	166.42	3.20	158.60	2.33
15YL38-1-5	601.41	1070.10	0.56	0.04951	0.00009	0.17560	0.00225	0.02567	0.00032	2.48	172.31	3.71	164.26	1.94	163.39	2.01
15YL38-1-6	685.81	1125.41	0.61	0.04890	0.00008	0.17364	0.00205	0.02571	0.00030	2.12	142.68	3.70	162.57	1.78	163.64	1.90
15YL38-1-7	547.31	1107.31	0.49	0.04993	0.00012	0.17772	0.00270	0.02577	0.00040	4.55	190.82	5.56	166.10	2.33	164.04	2.49
15YL38-1-8	638.96	1200.51	0.53	0.04931	0.00009	0.17703	0.00220	0.02600	0.00033	3.57	161.20	(0.92)	165.50	1.90	165.47	2.06
15YL38-1-9	795.19	1258.96	0.63	0.04910	0.00011	0.17536	0.00189	0.02585	0.00027	2.59	153.79	10.19	164.06	1.64	164.54	1.68
15YL40-1-1	358.68	1140.05	0.31	0.05499	0.00045	0.22502	0.00358	0.02947	0.00027	4.50	413.01	18.52	206.08	2.97	187.25	1.70
15YL40-1-10	372.00	621.29	0.60	0.05289	0.00075	0.21276	0.00530	0.02892	0.00040	3.84	324.13	33.33	195.87	4.44	183.78	2.53
15YL40-1-11	444.47	1456.14	0.31	0.04990	0.00009	0.20973	0.00281	0.03046	0.00039	2.59	190.82	3.70	193.33	2.36	193.41	2.46
15YL40-1-13	768.17	1757.84	0.44	0.05052	0.00019	0.20599	0.00281	0.02952	0.00034	3.29	220.44	9.26	190.18	2.37	187.52	2.14
15YL40-1-14	596.26	1782.88	0.33	0.04962	0.00007	0.20696	0.00236	0.03025	0.00035	1.98	176.01	8.33	191.00	1.99	192.11	2.17
15YL40-1-15	605.83	2039.05	0.30	0.04967	0.00007	0.20639	0.00283	0.03013	0.00041	2.13	188.97	3.70	190.52	2.39	191.35	2.58
15YL40-1-16	191.94	560.95	0.34	0.04976	0.00012	0.20605	0.00275	0.03003	0.00040	1.63	183.42	0.92	190.23	2.32	190.75	2.51
15YL40-1-17	390.92	748.99	0.52	0.04979	0.00014	0.20943	0.00278	0.03049	0.00038	0.54	183.42	0.92	193.07	2.34	193.59	2.36
15YL40-1-19	323.96	702.37	0.46	0.05171	0.00020	0.21538	0.00306	0.03010	0.00035	2.82	272.29	7.41	198.06	2.56	191.16	2.17
15YL40-1-2	437.80	1404.88	0.31	0.05080	0.00016	0.20800	0.00285	0.02964	0.00035	3.69	231.55	2.78	191.87	2.40	188.31	2.22
15YL40-1-21	510.31	1257.63	0.41	0.04980	0.00027	0.20845	0.00351	0.03034	0.00048	14.13	187.12	12.96	192.25	2.95	192.69	2.98
15YL40-1-22	422.73	802.33	0.53	0.04980	0.00009	0.20890	0.00272	0.03040	0.00038	1.47	187.12	0.92	192.63	2.29	193.06	2.41
15YL40-1-23	671.30	1295.89	0.52	0.05046	0.00009	0.21131	0.00255	0.03034	0.00035	2.43	216.74	3.70	194.65	2.14	192.68	2.17
15YL40-1-24	148.40	368.95	0.40	0.04973	0.00017	0.20665	0.00318	0.03015	0.00046	2.15	188.97	7.41	190.74	2.68	191.46	2.89
15YL40-1-3	363.16	1285.72	0.28	0.04971	0.00008	0.20646	0.00223	0.03012	0.00032	1.65	188.97	3.70	190.58	1.89	191.29	2.00
15YL40-1-4	593.25	2052.31	0.29	0.05454	0.00047	0.22811	0.00415	0.03012	0.00035	9.90	394.50	20.37	208.64	3.43	191.31	2.18
15YL40-1-5	303.70	1074.16	0.28	0.05370	0.00011	0.22423	0.00313	0.03026	0.00040	6.32	366.72	3.70	205.42	2.60	192.15	2.50
15YL40-1-6	405.58	1512.44	0.27	0.04971	0.00007	0.20801	0.00255	0.03034	0.00037	2.35	188.97	(2.78)	191.88	2.15	192.66	2.30
15YL40-1-7	539.57	1087.40	0.50	0.04979	0.00008	0.20620	0.00283	0.03003	0.00041	1.58	187.12	0.92	190.36	2.39	190.71	2.54
15YL40-1-8	380.89	1427.80	0.27	0.04968	0.00008	0.20888	0.00256	0.03050	0.00037	1.74	188.97	3.70	192.61	2.15	193.66	2.35
15YL40-1-9	467.53	1337.95	0.35	0.05003	0.00007	0.21045	0.00228	0.03050	0.00033	2.28	198.23	1.85	193.93	1.91	193.69	2.04

