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Origin of the Jurassic-Cretaceous intraplate granitoids in Eastern China as a consequence of paleo-Pacific plate subduction

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A B S T R A C T

Jurassic-Cretaceous granitoids are widespread in eastern continental China and have been considered by many as resulting from paleo-Pacific subduction. However, the actual mechanism of their petrogenesis remains speculative. In order to address this important problem and on the basis of our regional study, we hypothesized that the coastal granitoids may result directly from the paleo-Pacific plate subduction, whereas the widespread granitoids in the continental interiors ultimately result from dehydration of the paleo-Pacific slab stagnated in the mantle transition zone (Niu et al., 2015). Here, we present the very first study testing this hypothesis. We sampled 18 Jurassic-Cretaceous granitoid plutons along a ~ 1300 km long traverse parallel to the inferred paleo-Pacific subduction from the southeast coastline to the Xiaoqinling in the continental interiors and carried out a detailed study on these plutonic samples, including zircon U—Pb geochronology, bulk-rock major and trace element compositions and Sr-Nd-Pb-Hf isotopic characteristics. These plutons give varying zircon crystallization ages of ~146 to 100 Ma. They are mostly granitic and minor granodioritic, quartz monzonitic and syenitic in composition, enriched in large ion lithophile elements (LILEs), depleted in high field-strength elements (HFSEs) and have varying negative Sr and Eu anomalies. The plutons in the continental interiors show significant positive correlations of Nd (ε_{Nd} (t) = −25.5 to −10.9) and Hf (ε_{Hf} (t) = −31.5 to −11.3) isotopes with Pb isotopes ($^{206}Pb/^{204}Pb$ (t) = 15.827 to 17.622), with the enriched endmember characterized by low ε_{Nd} (t), ε_{Hf} (t) and $^{206}Pb/^{204}Pb$ (t). The plutons towards the coastal region have relatively high ε_{Nd} (t) (−9.0 to −5.2), ε_{Hf} (t) (−11.2 to −4.1) and $^{206}Pb/^{204}Pb$ (t) (18.051 to 18.349). The coastal granitoids are best explained as resulting directly from subduction slab dehydration induced mantle wedge melting and resultant crustal anatexis, whereas the interior granitoids are best interpreted as resulting from mature crustal anataxis caused by basaltic magmatism associated with mantle lithosphere thinning, ultimately triggered by dehydration of paleo-Pacific slab stagnant in the mantle transition zone.

1. Introduction

Jurassic–Cretaceous granitoids are widespread in eastern continental China (from Northeast China to North China and to Southeast China and are distributed randomly in a wide zone in excess of 1000 km (Fig. 1). Of particular interest are series of granitoid plutons forming an apparent linear chain of NW-SE trending located north of the Qinling-Dabie Orogen, extending to the Xiaoqinling (Fig. 1) further to the west because of exhumation and outcropping in response to the continued South-NorthChina converge since the Mesozoic (Niu et al., 2015). This plutonic "chain" offers a prime opportunity to study the petrogenesis of these granitoids in time (varying ages) and space (distance to the coastal line). These granitoids were traditionally considered to have emplaced during the "Yanshanian" magmatic event. The isotopic age data, however, indicate two separate events of 190–150 and 140–85 Ma (Li, 2000; Wu et al., 2005a, 2005b), defining the early and late Yanshanian granitoid magmatism. The origin of the Jurassic-Cretaceous granitoids remains under debate. There are four major models (1) slab-tearing during paleo-Pacific subduction (Wu et al., 2012); (2) crust-mantle interaction in an extensional setting, due

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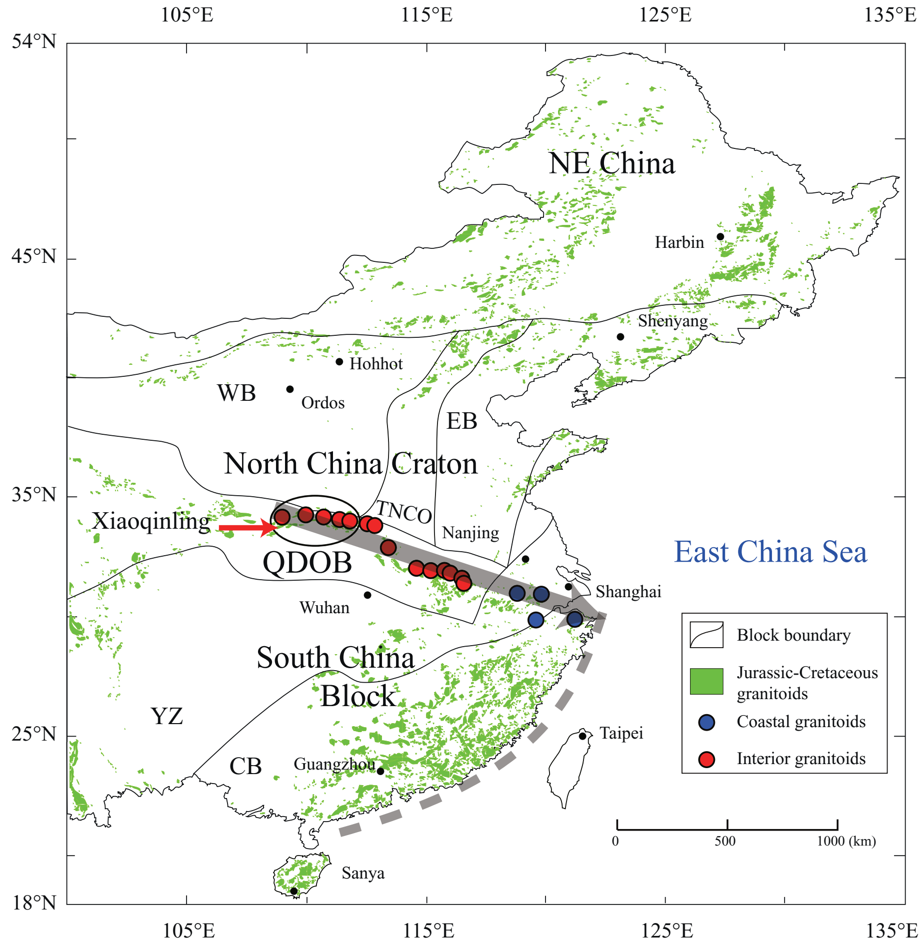

Fig. 1. Simplified geological map of eastern continental China, showing the distribution of Jurassic-Cretaceous granitoids (after 1:1,000,000 Geological Map and Data Base by the Chinese Geological Survey, 2005). Our sampled plutons are distributed along a ~ 1300 km long traverse parallel to the inferred paleo-Pacific subduction from the southeast coastline to the Xiaoqinling in the continental interiors. Although, the exact paleo-Trench location is unknow, but is likely parallel to and in the vicinity of the South-East China coastal line indicated by thick gray dashed line (Niu et al., 2015). The thick gray-arrowed line indicates the shortest distance of each sampled pluton to the inferred continental arc (i.e., coastline of the southeast continental China). The tectonic units indicated are West Block (WB), East Block (EB) and Trans-North China Orogen (TNCO) of the North China Craton (NCC), Yangtze Craton (YZ) and Cathaysia Block (CB) of the South China Block and Qinling-Dabie Orogen (QDO).

to lithospheric thinning caused by westward subduction of the paleo-Pacific plate (Gao et al., 2014); (3) crustal remelting/anataxis during post-collisionalcompression-extension transition and the back-arc extension related to paleo-Pacific subduction (e.g., Li et al., 2018; Zhou et al., 2006); (4) upwelling of the asthenospheric mantle, causing crustal melting due to a slab break-off and rollback of the subducting paleo-Pacific Plate (Li et al., 2014). Based on the analysis of the distribution of Mesozoic granitoids in eastern continental China in space and time, Niu et al. (2015) hypothesized that the process of basal hydration weakening that weakens and converts the basal lithosphere into asthenosphere while producing basaltic melts from the being-converted mantle lithosphere, which rise and underplate, causing crustal melting for these Jurassic-Cretaceous granitoids in the continental interiors. However, the granitoids in the coastal region must have directly resulted from the paleo-Pacific subduction before the trench jam and subduction cessation at ~ 100 Ma (Niu et al., 2015).