TABLE 2. Lu-Hf DATA FOR ZIRCONS FROM THE SAMPLES OF THE HEILONGJIANG COMPLEX

Sample	¹⁷⁶ Hf/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf (2σ)	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Lu/ ¹⁷⁷ Hf (2σ)	¹⁷⁶ Yb/ ¹⁷⁷ Hf	¹⁷⁶ Yb/ ¹⁷⁷ Hf (2σ)	Age (Ma)	<i>T</i> _(DM) (Ga)	<i>T</i> _(DM) (1σ)	Hf i I = 1.865x	Epsilon (t)
15YL10-1-1	0.282883	0.000014	0.001403	0.000012	0.035105	0.000410	187.80	0.53	0.03	0.282878	7.88
15YL10-1-2	0.282895	0.000016	0.001405	0.000021	0.032449	0.000396	188.00	0.49	0.04	0.282895	8.49
15YL10-1-3	0.282959	0.000018	0.001390	0.000017	0.032637	0.000378	179.76	0.42	0.04	0.282954	10.38
15YL10-1-4	0.282916	0.000013	0.001133	0.000007	0.027297	0.000192	188.66	0.48	0.03	0.282912	9.09
15YL10-1-5	0.282892	0.000020	0.000896	0.000006	0.020968	0.000126	185.45	0.51	0.05	0.282892	4.24
15YL10-1-6	0.282934	0.000014	0.001031	0.000005	0.025181	0.000095	185.66	0.45	0.03	0.282930	9.68
15YL10-1-7	0.282909	0.000016	0.001302	0.000027	0.031041	0.000586	185.95	0.49	0.04	0.282905	8.78
15YL10-1-8	0.282932	0.000014	0.001047	0.000005	0.025031	0.000107	187.40	0.46	0.03	0.282928	9.65
15YL10-1-9	0.282956	0.000016	0.001504	0.000012	0.037100	0.000329	183.12	0.43	0.04	0.282951	10.34
15YL10-1-10	0.282896	0.000015	0.000761	0.000002	0.018381	0.000079	182.64	0.50	0.03	0.282893	8.30
15YL12-4-1	0.282829	0.000023	0.002464	0.000044	0.062823	0.001115	184.11	0.63	0.05	0.282820	5.74
15YL12-4-2	0.282917	0.000017	0.001852	0.000058	0.048315	0.001456	181.46	0.49	0.04	0.282910	8.88
15YL12-4-3	0.282918	0.000013	0.001970	0.000045	0.052278	0.001257	185.77	0.49	0.03	0.282911	9.00
15YL12-4-4	0.282897	0.000015	0.001701	0.000024	0.046067	0.000577	184.00	0.51	0.03	0.282891	8.26
15YL12-4-5	0.282894	0.000016	0.002168	0.000038	0.057283	0.000907	185.76	0.53	0.04	0.282887	8.14
15YL12-4-6	0.282936	0.000024	0.001894	0.000025	0.047914	0.000878	186.17	0.46	0.06	0.282930	9.66
15YL12-4-7	0.282922	0.000013	0.001721	0.000016	0.044059	0.000265	185.16	0.48	0.03	0.282916	9.17
15YL12-4-8	0.282900	0.000014	0.001983	0.000032	0.052772	0.000769	183.69	0.51	0.03	0.282893	8.32
15YL12-4-9	0.282901	0.000018	0.002307	0.000015	0.060753	0.000364	181.44	0.52	0.04	0.282893	8.25
15YL12-4-10	0.282944	0.000017	0.002122	0.000019	0.055502	0.000474	185.80	0.45	0.04	0.282937	9.91
15YL12-4-11	0.282881	0.000026	0.003309	0.000096	0.087368	0.002738	181.59	0.56	0.06	0.282870	7.45
15YL12-4-12	0.282960	0.000020	0.001530	0.000023	0.038912	0.000642	184.95	0.42	0.04	0.282954	10.51
15YL14-1-1	0.282731	0.000016	0.000731	0.000014	0.020240	0.000402	181.49	0.74	0.04	0.282728	2.44
15YL14-1-2	0.282709	0.000020	0.000895	0.000008	0.023284	0.000215	183.76	0.77	0.05	0.282706	1.68
15YL14-1-3	0.282757	0.000015	0.000739	0.000007	0.019582	0.000188	184.74	0.70	0.03	0.282754	3.43
15YL14-1-4	0.282695	0.000015	0.001008	0.000017	0.026331	0.000361	178.22	0.79	0.03	0.282691	1.06
15YL14-1-5	0.282711	0.000023	0.000812	0.000030	0.021222	0.000805	186.27	0.76	0.05	0.282708	1.84
15YL14-1-6	0.282704	0.000020	0.000931	0.000015	0.024838	0.000429	182.98	0.78	0.05	0.282701	1.51
15YL14-1-7	0.282734	0.000017	0.000720	0.000023	0.016859	0.000726	181.96	0.73	0.04	0.282732	2.57
15YL14-1-8	0.282748	0.000013	0.001029	0.000004	0.027975	0.000135	183.35	0.72	0.03	0.282745	3.05
15YL14-1-9	0.282723	0.000037	0.001364	0.000061	0.035447	0.001702	178.22	0.76	0.08	0.282718	2.00
15YL14-1-10	0.282733	0.000012	0.000841	0.000003	0.022348	0.000046	184.07	0.73	0.03	0.282730	2.55
15YL18-4-1	0.282753	0.000016	0.001159	0.000007	0.030280	0.000123	184.58	0.71	0.04	0.282749	3.22
15YL18-4-2	0.282754	0.000016	0.001056	0.000010	0.028018	0.000275	184.30	0.71	0.04	0.282750	3.28
15YL18-4-3	0.282738	0.000018	0.001173	0.000052	0.032326	0.001862	181.85	0.73	0.04	0.282734	2.66
15YL18-4-4	0.282742	0.000021	0.001793	0.000019	0.049316	0.000507	185.89	0.74	0.05	0.282736	2.79
15YL18-4-5	0.282702	0.000024	0.000955	0.000036	0.025480	0.001071	178.37	0.78	0.05	0.282699	1.33
15YL18-4-6	0.282689	0.000019	0.001418	0.000052	0.038335	0.001477	179.00	0.81	0.04	0.282685	0.83
15YL18-4-7	0.282728	0.000021	0.001220	0.000026	0.032904	0.000927	178.39	0.75	0.05	0.282724	2.22
15YL18-4-8	0.282708	0.000018	0.001083	0.000017	0.028353	0.000467	178.08	0.78	0.04	0.282704	1.51
15YL18-4-9	0.282757	0.000027	0.001890	0.000082	0.059213	0.003357	179.54	0.72	0.06	0.282751	3.18
15YL18-4-10	0.282707	0.000015	0.001858	0.000062	0.048971	0.001667	180.50	0.79	0.03	0.282701	1.43
15YL18-4-11	0.282776	0.000021	0.001994	0.000049	0.055195	0.001358	183.22	0.69	0.05	0.282769	3.93
15YL28-1-1	0.282814	0.000021	0.000976	0.000014	0.024596	0.000371	185.80	0.62	0.05	0.282811	5.46
15YL28-1-2	0.282797	0.000016	0.001220	0.000010	0.030880	0.000239	183.39	0.65	0.04	0.282793	4.78
15YL28-1-3	0.282806	0.000017	0.000918	0.000002	0.022988	0.000070	184.90	0.63	0.04	0.282803	5.16
15YL28-1-4	0.282832	0.000016	0.000878	0.000003	0.022257	0.000040	185.15	0.60	0.04	0.282829	6.09
15YL28-1-5	0.282820	0.000016	0.000900	0.000005	0.023168	0.000160	186.36	0.61	0.04	0.282816	5.66
15YL28-1-6	0.282796	0.000018	0.001122	0.000025	0.028338	0.000707	186.51	0.65	0.04	0.282792	4.81
15YL28-1-7	0.282829	0.000015	0.001086	0.000006	0.027573	0.000173	187.21	0.60	0.03	0.282826	6.00
15YL28-1-8	0.282790	0.000029	0.001106	0.000007	0.027666	0.000214	186.23	0.66	0.07	0.282786	4.57
15YL28-1-9	0.282788	0.000049	0.000871	0.000006	0.021954	0.000199	184.69	0.66	0.11	0.282785	4.53
15YL28-1-10	0.282781	0.000017	0.000710	0.000003	0.017658	0.000095	183.25	0.66	0.04	0.282779	4.27

Note: TDM = 1/λ×ln(1+[(¹⁷⁶Hf/¹⁷⁷Hf)_S-(¹⁷⁶Hf/¹⁷⁷Hf)_{DM}]/[(¹⁷⁶Lu/¹⁷⁷Hf)_S-(¹⁷⁶Lu/¹⁷⁷Hf)_{DM}]). S—Sample; DM—depleted mantle; t—Measured zircon U-Pb ages. λ = 1.865×10⁻¹¹ a⁻¹. The (¹⁷⁶Hf/¹⁷⁷Hf)_{DM} and (¹⁷⁶Lu/¹⁷⁷Hf)_{DM} at present are 0.283251 and 0.0384, respectively. TCDM = 1/λ×ln(1+[(¹⁷⁶Hf/¹⁷⁷Hf)_S-(¹⁷⁶Hf/¹⁷⁷Hf)_{DM}]/[(¹⁷⁶Lu/¹⁷⁷Hf)_S-(¹⁷⁶Lu/¹⁷⁷Hf)_{DM}]). C—Crust. (¹⁷⁶Lu/¹⁷⁷Hf)_C = 0.015. (¹⁷⁶Hf/¹⁷⁷Hf)_i = (¹⁷⁶Hf/¹⁷⁷Hf)_S-(¹⁷⁶Lu/¹⁷⁷Hf)_S(e^{λt}-1). εHf(t) = 10000×[(¹⁷⁶Hf/¹⁷⁷Hf)_S-(¹⁷⁶Lu/¹⁷⁷Hf)_S(e^{λt}-1)]/[(¹⁷⁶Hf/¹⁷⁷Hf)_{CHUR}-(¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR}(e^{λt}-1)]. CHUR—Chondrite. The (¹⁷⁶Hf/¹⁷⁷Hf)_{CHUR} and (¹⁷⁶Lu/¹⁷⁷Hf)_{CHUR} at present are 0.282772 and 0.0332, respectively.

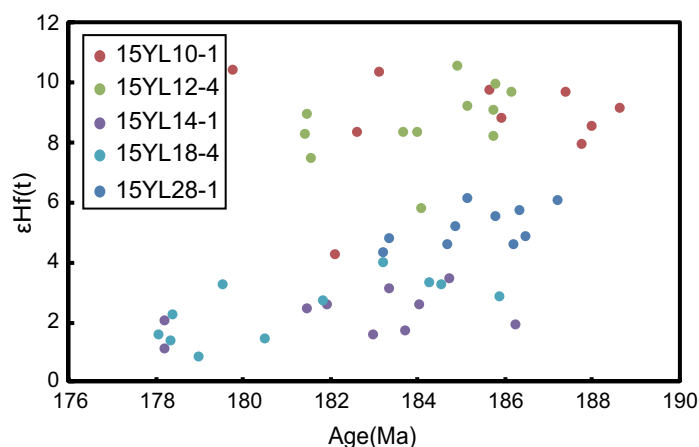


Figure 5. Plots of $\epsilon_{\text{Hf}}(t)$ versus age of representative samples.

gives a similar age of 182.7 ± 1.1 Ma with $\epsilon_{\text{Hf}}(t)$ values ranging from 0.83 to 3.93 (Figs. 4D and 5; Table 2).

Two samples, including one granodiorite (15YL10-1) and one granite (15YL12-4) from the central part of the area, yielded weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 185.54 ± 0.92 Ma and 184.19 ± 0.77 Ma, respectively (Figs. 4A, 4B); zircons have positive $\epsilon_{\text{Hf}}(t)$ values of 5.74–10.51 and 4.29–10.28, respectively (Fig. 5; Table 2).

A few silicic samples were dated from the Jilin area in the southern Zhangguangcailing orogen (Fig. 2B). A granodiorite sample (15YL38-1) yielded a young zircon $^{206}\text{Pb}/^{238}\text{U}$ age of 163.0 ± 1.2 Ma (Fig. 4G). To the southwest of the locality, zircons from one monzonite granite (15YL36-5) yielded a weighted age of 191.4 ± 1.2 Ma (Fig. 4F). Another monzonite granite (15YL40-1) gave a similar zircon $^{206}\text{Pb}/^{238}\text{U}$ age of 191.0 ± 1.2 Ma (Fig. 4H).

Whole-Rock Major and Trace Element Results

All the analyzed samples plot in the fields of monzonite, granodiorite, granite, and quartz diorite. All the granitic samples have variable major oxides with $\text{SiO}_2 = 65.14$ to 73.75 wt%, $\text{CaO} = 1.24$ – 3.47 wt%, $\text{Al}_2\text{O}_3 = 13.67$ – 15.85 wt%, $\text{Fe}_2\text{O}_3\text{t} = 1.81$ – 4.85 wt%, and total alkali (K_2O and Na_2O) from 6.42 to 8.41 wt% (Table 3; Fig. 6). These characteristics, together with $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios of 0.88 – 1.29 , suggest that most of the granites belong to the high-K calc-alkaline series (Fig. 7A). They have A/CNK values [molar $\text{Al}_2\text{O}_3/(\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O})$] of 0.93 – 1.04 , i.e., <1.1 , indicating that they are metaluminous granites (Fig. 7B). Most samples have Na_2O contents (>3.2 wt%) higher than those of S-type granites; this demonstrates an affinity with I-type granites. All samples have similar chondrite-normalized REE patterns, an enrichment in light (L) REEs [i.e., $(\text{La}/\text{Yb})_{\text{N}} = 9.38$ – 31.74], and weak to moderate negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.39$ – 0.93 ; Fig. 7A). In a primitive mantle-normalized spidergram, they display negative Nb, Ta, Ti anomalies and a strong Pb enrichment (Fig. 8B).

Several tectono-magmatic discrimination diagrams are used to interpret the tectonic setting of the granitoids from the Zhangguangcailing orogen. The rocks plot within the volcanic arc–granite fields, as shown in the Y versus Nb diagram (Fig. 7C; Pearce et al., 1984) and the Rb/30–Hf–Tax3 ternary plot of Harris et al. (1986). In an Sr/Y versus Y diagram all samples have low Sr/Y and high Y contents, and plot within the volcanic arc field (Fig. 7E).

Whole-Rock Sr–Nd Isotopes

Whole-rock Sr–Nd isotopic data are listed in Table 3. Initial isotopic ratios were calculated for the crystallization age of the granites. All rocks

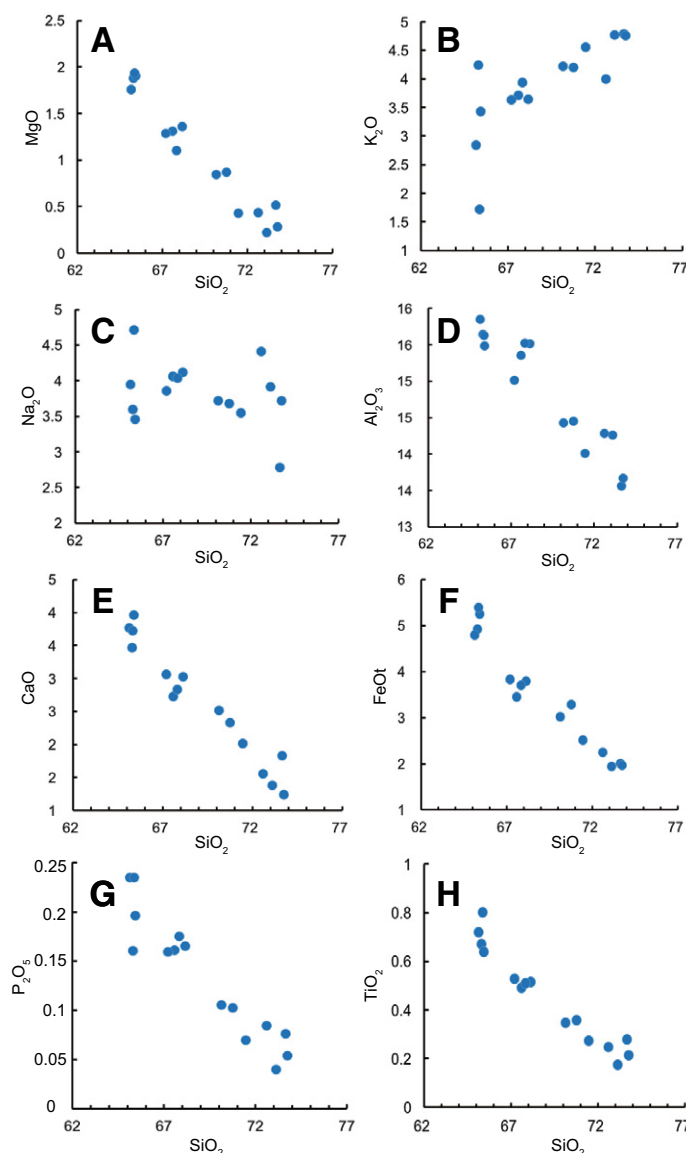


Figure 6. SiO_2 versus major elements.

show a considerable range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.706525 – 0.712784) and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.705349 and 0.704338 . In terms of Nd isotopic ratios, the granitic rocks are characterized by positive to slightly negative initial $\epsilon_{\text{Nd}}(t)$ values ranging from 1.0 to -1.2 and positive $\epsilon_{\text{Nd}}(t)$ values with the range of 1.6 – 3.1 .