The role of paleo-Pacific subduction is now widely accepted, but the exact mechanism of the granitoid magmatism remains unclear. With all these different views objectively considered, the hypothesis by Niu et al. (2015) is geologically testable. The ~ 1300 km long plutonic "chain", that is parallel to and located north of, the older (~ 230 Ma) Qinling-Dabie Orogen offers a test ground. We understand that this apparent linear granitoid chain does not represent the expected areal distribution of the granitoids in eastern continental China but results from preferential exhumation and exposure because of continued South-NorthChina convergence since the Mesozoic, as evidenced by the ~ 400 km offset along the sinistral Tan-Lu fault (Niu et al., 2015).

To test the hypothesis, we sampled 18 granitoid plutons along the "chain" (Fig. 1), and carried out detailed zircon U—Pb geochronology, bulk-rock major and trace element analysis and Sr-Nd-Pb-Hf isotopic geochemistry on representative samples of the 18 plutons.

2. Geological setting and petrography

2.1. Geological background

The eastern continental China includes the Northeast (NE) China and North China Craton (NCC) in the north, the Qinling-Dabie Orogen in the middle, and the South China Block (SCB) in the south (Fig. 1). NEChina is located in the eastern segment of the Central Asian Orogenic Belt and is generally considered to be a tectonic collage of several microcontinental blocks (Jahn et al., 2000a, 2000b, 2004; Li et al., 2013; Windley et al., 2007). The NCC is one of the oldest cratons in the world with an earliest record of >3.8 Gyrs (Jahn et al., 1987; Liu et al., 1992), and can be divided into West Block (WB), East Block (EB) and Trans-NorthChina Orogen (TNCO) based on ages, lithological assemblage, geochemistry and metamorphic history of basement rocks (Zhao et al., 2001; Fig. 1). The Qinling-Dabie Orogen represents the most important SCB-NCC continental collision largely completed in the Late Triassic (Fig. 1, Mattauer et al., 1985; Sengör, 1985; Hsü et al.,

Table 1
Geological setting of studied plutons from the eastern China.

Pluton	Location	Rock type	Description	References
Liangnong	Yuyao county Liangnong village	Granodiorite	The Liangnong intrusive complex is controled by NNE trending fault with composed of the Late Yanshanian granite and the Himalayan period granite. It crops out over an area of about 88.19 km^2, and intrudes Lower Cretaceous and Upper Jurassic strata. And it is overlain by Pliocene basalts of the Shengxian group.	Gao et al., 2014
Hecun	Southwest part of Yinzhubu area	Granite	This pluton intrudes Jurassic Yushanjian group and Wuzhao group, Ordovician strata of Yinzhubu group, Ningguo group, Hule group.	[1]; Wu et al., 2012
Moganshan	Eastern Tianmu mountain Early Cretaceous volcanic basin	Mainly middle-coarse grained and locally fine grained biotite K-feldspar granite and biotite monzogranite	The Moganshan pluton is controlled by NE trending Yucun fault, and outcrops 9.8 km^2 in the term of small irregular-shaped rock. It intrusively touchs with rhyolitic and dacitic volcanic rocks of Jiande group Huangjian series.	Zhang et al., 2012
Yunling	West part of Guanling area	Granodiorite	This pluton is distributed of NE trending, and overlian by the Quaternary strata, with formation of the Yunling golden mine.	Wu et al., 2012
Tianzhushan	Near Wuhe-Shuihou fault (WSF)	Mainly fine grained granodiorite with locally middle-fine grained diorite and quartz monzonite	This pluton is located at Wuhe-Shuihou fault which delimits the South Dabie ultra-pressure metamorphic belt and the North Dabie complex with NW to SE irregular extension. It is composed of few intrusive units and outcrops area of 120km^2.	Peng et al., 1994
Baimajian	Northwest part of the Eastern Dabie	Monzogranite and syenitegranite	The Baimajian pluton outcrops over 1000km^2 with few small intrusive unit of granodiorite and distribution of metamorphic rocks that are dominated by gneiss and eclogite. The contact between the granitic pluton and the Dabie complex in the region are generally sharp.	Zhang and Du, 1998; Kuang et al., 1999; Wang and Cong, 1998
Tiantangzhai	At the core of Dabie Mountain	Porphyritic granite	This pluton crops out over an area of 100km^2, intrusively contact with the Dabie gneiss and the early period pluton.	Sang et al., 2000
Shangcheng	From parts of the SN trending Shangcheng-Macheng fault (SMF) and the EW trending Guishan-Meishan fault (GMF)	Porphyritic granodiorite and porphyritic monzogranite	This pluton intrudes Carboniferous detrital rocks of Yangxiaozhuang group, Upper Jurassic volcanic rocks of Jingangtai group, Lower Cretaceous volcanic rocks, Middle-Neo Proterozoic metamorphic rocks of Guishan groups and Late Jurassic quartz monzodiorite of Chenxiangpu group. And it outcrops 131km^2 area.	Liu et al., 2003
Xinxian	In county of Chengguan village, Doushanhe village and Sidian village	Granite, porphyritic granite and quartz monzonite	This pluton outcrops an area of 190 km^2, with intrusive contacting with the host. And its south part intrudes Lower Proterozoic Xinxian group, middle part intrudes Lower Proterozoic Qijiaoshan group, north part intrudes Middle Proterozic Huwan group. The contact surface trends to the pluton.	Chen et al., 2013; Zhao et al., 2013
Jigongshan	Outcroping in Jigongshan and Pingjingguan area	Monzogranite	This pluton intrudes Tongbai gneiss, and intruded by Cheyunshan pluton and Lingshan pluton. And it has NW trending belt distribution.	Zhang et al., 2004a
Chunshui	North part of the North Qinling-North Huaiyang tectonic belt	Monzogranite, alkali feldspar granite and K-feldspar granite	This study area is divided into Huangshan, Zushiding and Jiaozishan three plutons from south to north. Huangshan pluton has NW-SE trending distribution and intrudes Neoproterozoic granite of Kuanping and Ruyang group. Zushiding pluton is located at the middle part of the study area with NW-SE distribution and intrusdes Ruyang group, being overlain by Quaternary strata. Jiaozishan pluton is located at the northest area. Its south part intrudes Neoproterozic granite and north part intrudes Ruyang group.	Zhou et al., 2008
Erdaoya	East part of Nanzhao county	Granite	This pluton intrudes the Proterozoic Songshan group, Maoji group and Sujiahe group.	[2]
Taishanmiao	North part of the EW trending Machaoying fault	Porphyritic granite, monzogranite and fine grained granite	This pluton outcrops an area of 300 km^2, with NE intruding the Middle Proterozoic strata of Xiongeer group Jidanping series. It belongs to Xionger-Waifangshan ore-formation areas of the North China margin ore-formation belt.	Ye et al., 2008
Heyu	Located in the vicinity of Luanchuan county Heyu	Monzogranite and porphyritic granite	This pluton is the biggest granitic pluton in the Yuxi district with croping out over an area of 784 km^2. It is formed by four times magmatic intrusion, the first stage at the core, the second stage around the first stage, the third stage is the biggest that located at the margin of the complex, the fourth stage is Yanshanian granitoids.	Guo et al., 2009
Huashan	Late period intrusion at the north margin of the Songping pluton	Granite	This pluton outcrops an area of 130km^2, with irregularly EW trending distribution. The host is Taihua group.	Meng and Zhang, 2000
Wenyu	Middle east part of the Xiaoqinling area	Monzogranite	This pluton outcrops an area of 71 km^2, with three phase belts. The margin phase is fine, middle-fine grained biotite monzogranite. Mainly part of the excessive phase is gray-white middle grained biotite monzogranite. The top phase is gray-white fine grained biotite monzogranite.	Hu et al., 2012
Laoniushan	Located in a zone between the southern margin of NCC and the North Qinling belt, northwest of the Dabie ultra-high pressure (UHP) orogenic belt	Biotite monzogranite, quartz diorite, hornblende monzonite, and quartz monzonite	The Laoniushan intrusive complex is a lenticular body that crops out over an area of about 440 km^2. It intrudes various Precambrian metamorphic rocks, including the Archean Taihua Group gneiss, the Paleoproterozoic Tietonggou Group quartzite, the Xiong'er Group mafic volcanic rocks and quartzites, and the Gaoshanhe Group slates.	Ding et al., 2010; Qi et al., 2012
Lantian	Southeast of the Lantian county	Monzogranite	This complex outcrops an area of 154 km^2, with EW trending distribution. Its south part intrudes the Tietonggou group, and east part intrudes the Taihua group.	Ding et al., 2010

Note: [1–2] from 1:500,000 geological map of Zhejiang province and Henan province (http://www.ngac.org.cn/Map)

Table 2
Petrography of studied plutons from the eastern China.

Pluton	Sample	Longitude (°, N)	Latitude (°, E)	shortest distance to Arc (km)	Rock type	Petrograpic description	Age (Ma)	Age data source
Liangnong	LN14–09	29.85	121.09	116	granitoids	Fresh; fine grained, K-feldspar granite, plagioclase (~ 32%), K-feldspar (~ 38%), quartz (~ 25%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	99.2 ± 2.0	this study
Hecun	HC14–01	29.83	119.62	244	quartz monzonite	Fresh; medium grained, flesh pink in color, monzogranite, plagioclase (~ 33%), K-feldspar (~ 38%), quartz (~ 24%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite, contains small mafic xenoliths.	136.1 ± 2.0	this study
Moganshan	MGS14–02	30.62	119.90	260	granite	Fresh; fine-to-medium grained, flesh pink in color, K-feldspar granite, plagioclase (~ 30%), K-feldspar (~ 42%), quartz (~ 23%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite, contains small mafic xenoliths.	128.1 ± 2.1	Zhang et al., 2012
Yunling	YL14–02	30.61	118.21	410	granodiorite	Fresh; fine grained, pale-gray in color porphyric, plagioclase (~ 40%), K-feldspar (~15%), quartz (~ 30%), amphibole and biotite (~ 15%); accessory minerals are zircon and apatite.	138.7 ± 1.8	this study
Tianzhushan	TZS14–02	30.71	116.40	567	granite	Fresh; medium-to-coarse grained, monzogranite, plagioclase (~ 36%), K-feldspar (~ 35%), quartz (~ 24%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	128 ± 3.0	Niu et al., 2015
Baimajian	BMJ14–01	31.14	116.33	591	granite	Fresh; fine-to-medium grained, monzogranite, plagioclase (~ 33%), K-feldspar (~ 37%), quartz (~ 25%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	125.4 ± 2.8	this study
Tiantangzhai	TTZ14–05	31.28	115.59	661	syenite	Fresh; flesh pink in color, medium-to-coarse grained, K-feldspar granite, plagioclase (~ 10%), K-feldspar (~ 73%), quartz (~ 12%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	131 ± 1.0	Niu et al., 2015
Shangcheng	SC14–02	31.77	115.23	716	granodiorite	Fresh; fine grained, porphyric, plagioclase (~ 45%), quartz (~ 40%), amphibole and biotite (~ 15%); accessory minerals are zircon, magnetite, titanite and apatite.	137 ± 1.2	Niu et al., 2015
Xinxian	XX14–01	31.71	114.81	750	granite	Fresh; flesh pink in color, medium-to-coarse grained, K-feldspar granite, plagioclase (~ 30%), K-feldspar (~ 42%), quartz (~ 23%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	123.6 ± 1.1	Niu et al., 2015
Jigongshan	JGS14–01	31.84	114.07	820	granite	Fresh; flesh pink in color, fine-to-medium grained, K-feldspar granite, plagioclase (~ 30%), K-feldspar (~ 43%), quartz (~ 22%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	128 ± 1.2	Wei et al., 2016
Chunshui	CS14–01	33.03	113.42	924	granite	Fresh; pale-gray in color, medium grained, biotite monzogranite, plagioclase (~ 50%), K-feldspar (~ 20%), quartz (~ 26%), amphibole and biotite (~ 4%); accessory minerals are zircon, titanite and apatite.	133.4 ± 1.5	this study
Erdaoya	EDY14–01	33.74	112.45	1033	granite	Fresh; pale-gray in color medium-to-coarse grained, monzogranite, plagioclase (~ 34%), K-feldspar (~ 36%), quartz (~ 25%), amphibole and biotite (~ 6%); accessory minerals are zircon, magnetite, titanite and apatite.	138.1 ± 2.4	this study
Taishanmiao	TSM14–02	33.79	112.25	1053	granite	Minor alteration; medium-to-coarse grained, alkali feldspar granite, plagioclase (~ 30%), K-feldspar (~ 43%), quartz (~ 22%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	115 ± 1.0	Niu et al., 2015
Heyu	HY14–09	33.98	111.86	1094	granodiorite	Fresh; fine-to-medium grained, porphyric, plagioclase (~ 35%), K-feldspar (~ 15%), quartz (~ 35%), amphibole and biotite (~ 15%); accessory minerals are zircon and apatite.	134 ± 2.5	Niu et al., 2015
Huashan	HS14–02	34.32	111.71	1119	granite	Fresh; coarse grained, biotite monzogranite, plagioclase (~ 33%), K-feldspar (~ 37%), quartz (~ 25%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	132.5 ± 1.5	this study
Wenyu	WY14–07	34.51	110.48	1233	granite	Fresh; pale-gray in color, fine-to-medium grained, biotite monzogranite, plagioclase (~ 42%), K-feldspar (~ 33%), quartz (~ 20%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	131 ± 3.0	Niu et al., 2015
Laoniushan	LNS14–03	34.38	110.00	1267	granite	Fresh; flesh pink in color, medium-to-coarse grained, K-feldspar granite, plagioclase (~ 30%), K-feldspar (~ 43%), quartz (~ 22%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	143.4 ± 2.3	this study
Lantian	LT14–03	34.12	109.44	1310	granite	Fresh; medium-to-coarse grained, biotite monzogranite, plagioclase (~ 33%), K-feldspar (~ 35%), quartz (~ 27%), amphibole and biotite (~ 5%); accessory minerals are zircon, magnetite, titanite and apatite.	146.7 ± 2.3	this study

1987; Zhang, 1985). The SCB can be further divided into the Yangtze (YZ) Craton to the northwest and the Cathaysia Block (CB) to the southeast (Fig. 1). It is generally considered that the amalgamation of the Yangtze Craton and Cathaysia Block took place during the Late Mesoproterozoic at ~0.9 Ga associated with the supercontinent Rodinia amalgamation (Li et al., 2009). The Xiaoqinling granitoid “chain” is located at the southern margin of the NCC, immediately north of the Qinling-Dabie Orogen (Fig. 1), intruding the Neoarchaean to Palaeoproterozoic amphibolite- to granulite-facies metamorphic basement of the Taihua Group dominated by amphibolite with varying amounts of biotite plagioclase gneiss, migmatite, quartzite, and marble.