DISCUSSION

Petrogenesis of the I-Type Granites

All granitoid samples from the Zhangguangcailing orogen have chemical characteristics typical of high-K calc-alkaline I-type granitoids, as indicated by their metaluminous nature and the presence of hornblende. The origin of high-K calc-alkaline granitoids has long been a subject of debate; two main models have been proposed to interpret their petrogenesis: (1) pure crustal melts from partial melting of mafic lower crust at relatively high pressures, or (2) evolution of a mixture of crustal- and mantle-derived magmas. Samples from the Zhangguangcailing orogen show the typical arc magma

TABLE 3. MAJOR AND TRACE ELEMENT AND Si-nd ISOTOPIC DATA FOR GRANITIC ROCKS FROM THE ZHANGGUANGCAILING OROGEN

	15YL10-1		15YL36-2	15YL18-2	15YL14-4	15YL28-1	15YL36-5	15YL40-2	15YL41-5	15YL10-5	15YL14-2	15YL36-4	15YL38-2	15YL38-3	15YL40-4
	granodiorite	granite	granodiorite	granodiorite	granite	granite	monzogranite	monzogranite	granodiorite	granodiorite	granodiorite	monzogranite	granodiorite	granodiorite	granite
SiO ₂	68.14	70.76	65.14	66.14	73.65	70.14	73.75	72.61	65.35	67.58	67.20	73.12	65.41	67.82	71.45
TiO ₂	0.515	0.359	0.720	0.720	0.279	0.346	0.213	0.248	0.802	0.492	0.529	0.173	0.639	0.511	0.273
Al ₂ O ₃	15.52	14.45	15.85	15.85	13.56	14.43	13.67	14.28	15.63	15.36	15.01	14.26	15.48	15.52	14.01
Fe ₂ O ₃	3.41	2.95	4.32	4.32	1.81	2.71	1.77	2.02	4.85	3.11	3.45	1.75	4.72	3.34	2.27
FeO _{3T}	3.79	3.28	4.79	4.79	2.01	3.02	1.97	2.24	5.39	3.45	3.83	1.94	5.25	3.71	2.52
MnO	0.062	0.052	0.065	0.065	0.052	0.059	0.040	0.064	0.091	0.061	0.051	0.033	0.078	0.055	0.037
MgO	1.36	0.867	1.76	1.76	0.514	0.848	0.283	0.435	1.94	1.31	1.29	0.223	1.91	1.10	0.426
CaO	3.03	2.33	3.76	3.76	1.83	2.51	1.24	1.55	3.73	2.73	3.06	1.38	3.96	2.83	2.02
Na ₂ O	4.12	3.68	3.94	3.94	2.78	3.71	3.72	4.41	4.71	4.06	3.85	3.91	3.46	4.04	3.54
K ₂ O	3.65	4.20	2.84	2.84	4.79	4.22	4.75	3.99	1.71	3.71	3.63	4.77	3.43	3.94	4.56
P ₂ O ₅	0.165	0.102	0.235	0.235	0.076	0.106	0.054	0.084	0.235	0.161	0.159	0.040	0.196	0.175	0.070
LOI	0.52	0.58	0.79	0.79	0.57	0.79	0.60	0.39	0.62	0.90	1.66	0.43	0.74	0.55	1.32
Mg#	39.27	32.23	39.77	39.77	31.51	33.60	20.57	25.88	39.28	40.57	37.73	17.14	39.55	34.85	23.35
Sc	5.52	6.29	5.89	5.89	3.82	5.11	3.71	3.75	7.46	5.45	5.84	4.32	8.44	6.87	2.86
V	60.25	39.89	68.20	68.20	18.01	31.98	10.01	14.01	50.27	55.42	61.18	72.33	80.79	43.57	10.05
Cr	9.12	9.73	15.47	15.47	25.05	10.83	4.55	4.42	36.19	9.27	9.59	14.79	28.12	13.05	6.38
Co	6.58	5.63	8.21	8.21	1.95	4.80	1.72	1.85	10.62	6.51	7.48	9.52	11.34	5.56	2.99
Ni	4.36	2.70	7.07	7.07	12.04	3.09	0.95	1.32	9.27	4.32	4.77	0.56	41.07	4.28	1.26
Mh	502.51	454.82	581.23	581.23	450.89	505.12	331.50	551.26	749.46	493.33	419.87	277.35	687.98	457.61	301.76
Cu	5.06	3.40	13.42	13.42	2.32	2.85	1.83	1.70	6.41	4.60	22.83	1.78	7.78	3.67	4.38
Zn	47.30	63.09	76.02	76.02	55.72	56.40	54.97	65.17	76.57	49.65	49.84	56.05	74.05	55.66	88.26
Ga	17.52	18.88	23.50	23.50	18.44	17.60	17.39	17.47	21.54	17.08	17.39	19.73	19.01	19.90	19.78
Cs	4.69	6.35	7.26	7.26	5.58	9.32	2.67	2.60	5.40	6.55	8.58	3.67	5.64	9.50	14.93
Rb	120.78	122.94	114.70	114.70	185.49	140.09	155.60	108.65	135.10	113.11	124.29	141.43	99.99	150.06	141.24
Ba	580.69	505.67	516.89	516.89	614.71	431.53	716.09	614.39	260.11	570.35	571.73	470.68	556.58	546.96	1213.82
Th	12.89	14.79	19.99	19.99	22.00	17.89	18.72	11.12	12.84	16.49	13.42	18.09	12.00	21.12	21.61
U	1.76	3.00	7.73	7.73	6.02	3.98	6.03	2.17	3.35	2.92	4.52	2.35	2.23	4.19	7.88
Nb	8.93	9.50	11.07	11.07	11.12	7.27	8.92	8.55	11.38	9.29	9.53	10.27	7.92	10.62	8.03
Ta	0.79	0.97	0.90	0.90	1.05	0.73	0.70	0.63	1.10	0.85	0.80	0.88	0.77	1.16	0.63
La	24.30	33.08	51.16	51.16	43.82	28.77	51.25	27.12	28.92	25.37	23.41	35.35	27.83	32.92	58.13
Ce	47.93	67.51	96.18	96.18	82.43	54.61	92.47	54.66	62.52	48.48	46.26	77.81	56.79	70.09	108.56
Pb	9.63	20.37	14.13	14.13	29.06	24.52	19.73	15.40	13.62	10.07	9.21	24.51	17.90	19.55	22.65
Pr	5.22	7.38	10.09	10.09	8.51	5.64	9.26	6.09	7.41	5.01	5.07	7.85	6.16	7.48	10.95
Sr	421.90	256.00	564.11	564.11	218.26	249.40	100.97	217.93	336.79	435.30	377.07	135.04	409.51	330.78	502.55
Nd	19.28	26.25	34.71	34.71	27.78	19.91	29.35	21.97	28.51	17.86	18.75	27.51	22.20	27.38	36.77
Zr	152.03	160.92	199.57	199.57	172.57	125.06	169.16	165.99	193.33	161.14	167.33	152.58	120.02	211.65	149.51
Hf	4.18	4.69	5.14	5.14	4.90	3.54	4.41	4.52	5.53	4.59	4.52	4.58	3.15	5.75	4.26
Sm	3.46	4.91	5.42	5.42	4.62	3.55	4.88	3.98	5.85	3.14	3.43	4.99	4.16	5.21	4.98
Eu	0.94	0.77	1.21	1.21	0.70	0.73	0.55	0.83	1.12	0.88	0.91	0.59	1.00	1.03	0.95
Ti	3012.32	2345.09	5041.45	5041.45	1789.40	2221.97	1314.67	1613.89	5162.75	2941.17	3187.92	1065.07	4128.51	3182.89	1645.86
Gd	2.77	4.01	3.90	3.90	3.70	2.83	4.07	3.18	4.85	2.51	2.72	4.80	3.42	4.25	3.31
Tb	0.42	0.63	0.52	0.52	0.60	0.43	0.66	0.50	0.74	0.38	0.42	0.76	0.50	0.66	0.45
Dy	2.38	3.67	2.57	2.57	3.57	2.44	3.96	2.95	4.13	2.15	2.42	4.38	2.81	3.66	2.31
Y	13.41	20.54	13.87	13.87	23.14	14.17	24.84	17.72	22.63	12.32	13.43	25.57	16.40	20.31	13.72
Ho	0.46	0.72	0.46	0.46	0.75	0.47	0.81	0.58	0.77	0.42	0.47	0.86	0.53	0.70	0.45
Er	1.42	2.10	1.28	1.28	2.38	1.40	2.51	1.78	2.22	1.31	1.43	2.60	1.55	2.05	1.40
Tm	0.21	0.31	0.18	0.18	0.38	0.21	0.38	0.26	0.32	0.21	0.22	0.32	0.22	0.30	0.21
Yb	1.48	2.04	1.16	1.16	2.68	1.43	2.62	1.81	2.11	1.40	1.48	2.53	1.47	1.97	1.42
Lu	0.23	0.30	0.17	0.17	0.41	0.22	0.40	0.27	0.31	0.22	0.23	0.37	0.22	0.29	0.22