However, a detailed analysis of the Jurassic-Cretaceous granitoid magmatism throughout eastern continental China shows random distribution in space and time with no recognizable trends in a wide W-E zone in excess of 1000 km (Niu et al., 2015). This leads to the hypothesis that the stagnant paleo-Pacific slab in the mantle transition zone beneath the region dehydrated and released water in the form of hydrous melt that percolated through and metasomatized the upper mantle, weakened the base of the lithosphere while producing basaltic melt as the heat source (also material contribution) for crustal melting and the granitoid magmatism (Niu et al., 2015).

2.2. Petrography

The 18 Jurassic-Cretaceous (106.2–154 Ma) granitoid plutons (GPS data are given in Table 2) crop out along a traverse of ~ 1300 km and over an area of ~10 to 784 km^2(Table 1). The granitoids are mainly granitic with minor syenitic, quartz monzonitic and granodioritic compositions (Table 2) with varying grain size (Fig. 2). The mineralogy is simple, dominated by plagioclase (30–42%), K-feldspar (30–38%), quartz (20–30%), biotite (5%) and minor amphibole (2–10%) (Fig. 2). Accessory minerals include apatite, zircon, and Fe—Ti oxides. The petrographic detail is given in Table 2.

3. Analytical methods

3.1. Zircon U—Pb dating

Nine samples were selected for zircon U—Pb dating. Zircon LA-ICP-MS U—Pb dating was carried out at the Laboratory of Ocean Lithosphere and Mantle Dynamics, Institute of Oceanology, Chinese Academy of Sciences (IOCAS). Laser sampling was performed using a Photon Machines Excite 193 nm excimer laser system. An Agilent 7900 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) instrument was used to acquire ion-signal intensities. Spot diameter was set 35 μm. Zircon 91,500 was used as external standard for U—Pb dating (Wiedenbeck et al., 1995), and analysed twice between every 5 unknown analyses. The standard silicate glass NIST SRM610 was used to calibrate U, Th and Pb concentrations. The analytical detail is given in Xiao et al. (unpublished).

3.2. Major and trace elements

Bulk-rock major elements were analysed using an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Agilent 5100) in the IOCAS. The replicate sample was used to monitor precisions (<5.0%, see Appendix A). The USGS standard STM-2, RGM-2, W-2 and the replicate sample were used to monitor the analytical accuracy (±5%, see Appendix B) and precision (1σ, <2.0%). The analytical detail is given in Kong et al. (in preparation). Trace elements were analysed using an ICP-MS (Agilent 7900) after total acid digestion in Teflon bombs and dilution. The replicate sample was used to monitor precisions (<5.0%, see Appendix A). Repeated analyses of USGS reference

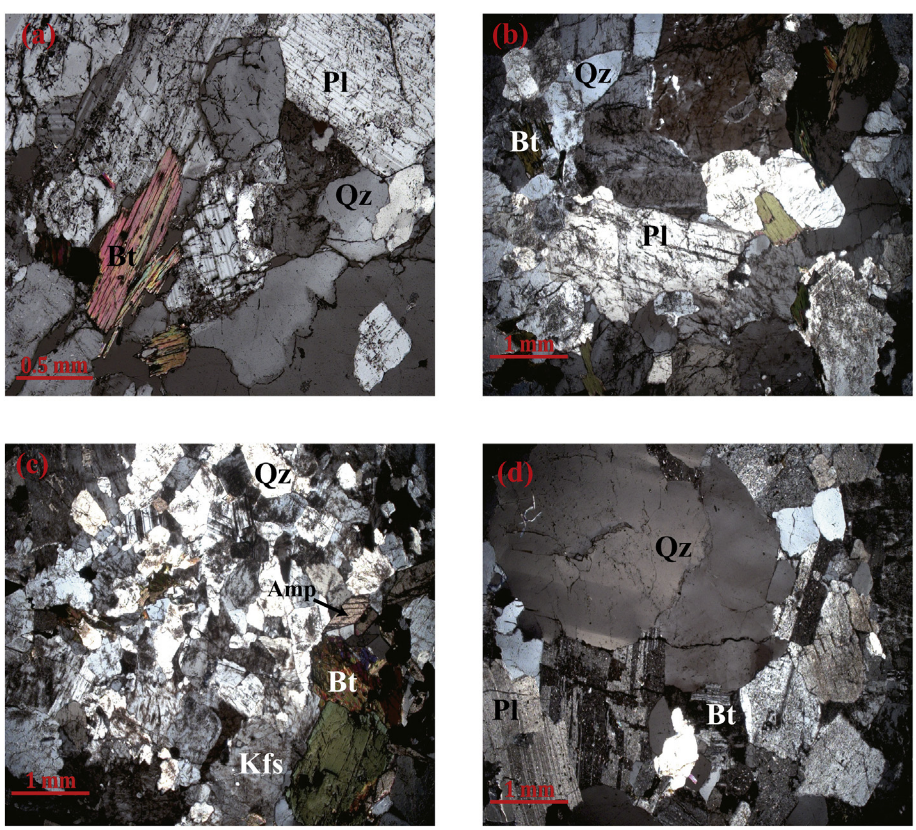

Fig. 2. Photomicrographs showing mineral assemblage of representative granitoids ((a) sample XX14–01, (b) sample WY14–07, (c) sample TTZ14–05, (d) sample CS14–01). The abbreviations are: Pl-plagioclase, Qz-quartz, Bt-biotite, Kfs-K-feldspar, Amp-amphibole.

Table 3
Sr-Nd-Hf-Pb isotopic compositions of studied granitoids from the eastern China.

Laboratory	Samples	$^{87}Sr/^{86}Sr$	2σ	$^{143}Nd/^{144}Nd$	2σ	$^{176}Hf/^{177}Hf$	2σ	$^{208}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{206}Pb/^{204}Pb$	2σ	$^{87}Sr/^{86}Sr$ (t)	$^{143}Nd/^{144}Nd$ (t)	$^{176}Hf/^{177}Hf$ (t)	$^{208}Pb/^{204}Pb$ (t)	$^{207}Pb/^{204}Pb$ (t)	$^{206}Pb/^{204}Pb$ (t)	$\varepsilon_{Nd}(t)$	$\varepsilon_{Hf}(t)$	Age (Ma)	Age data source
UQ	LN14–09	0.711019	7	0.512287	5	0.282607	5	39.0052	25	15.6567	7	18.5145	8	0.708004	0.512223	0.282594	38.751	15.648	18.320	−5.6	−4.1	99.2 ± 2.0	this study
	HC14–01	0.711253	9	0.512310	5	0.282607	5	38.7000	28	15.5847	8	18.3614	8	0.708048	0.512195	0.282562	38.343	15.570	18.051	−5.2	−4.4	136.1 ± 2.0	this study
	MGS14–02	0.754702	11	0.512298	5	0.282630	5	39.1838	34	15.6223	9	18.9283	9	0.708151	0.512172	0.282563	38.532	15.591	18.264	−5.9	−4.6	128.1 ± 2.1	Zhang et al., 2012
	YL14–02	0.709059	9	0.512098	4	0.282400	6	39.0369	35	15.6236	10	18.7736	9	0.707792	0.511996	0.282369	38.442	15.603	18.349	−9.0	−11.2	138.7 ± 1.8	this study
	TZS14–02	0.711234	10	0.511608	5	0.282004	5	37.5094	37	15.3416	10	16.4825	8	0.707583	0.511530	0.281988	37.152	15.334	16.319	−18.4	−24.9	128 ± 3.0	Niu et al., 2015
	BMJ14–01	0.712572	9	0.511249	4	0.281819	5	37.3228	31	15.2268	9	15.9514	7	0.708979	0.511169	0.281803	36.988	15.221	15.827	−25.5	−31.5	125.4 ± 2.8	this study
	TTZ14–05	0.710290	8	0.511650	4	0.282130	5	38.0531	31	15.4219	8	16.9924	7	0.709036	0.511576	0.282114	37.719	15.419	16.929	−17.4	−20.4	131 ± 1.0	Niu et al., 2015
	SC14–02	0.708937	8	0.511487	4	0.281935	5	37.4996	24	15.3039	7	16.4677	6	0.707931	0.511401	0.281928	37.323	15.292	16.216	−20.7	−26.8	137 ± 1.2	Niu et al., 2015
	XX14–01	0.735741	8	0.511520	5	0.282092	5	37.7904	29	15.3373	9	16.8009	8	0.707921	0.511446	0.282078	37.454	15.328	16.612	−20.2	−21.8	123.6 ± 1.1	Niu et al., 2015
	JGS14–01	0.708808	8	0.511538	5	0.281939	5	37.5438	30	15.3089	9	16.6313	8	0.707784	0.511450	0.281931	37.386	15.303	16.508	−20.0	−26.9	128 ± 1.2	Wei et al., 2016
	CS14–01	0.710721	11	0.511885	5	0.282274	5	38.1170	32	15.4629	9	17.3658	8	0.708459	0.511802	0.282263	37.796	15.454	17.177	−13.0	−15.1	133.4 ± 1.5	this study
	EDY14–01	0.709748	8	0.511752	5	0.282188	4	37.9197	30	15.4574	9	17.1772	8	0.708725	0.511669	0.282180	37.842	15.455	17.130	−15.5	−17.9	138.1 ± 2.4	this study
	TSM14–02	0.714532	9	0.511893	5	0.282350	4	38.7376	31	15.4837	8	17.6661	8	0.709070	0.511814	0.282320	38.118	15.472	17.349	−13.2	−22.2	115 ± 1.0	Niu et al., 2015
	HY14–09	0.711700	8	0.511728	5	0.282228	5	38.8169	28	15.5132	8	17.7985	7	0.709100	0.511650	0.282219	38.325	15.503	17.622	−15.9	−16.1	134 ± 2.5	Niu et al., 2015
	HS14–02	0.709494	10	0.511712	5	0.282079	5	38.0435	30	15.4726	9	17.4477	8	0.708236	0.511632	0.282062	37.877	15.468	17.454	−16.3	−18.3	132.5 ± 1.5	this study
	WY14–07	0.709356	9	0.511845	5	0.282252	6	38.3751	29	15.5020	8	17.8067	8	0.708444	0.511759	0.282237	38.187	15.493	17.423	−13.9	−13.5	131 ± 3.0	Niu et al., 2015
	LNS14–03	0.711062	9	0.511737	6	0.282183	5	38.1131	30	15.4929	8	17.6271	7	0.708628	0.511644	0.282165	37.935	15.485	17.587	−15.8	−16.6	143.4 ± 2.3	this study
	LT14–03	0.711195	7	0.511984	6	0.282372	5	38.3517	37	15.5051	10	17.7105	9	0.708227	0.511889	0.282361	37.970	15.491	17.421	−10.9	−11.3	146.7 ± 2.3	this study
IOCAS	LN14–09^{REP}	0.711026	8	0.512275	3	0.282618	7	38.9790	18	15.6568	6	18.5045	6	0.708010	0.512211	0.282605	38.694	15.646	18.310	−5.6	−4.1	99.2 ± 2.0	this study
	MGS14–02^{REP}	0.754990	10	0.512261	4	0.282628	4	39.0334	24	15.6210	9	18.8941	11	0.708438	0.512135	0.282560	38.304	15.585	18.230	−5.9	−4.6	128.1 ± 2.1	Zhang et al., 2012
	BMJ14–01^{REP}	0.712573	9	0.511208	4	0.281843	10	37.2826	23	15.2273	9	15.9435	8	0.708980	0.511127	0.281826	36.908	15.221	15.819	−25.5	−31.5	125.4 ± 2.8	this study
	SC14–02^{REP}	0.708939	8	0.511457	4	0.281938	7	37.4980	19	15.3125	6	16.5029	6	0.707932	0.511371	0.281931	37.300	15.299	16.252	−20.7	−26.8	137 ± 1.2	Niu et al., 2015
	LNS14–03^{REP}	0.711035	6	0.511722	3	0.282189	5	38.1104	21	15.5025	7	17.6378	8	0.708601	0.511629	0.282171	37.910	15.493	17.465	−15.8	−16.6	143.4 ± 2.3	this study

REP: replicate sample. UQ represents samples analysed at the Radiogenic Isotope Facility at The University of Queensland, Australia; IOCAS represents samples reanalysed at the Laboratory of Ocean Lithosphere and Mantle Dynamics (IOCAS), Institute of Oceanology, Chinese Academy of Sciences. Age data were used to calculate the initially isotopic data.
$(^{87}Sr/^{86}Sr)_{(t)} = (^{87}Sr/^{86}Sr)_{Sample} - {}^{87}Rb/^{86}Sr(e^{\lambda t} - 1)$, $\lambda = 1.42 \times 10^{-11} a^{-1}$, t = Age Ma.
$(^{143}Nd/^{144}Nd)_t = (^{143}Nd/^{144}Nd) - (^{147}Sm/^{144}Nd) \times (e^{\lambda t} - 1)$, $\varepsilon_{Nd}(t) = [(^{143}Nd/^{144}Nd)/(^{143}Nd/^{144}Nd)_{CHUR}(t) - 1] \times 10^4$, $(^{143}Nd/^{144}Nd)_{CHUR}(t) = 0.512638–0.1967\times (e^{\lambda t} - 1)$, $\lambda_{Sm\text{-}Nd} = 6.54 \times 10^{-12} a^{-1}$, t = Age Ma.
$(^{176}Hf/^{177}Hf)_t = [(^{176}Hf/^{177}Hf) - (^{176}Lu/^{177}Hf) \times (e^{\lambda t} - 1)$, $\varepsilon_{Hf}(t) = [(^{176}Hf/^{177}Hf)/(^{176}Hf/^{177}Hf)_{CHUR}(t) - 1] \times 10^4$, $(^{176}Lu/^{177}Hf)_{CHUR} = 0.0332$, $^{176}Hf/^{177}Hf_{CHUR} = 0.282772$, $\lambda = 1.867 \times 10^{-11} a^{-1}$, t = Age Ma.
Initial Pb isotope ratios were calculated by t = Age Ma. $(^{207}Pb/^{204}Pb)_{NHRL} = 0.1084 \times (^{206}Pb/^{204}Pb)_t + 13.491$, $(^{208}Pb/^{204}Pb)_{NHRL} = 1.209 \times (^{206}Pb/^{204}Pb)_t + 15.627$ (Hart, 1984).