(continued)

TABLE 3. MAJOR AND TRACE ELEMENT AND Sr-Nd ISOTOPIC DATA FOR GRANITIC ROCKS FROM THE ZHANGGUANGCAILING OROGEN (continued)

Age (Ma)	185.54	184.19	182.7	182	190	190	191	189
$^{87}\text{Rb}/^{86}\text{Sr}$	0.82898	0.79348	0.61365	1.27727	1.31365	0.81378	3.05837	1.27551
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70652	0.70648	0.70645	0.70827	0.70838	0.70755	0.71278	0.70810
$^{87}\text{Sr}/^{86}\text{Sr}$ (i)	0.70434	0.70440	0.70486	0.70493	0.70483	0.70535	0.70448	0.70467
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1086	0.1101	0.1252	0.1089	0.1151	0.0819	0.1106	0.1224
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51269	0.51269	0.51268	0.51263	0.51262	0.51258	0.51262	0.51263
$^{143}\text{Nd}/^{144}\text{Nd}$ (i)	0.512557	0.512559	0.512531	0.512496	0.512477	0.512475	0.512480	0.512481
$\varepsilon\text{Nd}(0)$	1.0	1.0	0.8	-0.2	-0.4	-1.2	-0.4	-0.2
$\varepsilon\text{Nd}(t)$	3.1	3.1	2.5	1.9	1.6	1.6	1.7	1.6
Jsm/Nd	-0.448	-0.440	-0.364	-0.446	-0.415	-0.583	-0.438	-0.378
TDM2(Ma)	729	728	776	829	854	856	847	853
TDM2(Ga)	0.725	0.723	0.760	0.823	0.844	0.872	0.840	0.837

Note: $\varepsilon\text{Nd} = [({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{sample}} / ({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{CHUR}} - 1] \times 10,000$, $\text{Jsm}/\text{Nd} = [({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{sample}} / ({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{CHUR}} - 1]$, $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{CHUR}} = 0.512638$, and $({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{CHUR}} = 0.1967$. The model ages were calculated using a linear isotopic ratio growth equation: $\text{TDM} = 1/\lambda \ln \{ [({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{sample}} - 0.51315] / [({}^{147}\text{Sm}/{}^{144}\text{Nd})_{\text{sample}} - 0.2137] \}$.

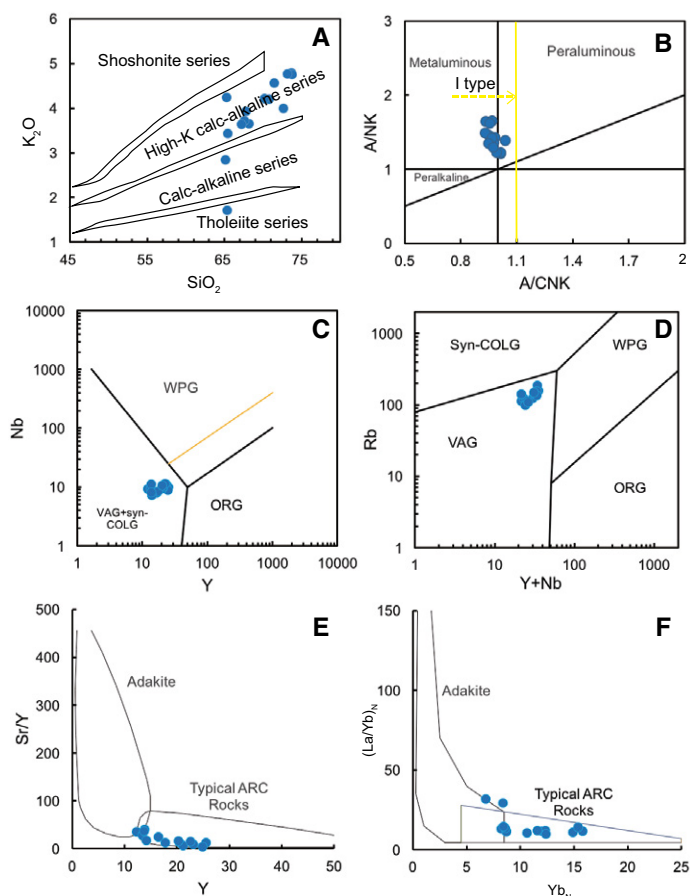


Figure 7. Geochemical classification of the granitic samples. (A) K_2O versus SiO_2 (Peccerillo and Taylor, 1976). (B) A/NK [molar ratio $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$] versus A/CNK [molar ratio $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$] diagram. (C) Plots of Nb versus Y . WPG—within plate granites; ORG—ocean ridge granites; VAG—volcanic arc granites; COLG—collision granites. (D) Rb versus $\text{Y} + \text{Nb}$ for granitoids. (E) Sr/Y versus Y discrimination diagram for adakites. (F) $(\text{La}/\text{Yb})_{\text{N}}$ versus Yb_{N} discrimination diagram for adakites.

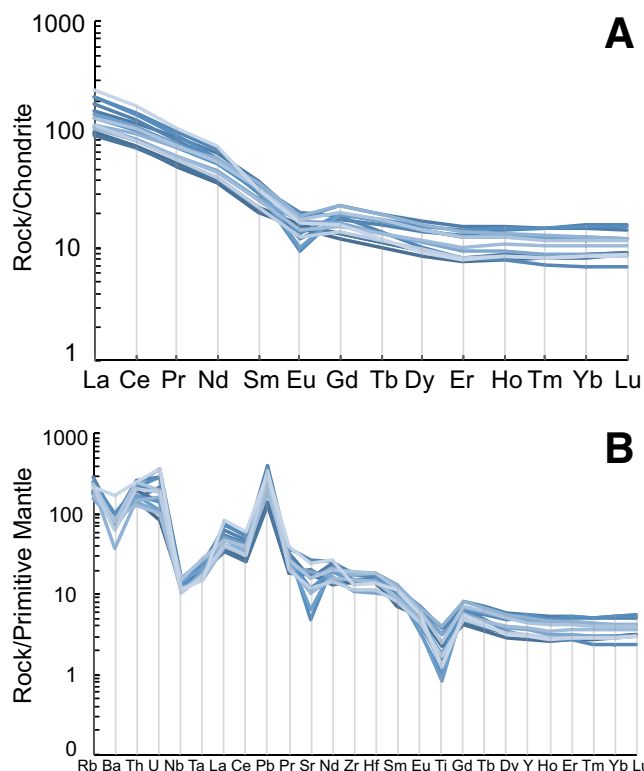


Figure 8. (A) Chondrite normalized rare earth element patterns. (B) Primitive mantle-normalized trace elements patterns for the granitic samples.

signature, including LREE enriched patterns with strong negative Eu anomalies, distinctive Ta-Nb-Ti anomalies, positive zircon $\epsilon_{\text{Hf}}(t)$ (0.83–10.51), Neoproterozoic crustal model ages (0.65–1.17 Ga), and positive $\epsilon_{\text{Nd}}(t)$ values (1.6–3.1; Table 2). Therefore, an origin from the lower crust can be ruled out for the granitoids within the Zhangguangcailing orogen. Instead, a high proportion of juvenile or mantle-derived material was involved in the formation of the granitic rocks. The bulk-rock Sr and Nd isotopic compositions [$I_{\text{Sr}} = 0.704338\text{--}0.705349$, $\epsilon_{\text{Nd}}(t) = 1.6\text{--}3.1$], which plot on a curve using Sr-Nd isotopic modeling, suggest that the parental melts of the granitoids were possibly derived from interaction between depleted mantle and lower crust that was composed of subducted oceanic crust, a seamount, an accretionary complex, and a sedimentary cover sequence (Fig. 9A). This interpretation is also consistent with the idea that I-type granitoids were formed by the reworking of sedimentary materials by mantle-like magmas (Kemp et al., 2007). Therefore, the I-type, high-K calc-alkaline granitoids from the Zhangguangcailing orogen were most likely generated from lower crustal material heated by, and mixed to some degree with, contemporaneous, underplated, and/or intruded depleted mantle-derived magmas.