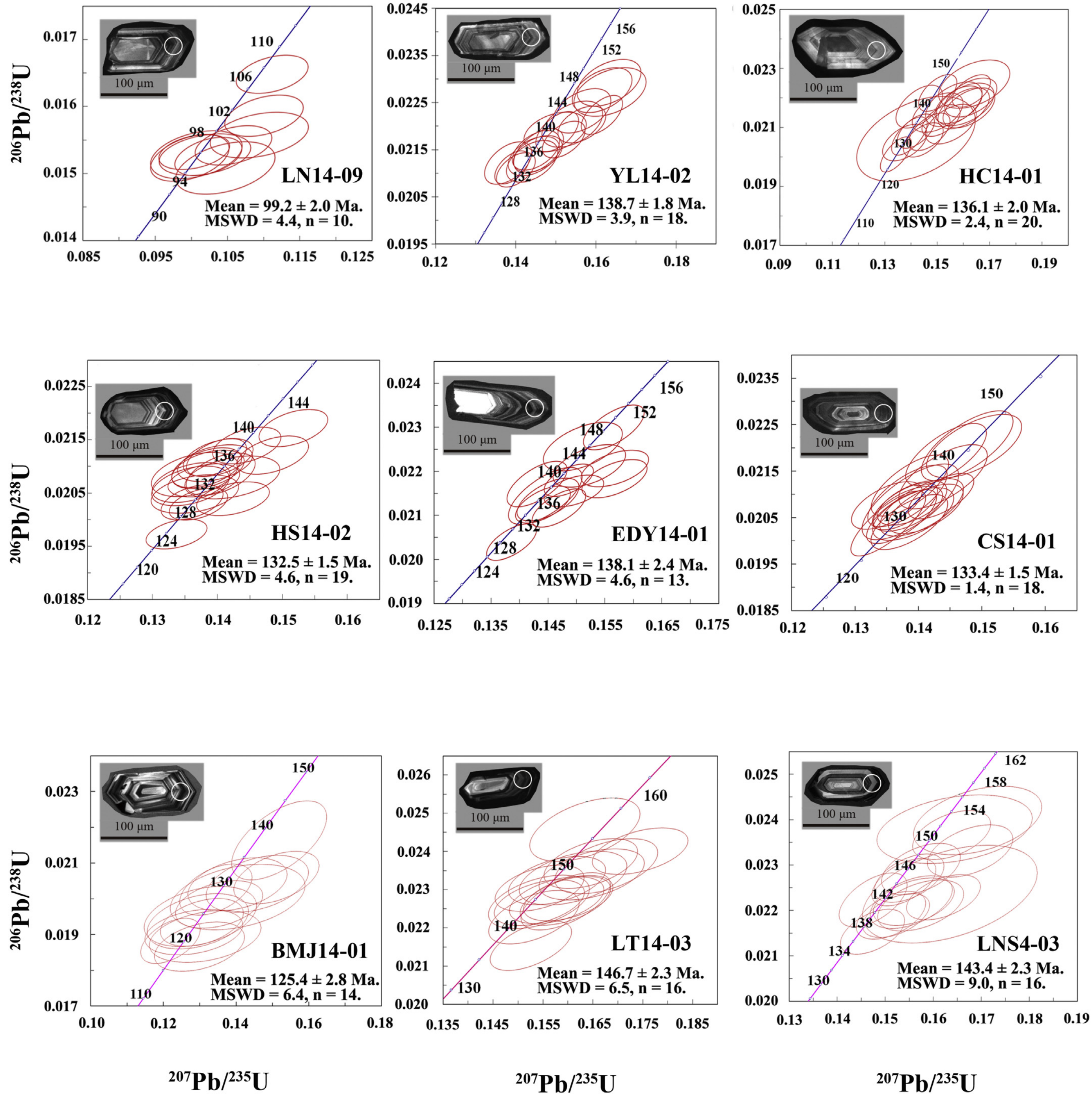

Fig. 3. Zircon U—Pb Concordia diagrams of nine selected plutons represented by samples LN14–01, YL14–03, HC14–01, EDY14–01, HS14–02, CS14–01, BMJ14–01, LT14–03, LNS14–03. The crystallization ages for these plutons varies from 99.2 ± 2.0 to 146.7 ± 2.3 Ma with no obvious spatial correlation except for the youngest (~ 99.2 Ma) pluton represented by LN14–9 at the southeast cost (see Fig. 9 below).

rock standards BCR-2, BHVO-2, AGV-2, RGM-2 and GSP-2 give analytical precision better than 5% and accuracies better than 10% for all elements but Be (12%). The analytical detail is given in Chen et al. (2017). The analytical results are given in Appendix C.

3.3. Sr-Nd-Pb-Hf isotopes

Sr-Nd-Pb-Hf isotopes were measured using Nu Plasma Multi-Collector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS) at the Radiogenic Isotope Facility at The University of Queensland, Australia (UQ). Analytical details for sample digestion and Sr-Nd-Pb-Hf elemental separation are given in Guo et al. (2014) and Sun et al. (2017). The measured $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{179}Hf/^{177}Hf$ isotope ratios were corrected for instrumental mass fraction using the exponential law to $^{86}Sr/^{88}Sr = 0.1194$, $^{146}Nd/^{144}Nd = 0.7219$, $^{179}Hf/^{177}Hf = 0.7325$, respectively. The measured average value for NBS-987 Sr standard is $^{87}Sr/^{86}Sr = 0.710249 \pm 15$ (n = 34, 2σ), identical to measured using TIMS within error ($^{87}Sr/^{86}Sr = 0.710250 \pm 11$ (n = 15, 2σ)). The Nd metal 50 ppb, an in-house Nd standard, gives an average $^{143}Nd/^{144}Nd$ of 0.511966 ± 6 (n = 21, 2σ). The repeated measurement of Hf standard (40 ppb) gives an average $^{176}Hf/^{177}Hf$ value of 0.282145 ± 6 (n = 14, 2σ). Pb isotope ratios were normalized for instrumental mass

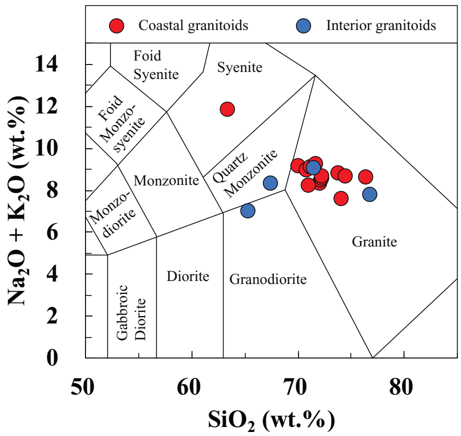

Fig. 4. Total alkalis ($Na_2O + K_2O$) versus SiO_2 (TAS) diagram showing the compositional variation of the plutons we study. They are mainly granitic in compositions.

fraction relative to NBS/SRM 997 $^{203}Tl/^{205}Tl = 0.41891$, which were then normalized against NBS981 (analysed as a bracketing standard every six samples; White et al., 2000) using $^{206}Pb/^{204}Pb = 16.9410$, $^{207}Pb/^{204}Pb = 15.4944$, and $^{208}Pb/^{204}Pb = 36.7179$ (Collerson et al., 2002). The Geological Survey of Japan (GSJ) rock reference sample JG-3 and the U.S. Geological Survey (USGS) rock standard BCR-2 were repeatedly measured along with our samples, which were consistent with the reference values (GeoReM, http://georem.mpch-mainz.gwdg.de/). See Appendix D for Sr-Nd-Pb-Hf isotope analytical results of the GSJ and USGS reference materials JG-3 and BCR-2, and they are within the recommended values.

Given the significant positive correlations of Nd, Hf isotopes with Pb isotopes of the interior granitoids (see below), we reanalysed five samples (LN14–09, MGS14–02, BMJ14–01, SC14–02, LNS14–03) at the IOCAS using Nu Plasma IIMC-ICP-MS to verify the Sr-Nd-Pb-Hf isotope data obtained from UQ are fully reproducible (see Table 3 and Appendix F). Analytical details for sample digestion and Sr-Nd-Pb-Hf elemental separation are given in Sun et al. (unpublished). The measured $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ isotope ratios were normalized for instrumental mass fraction using the exponential law to $^{86}Sr/^{88}Sr = 0.1194$, $^{146}Nd/^{144}Nd = 0.7219$ and $^{179}Hf/^{177}Hf = 0.7325$, respectively. International standards of NBS-987, JNdi-1 and Alfa Hf were used as bracketing standards every five samples to monitor the instrument drift during the analysis of Sr, Nd and Hf isotopes, respectively. Repeated analysis for NBS-987 gives an average $^{87}Sr/^{86}Sr = 0.710250 \pm 22$ ($n = 4$, 2σ). Repeated analysis for JNdi-1 gives an average $^{143}Nd/^{144}Nd = 0.512089 \pm 5$ ($n = 3$, 2σ), and repeated analysis for Alfa Hf gives an average $^{176}Hf/^{177}Hf = 0.282198 \pm 9$ ($n = 5$, 2σ). Pb isotope ratios were normalized for instrumental mass fraction relative to NBS/SRM 997 $^{203}Tl/^{205}Tl = 0.41891$. The international standard NBS-981 was used to monitor the instrument drift during the analysis of Pb isotopes. Repeated analysis of NBS-981 gives average $^{206}Pb/^{204}Pb = 16.934 \pm 0.002$ ($n = 4$, 2σ), $^{207}Pb/^{204}Pb = 15.493 \pm 0.003$ ($n = 4$, 2σ), and $^{208}Pb/^{204}Pb = 36.689 \pm 0.007$ ($n = 4$, 2σ). Analytical results of the USGS reference material AGV-2 and GSP-2 are summarized in Appendix D, and they are within the recommended values.

4. Data

4.1. Zircon U—Pb ages

The results of the U—Pb dating are given in Appendix E and shown in Fig. 3. These zircons are transparent, euhedral, prismatic crystals and have regular oscillatory magmatic zoning (Fig. 3). They have varying Th (67 to 3352 ppm) and U (167 to 2288 ppm) contents with Th/U ratios of 0.39 to 3.51. They give weighted mean crystallization ages varying from 99.2 ± 2.0 to 146.7 ± 2.3 Ma (Fig. 3).

4.2. Major and trace elements

Major and trace element data are given in Appendix A. As shown in the TAS diagram (Fig. 4), these granitoids are dominated by granite with minor syenite, quartz monzonite and granodiorite, which is consistent with the petrography. These granitoids show rough negative trends in SiO_2-variation diagrams (Fig. 5), especially TiO_2, Al_2O_3, $^{T}Fe_2O_3$ and CaO, which likely reflecting varying extents of fractional crystallization although these plutons and samples do not share a common lineage because their emplacement differ in time and space and because they do not show correlated trends for P_2O_5, Zr, Sr and Eu/Eu*. In the primitive mantle normalized multi-element diagram (Fig. 6), all the samples show spikes of some large ion lithophile elements (LILE; e.g., Rb, Th, U, K, Pb) and troughs of high field-strength elements (HFSE; e.g., Ni, Ta, Ti, P), resembling the pattern of the bulk continental crust (BCC; Rudnick and Gao, 2003).

4.3. Sr-Nd-Pb-Hf isotopes

The bulk-rockSr-Nd-Pb-Hf isotopic data are given in Table 3 and shown in Fig. 7. The initial Sr-Nd-Pb-Hf isotope ratios were calculated using the zircon U—Pb ages. These granitoids have moderately high initial $^{87}Sr/^{86}Sr$ ratios (0.7076 to 0.7091), relatively low $\varepsilon_{Nd}(t)$ (-3.1 to -22.6) and ε_{Hf} (t) (-4.1 to -31.5), and varying Pb isotopes $(^{208}Pb/^{204}Pb)_t = 36.948$ to 38.720, $(^{207}Pb/^{204}Pb)_t = 15.22$ to 15.646, $(^{206}Pb/^{204}Pb)_t = 16.216$ to 18.349. They plot to the left of the north-hemisphere reference line (NHRL) (Fig. 7). Our samples have positive correlation between Nd and Hf isotopes as expected (Vervoort et al., 2011; Vervoort and Blichert-Toft, 1999), but unexpectedly positive correlations of Nd and Hf isotopes with Pb isotopes for granitoids in the continental interiors in terms of magmatic processes recorded in the sources and source histories (Fig. 7). These correlations reflect a two-component mixing process of the plutons in the continental interiors, with the enriched endmember and the less enriched endmember (Fig. 7, ε_{Nd} (t) (-25.5 to -10.9), ε_{Hf} (t) (-31.5 to -11.3) and $^{206}Pb/^{204}Pb$ (t) = (15.827 to 17.622)). In contrast, the coastal granitoids have high ε_{Nd} (t) (-9.0 to -5.2), ε_{Hf} (t) (-11.2 to -4.1) and $^{206}Pb/^{204}Pb$ (t) (18.051 to 18.349).

The lower continental crust from the Dabie, the North China Craton, the Northern Qinling, the south margin of the North China Craton, Yangzi Craton and Cathaysia Block are characterized by high initial $^{87}Sr/^{86}Sr$ ratios, low ε_{Nd} (t) and $^{206}Pb/^{204}Pb$ (t), which differs from those of the coastal granitoids (Fig. 7). Thus, their differences cannot cause the isotopic differences of the plutons in the continental interiors, as well as the distinct Sr-Nd-Pb-Hf isotopic values between the coastal granitoids and the interior granitoids.

5. Discussion

5.1. Origin of the interior granitoids

Isotopically, the two-component mixing for the interior granitoids provide clues on their petrogenesis. The lower continental crust is characterized by low U/Pb, Th/Pb, Sm/Nd and Lu/Hf and high Rb/Sr elemental ratios (Fig. 6; Rudnick and Gao, 2003) relative the primitive mantle (Sun and McDonough, 1989) and will develop, with time, unradiogenic Nd (low ε_{Nd}(t)), Hf (low ε_{Hf}(t)) and Pb (low $^{206}Pb/^{204}Pb$ (t), $^{208}Pb/^{204}Pb$ (t)), and relatively radiogenic Sr (high $^{87}Sr/^{86}Sr$(t)). Therefore, the mature lower continental crust is most likely the enriched isotopic endmember of the two-component mixing. This enriched component is isotopically equivalent to the EM1-like (enriched mantle I) endmember, which is indeed characteristic of the lower crust as