However, hybrid melts with variable contributions of predominantly mantle-derived materials and lower crust-derived components alone are insufficient to explain the bulk-rock geochemistry of the Zhangguangcailing orogen granitoids. Significant fractional crystallization has played a role in the evolution of the granitoids, as indicated by geochemical indices such as silica enrichment and depletion in Ba, Nb, Ta, Sr, and Ti (Fig. 8B). The negative correlations of CaO, FeO, and MgO with SiO_2 may reflect clinopyroxene fractionation (Fig. 6). The increase of K_2O with increasing SiO_2 indicates that K-feldspar was not an early fractionation phase. Separation of Ti-bearing phases (such as ilmenite and titanite) and apatite resulted in strong depletion in Nb-Ta-Ti and P, respectively. The small negative Eu anomaly implies that plagioclase fractionation played a role in their genesis.

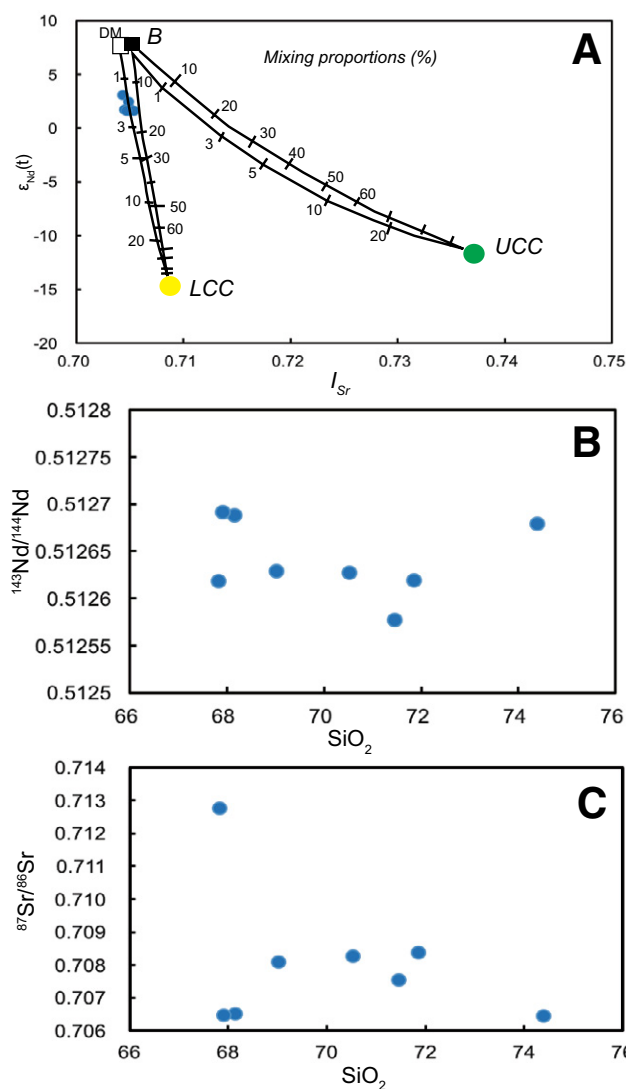


Figure 9. (A) Plot of $\epsilon_{\text{Nd}}(t)$ versus I_{Sr} isotopic ratios showing mixing proportions between two end members: depleted mantle or juvenile components (DM—upper mantle peridotite; or B—basalt) and crustal components (LCC—lower continental crust; or UCC—upper continental crust, both of which are represented by the Mashan Group gneisses in the Jiamusi block). (B) $^{143}\text{Nd}/^{144}\text{Nd}$ versus SiO_2 . (C) $^{87}\text{Sr}/^{86}\text{Sr}$ versus SiO_2 for the granitic samples.

However, upper crustal contamination was inevitable during the ascent of the magmas, as indicated by the strong enrichments in Th (14.5–21.6) and Pb (9.2–29.1). Unlike fractional crystallization and crustal contamination, assimilation plays a minor role in the generation of magmas, as indicated by the weak correlation between $^{143}\text{Nd}/^{144}\text{Nd}$ versus SiO_2 or $^{87}\text{Sr}/^{86}\text{Sr}$ versus SiO_2 (Figs. 9B, 9C). In summary, the parental melts of these I-type granitoids originated from interaction between lower crust materials and depleted mantle-derived magmas, and they underwent fractional crystallization and upper crustal contamination during their evolution.

Geochronology of the Granitoids in the Zhangguangcailing Orogen

Mapping and detailed field observations revealed that Mesozoic granitoids are widespread within the Zhangguangcailing orogen (Fig. 2B). However, the ages of these rocks have often been questioned due to the lack of high-quality age data. Recent reliable zircon U-Pb, Rb-Sr, and

Ar/Ar dating indicate that most of the Mesozoic granitoids formed between 230 and 163 Ma (Yang et al., 2012; Wu et al., 2002, 2003a). Among these, the 187–175 Ma granitoids consist of major I-type calc-alkaline and minor aluminous A-type granitoids; these granitoids are widespread and constitute more than 70% of total Jurassic igneous rocks (Fig. 10). Compared with massive 187–175 Ma granitoids, the 230–210 Ma A-type granitoids are less widespread and limited to the southeastern margin of the Zhangguangcailing orogen.

Geodynamic Scenario for the Jurassic Magmatism in the Zhangguangcailing Orogen

Immense volumes of Mesozoic granitoid rocks are widespread throughout the Zhangguangcailing orogen in northeastern China; their precise geochronological framework and origin have long been controversial (Wu et al., 2011). They were previously considered to be associated with the orogenic collapse of the Central Asian orogenic belt (Wu et al., 2002). However, these granitic rocks are aligned in a roughly north-south direction within the Zhangguangcailing orogen, different from the east-west distribution of the counterparts in the Central Asian orogenic belt (Wu et al., 2011). Some studies have proposed that most of these granitic rocks were likely related to subduction and collision between the Jiamusi and Songliao blocks, because their emplacement ages are comparable to the timing of blueschist facies metamorphism (180–170 Ma) from the Heilongjiang complex (Wu et al., 2011).

Recent data also suggest that the widespread Jurassic high-K I-type calc-alkaline granitoids in the Zhangguangcailing orogen were generated by subduction, as indicated by negative Nb and Ta and positive Pb anomalies, as well as enrichments in large ion lithophile elements (LILEs) and LREEs (Wu et al., 2002, 2003b; Yang et al., 2012). In addition, the isotopic compositions of these granitoids are thought to reflect a mixture of depleted mantle-derived and lower crustal-derived magmas. The coexistence of mature continental crust and mantle-derived melt in space and time are consistent with a tectonic setting that resembles an active continental margin (Zhu et al., 2009); that is, subduction of oceanic lithosphere beneath mature continental lithosphere leads to mantle-wedge melting that produces a basaltic melt (Zhu et al., 2009). This mantle melt will underplate or intrude the overlying mature continental crust, causing crustal melting and forming hybrid melts (Karsli et al., 2007, 2010; Li et al., 2007; Rapp and Watson, 1995).

In this regard, I-type granitoids from the Zhangguangcailing orogen were generated in an active continental margin during Early to Middle Jurassic time (191–163 Ma), suggesting that oceanic subduction between the Jiamusi and Songliao blocks may have begun in the Early Jurassic.

Other than the I-type granitoids, the Early Jurassic (ca. 190 Ma) A-type granitoid plutons (aluminous and peralkaline) constitute a small part of the Jurassic granitic magmatism, but they have identical Sr-Nd isotope characteristics, such as low $^{87}\text{Rb}/^{86}\text{Sr}$; I_{Sr} of 0.704–0.705; young Nd model ages of 860–720 Ma; and positive $\epsilon_{\text{Nd}}(t)$ of 3.1–1.6, suggesting they were derived from the same source as the I-type granitoids (Wu et al., 2002). The low Hf/Sm values (3.58–0.17) in these A-type granitic magmas suggest that they may have undergone metasomatism by fluids from subducted sediments during their ascent, because Hf/Sm ratios are immune to crustal contamination and reflect their source compositions (Ben Othman et al., 1989; Dupuy et al., 1992; Peters et al., 2008; Prelević et al., 2012; Weyer et al., 2003; Wu et al., 2002). Moreover, the coeval mafic-ultramafic intrusions, composed of olivine-gabbro, hornblende, gabbro, hornblende-gabbro, and gabbro-diorite, are characterized by enrichments in LILEs and depletions in high field strength elements (i.e., Nb, Ta, Eu). Accordingly, they were likely derived from the partial

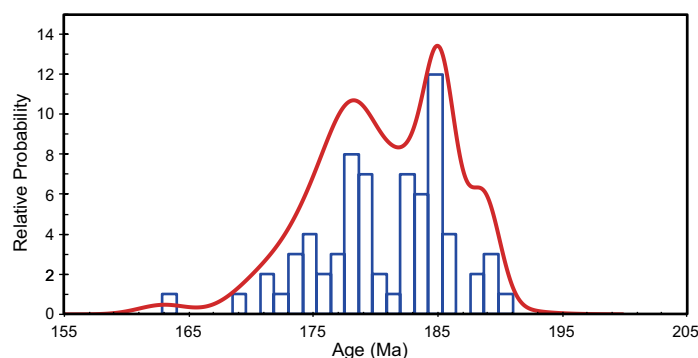


Figure 10. Compilation of current geochronological data for the Mesozoic granitic rocks from the Zhangguangcailing orogen.

melting of a depleted lithospheric mantle metasomatized by subducted slab-derived fluids (Yu et al., 2012), implying their possible association with an active continental margin setting (Guo et al., 2015). Thus, there was an active continental margin in and/or below the Zhangguangcailing orogen between the Jiamusi and Songliao blocks during Jurassic time.

RELATIONSHIPS BETWEEN THE JIAMUSI AND SONGLIAO BLOCKS FROM PERMIAN TO EARLY CRETACEOUS TIME

There is a broad consensus that the Heilongjiang complex, a high-pressure metamorphic belt constituting an important part of the Zhangguangcailing orogen between the Jiamusi and Songliao blocks, represents the remnant of an oceanic plate; however, the origin and evolution of this ocean remain unresolved (Wang et al., 2012b; Wu et al., 2011; Xu et al., 2009, 2013; Zhou et al., 2009, 2010a, 2010b; Zhu et al., 2015, 2016). Several competing models have been proposed, with one group suggesting that the oceanic subduction between the Jiamusi and Songliao blocks took place during Late Ordovician time, followed by Middle Silurian collision (Wang et al., 2012a, 2012b, 2014; Xu et al., 2009, 2013). However, this model has been challenged by the identification of a Mesozoic high-pressure metamorphic belt (Heilongjiang complex) as a remnant of oceanic crust between the Jiamusi and Songliao blocks (Wu et al., 2011; Zhou et al., 2010a, 2010b; Zhu et al., 2015, 2016).

We interpret the ocean between the Jiamusi and Songliao blocks as having evolved from an intracontinental rift, based on recent data from the blueschists, greenschists, amphibolites, and bimodal volcanic rocks (Zhu et al., 2015, 2016). Petrologic studies indicate that the protoliths of the blueschists, greenschists, and amphibolites are predominately tholeiitic mafic rocks, which were formed ca. 275–220 Ma and are characterized by enriched mid-oceanic ridge basalt (E-MORB) geochemical affinities (Zhou et al., 2009, 2010a, 2010b; Zhu et al., 2015, 2016). These tholeiitic mafic rocks contain numerous inherited or xenocrystic zircons with ages as old as 1300 Ma, precluding an origin by partial melting of the oceanic crust (Zhou et al., 2009, 2010a, 2010b; Zhu et al., 2015, 2016). Coeval with the tholeiitic mafic rocks were late Permian to Triassic bimodal igneous rocks; these represent products of crustal extension and are distributed along the Zhangguangcailing orogen (Meng et al., 2011; Wang et al., 2015; Yu et al., 2013). Extensive occurrence of mafic magmas and bimodal volcanic rocks testifies to significant crustal rifting during the late Permian to Early Triassic, which led to the opening of the Heilongjiang ocean that separated the Jiamusi block from the Songliao block (Zhou et al., 2009, 2010; Zhu et al., 2015, 2016). Some proposed that the Heilongjiang ocean was part of the paleo-Pacific Ocean, and expanding on this view, they interpreted the Jiamusi block as an exotic continental block

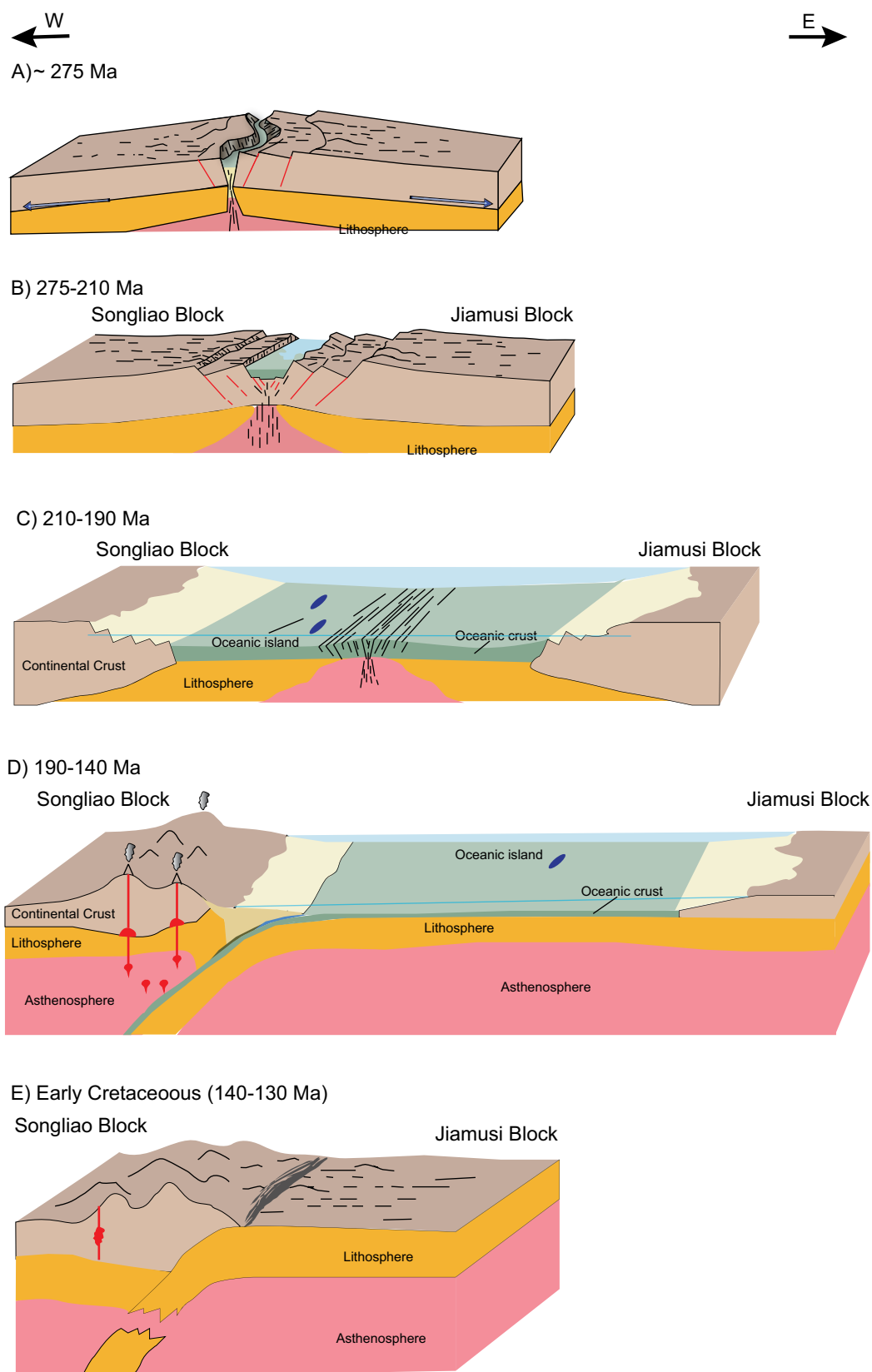


Figure 11. An updated scenario for our proposed model for the tectonic evolution of the Heilongjiang complex: (A) rifting began ca. 275 Ma between the Jiamusi and Zhangguangcailing orogen; (B) opening of an ocean between the two blocks; (C) the Heilongjiang ocean between the two blocks; (D) subduction between the Jiamusi and Songliao blocks; (E) closure of the Heilongjiang ocean between the two blocks.

(Wu et al., 2011). However, such a viewpoint fails to explain the E-MORB geochemical affinities of tholeiitic mafic magmas from the Heilongjiang complex and the massive 1300–500 Ma inherited or xenocrystic zircons therein (Zhou et al., 2009; Zhu et al., 2015, 2016). Therefore, we argue that the Heilongjiang ocean represents an intervening ocean evolving from continental rifting between the Jiamusi and Songliao blocks during the late Permian to Early Triassic (Figs. 11A, 11B).

As discussed herein, the oceanic subduction between the Jiamusi and Songliao blocks resulted in the formation of an active continental margin, indicated by the presence of ca. 191–163 Ma subduction-related I-type calc-alkaline granitoids in the Zhangguangcailing orogen. In addition to these granitoids, the Heilongjiang complex, the remnant of the oceanic plate (the Heilongjiang ocean) within the Zhangguangcailing orogen, provides more evidence for this model. The Heilongjiang complex has undergone blueschist facies to greenschist facies metamorphism resulting from subduction of the oceanic plate and tectonic exhumation. The timing of this metamorphism is constrained by mica Rb-Sr and $^{39}\text{Ar}/^{40}\text{Ar}$ methods to 167–184 Ma from the blueschists, supporting the interpretation that the oceanic subduction beneath the Songliao block took place in the Early to Middle Jurassic (Fig. 11D; Wu et al., 2011).

As for the amalgamation between the two blocks, previous studies interpreted the age of metamorphism as the time of termination of subduction, suggesting that ocean closure was between 210 and 180 Ma (Zhao et al., 2009; Zhou et al., 2010b). However, one greenschist sample from the Heilongjiang complex with a protolithic age of 162 Ma similarly has an OIB chemical signature, further indicative of an open ocean during its formation (Zhu et al., 2016). Recent identification of the protolith of a blueschist sample generated in an oceanic island ca. 141.8 ± 1 Ma indicates that the closure of the Heilongjiang ocean must have been after 142 ± 1 Ma (Zhu et al., 2015). In addition to the information from the Heilongjiang complex, the granitoid magmatism in the Zhangguangcailing orogen provides further constraints on the amalgamation between the Jiamusi and Songliao blocks. The Early Cretaceous granitoids (130–120 Ma) show within-plate geochemical affinities, possibly generated in an anorogenic setting (Wu et al., 2002); this may suggest that closure of the Heilongjiang ocean was completed, and the Zhangguangcailing orogen became an intracontinental orogen, in the Early Cretaceous (Fig. 11E). Thus, we propose that termination of subduction and collision processes between the Jiamusi and Songliao blocks took place in the earliest Cretaceous (140–130 Ma).

In summary, we propose that the Jiamusi and Songliao blocks belonged to a single tectonic unit during Permian time, and they rifted apart in the late Permian to give rise to the Heilongjiang ocean. Later, an active continental margin situated along the Zhangguangcailing orogen in the Early-Middle Jurassic was the site of large volumes of intruded subduction-related igneous rocks, including I- and A-type granitoids and mafic rocks. Closure of the Heilongjiang ocean and collision of the Jiamusi and Songliao blocks was concluded by the Early Cretaceous.

CONCLUSIONS

The following conclusions can be drawn based on our new geochronological, geochemical, and Sr-Nd isotopic data from granitoids, integrated with previous studies, throughout the Zhangguangcailing orogen.

1. The studied granitoids in the Zhangguangcailing orogen are composed of granodiorite, monzonitic granite, quartz diorite, and granite. They are high-K, calc-alkaline, and I-type in composition, and are widespread throughout the Zhangguangcailing orogen.

2. The granitic rocks are characterized by negative Nb and Ta and positive Pb anomalies, as well as enrichments in LILEs and LREEs, indicating a subduction-related origin. The geochemistry and isotopic compositions

of the derivative granitoid magmas indicate that they were derived from lower-middle crustal material heated by, and mixed to some degree, with contemporaneous hot, mantle-like basaltic magmas during underplating and/or intrusion.

3. The I-type granitoids from the Zhangguangcailing orogen were derived from an active continental margin during Early and Middle Jurassic time (191–163 Ma).

4. The Jiamusi and Songliao blocks were a single tectonic unit during Permian time, but underwent rifting in the late Permian, which gave rise to the opening of the Heilongjiang ocean. Subduction beneath the Songliao block in Early-Middle Jurassic time led to final collision of the Jiamusi and Songliao blocks that was terminated by the Early Cretaceous.

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APPENDIX 1. SAMPLE DESCRIPTIONS

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Sample number	Age (Ma)	Location		Description
		Lat (°N)	Long (°E)	
<u>Zhangguangcailing orogen</u>				
15YL10-1	185.54 ± 0.92	45°41′	127°29′	granodiorite, light gray-white, porphyritic texture, fresh outcrop
15YL10-5				
15YL10-6				
15YL12-4	184.19 ± 0.77	45°39′	127°21′	granite, pinkish, medium size, granular texture
15YL14-1	182.8 ± 1.3	47°36′	128°30′	granodiorite, light gray-white, porphyritic texture, fresh outcrop
15YL14-2				granodiorite, light gray-white, porphyritic texture, fresh outcrop
15YL18-2	182.7 ± 1.1	46°55′	128°11′	
15YL18-4				
15YL28-1	185 ± 0.62	47°21′	129°32′	granite, pinkish
15YL36-5	191.4 ± 1.2	43°53′	126°55′	monzogranite, pinkish, tectonic contact with granodiorite
15YL36-4				granodiorite, light gray-white, granular texture
15YL38-2		44°21′	127°01′	
15YL38-3				
15YL40-1	191.0 ± 1.2	43°49′	126°43′	granite, light gray-white, granular texture
15YL40-2				granodiorite, light gray-white, granular texture
15YL40-4				
15YL41-5		43°45′	126°48′	

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