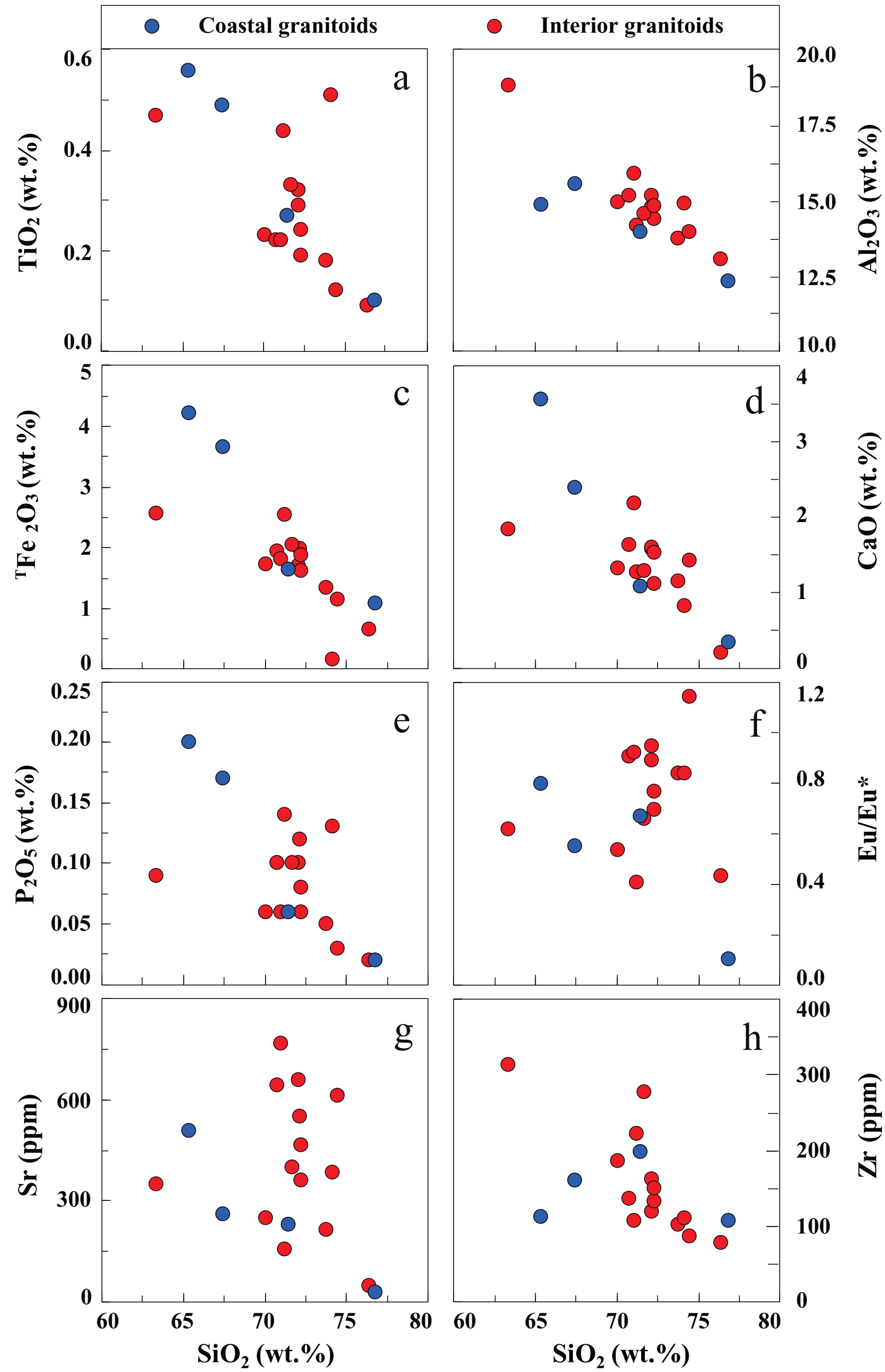

Fig. 5. SiO_2 variation diagrams of representative major (wt%) and selected trace (ppm) elements of the plutons/samples we study, showing large compositional variability with first-order trends consistent with varying extents of fractional crystallization although these plutons/samples do not share common liquid lines of descent in space and time.

revealed through isotopic studies of the lower crustal xenoliths (e.g., Liu et al., 2004; Zhou et al., 2002). This observation supports the hypothesis of mature lower continental crust melting for the granitoids (Niu et al., 2015).

Melting of the mature lower continental crust requires heat and such heat can only be made available by volumetrically significant mantle-derived basaltic melts that underplate/intrude the deep crust (Niu, 2005). This is indeed the case beneath eastern continental China in the Mesozoic because of the widespread lithosphere thinning throughout entire eastern China(Niu, 2005, 2014; Niu et al., 2015), with the intense lithosphere thinning taking place beneath the North China Craton (NCC) from ~ 200 km in the late Paleozoic to the present-day thin lithosphere of ~ 80 km or less (e.g., Menzies et al., 1993; Deng et al., 1998; Griffin et al., 1998; Xu, 2001; Gao et al., 2002, 2004; Yang, 2003; Zhu et al., 2012). There are several ideas on the lithosphere thinning, including lithosphere delamination (Deng et al., 1998; Gao et al., 2004; Griffin et al., 1998; Menzies et al., 1993; Xu, 2001), mantle plume heating (Deng et al., 1998), thermal and chemical metasomatism/erosion (Griffin et al., 1998; Zhang et al., 2003, 2004b), and paleo-Pacific plate subduction (Niu, 2005, 2006, 2009; Zhu et al., 2013a; Zhu et al.,

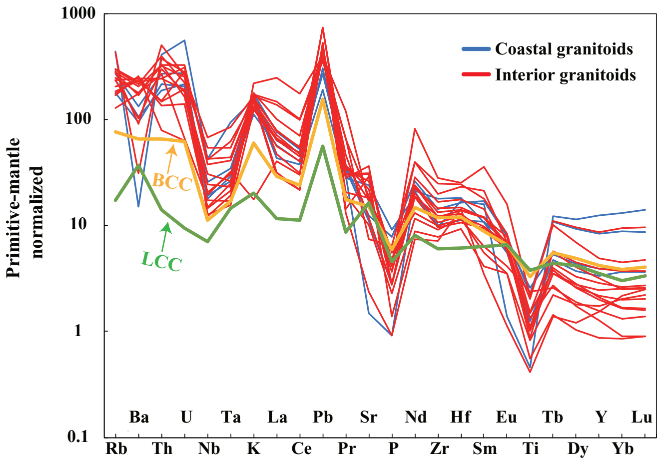

Fig. 6. Primitive mantle-normalized (Sun and McDonough, 1989) multi-element patterns for our studied plutons. The model bulk continental crust and lower continental crust (BCC and LCC; Rudnick and Gao, 2003) are plotted for comparison.

2013b), but physically the most likely mechanism is the basal hydration weakening by converting the basal portions of the lithosphere (i.e., subcontinental lithospheric mantle or SCLM) into the asthenosphere accompanied by partial melting and basaltic magmatism (Niu, 2005, 2006, 2009, 2014; Niu et al., 2015). The water required for such dehydration weakening originated from the paleo-Pacific plate lying stagnantly in the mantle transition zone (Niu, 2005, 2014). The ascent, intruding and underplating of the basaltic magmas provides the heat for the widespread crustal melting for the granitoid magmatism (Niu et al., 2015). Tomographic images beneath eastern China shows that the cold, flat slabs distribute widely throughout eastern China within the mantle transition zone (Zhang et al., 2004b), suggesting that melting of the subducted slab was limited and cannot produce voluminously basaltic melts. Thus, the basal portions of the SCLM is the very source of these basaltic melts, rather than the stagnated subducting slabs.

It is conceptually important to note, however, that the heat for the crustal melting is carried by the SCLM-derived basaltic melts and such melts thus have material contribution to the granitoid magmatism. This is indeed the case as evidence in the isotope spaces, especially those involving Pb isotopes (Fig. 7; also see below).

Because of the metasomatic histories of the SCLM, its basaltic magmas are expected to have more enriched Sr-Nd-Hf isotopes (e.g., lower Nd, Hf and higher Sr isotope values) than the DMM (depleted MORB mantle) but would still have less enriched Nd-Hf-Sr isotopes than the LCC (mature lower continental crust), which is expected to have relatively unradiogenic Pb isotopes as discussed above (Guo et al., 2014; Zhang et al., 2002, 2003). The interior granitoids plot in the field between the LCC and the SCLM(Fig. 7), suggesting that they are isotopic endmembers for the interior granitoids. Therefore, the widespread Jurassic-Cretaceous granitoids in eastern China result from crustal melting induced by basaltic melts derived from partial melting of the SCLM that was undergoing dehydration weakening and thinning (Niu et al., 2015).

Importantly, we recognize a systematic Nd-Hf-Pb isotope ratio increase for the interior granitoids from the coastline to the continental interior (Fig. 8), pointing to the increasing SCLM-over-LCC source contribution to the granitoids.

5.2. Origin of the coastal granitoids

Many studies consider that the Jurassic-Cretaceous granitoids along the southeast coastline resulted from paleo-Pacific subduction (e.g., Niu et al., 2015; Zhou et al., 2006). The present-day trench is hundreds of kilometers away from the southeastern coastline. However, the isotopic features of these coastal granitoids indicate that they were produced in a subduction zone setting. We suggest that our geochemical observations support the hypothesis that in the Mesozoic when these 'coastal granitoids' formed, the southeastern coastline of SEChina was the location of the trench (see Fig.1, Niu et al., 2015).

Fig. 7 and Fig. 8 show that the coastal granitoids differ distinctly from those of the continental interiors by having high Nd-Hf-Pb isotopes, indicating greater asthenospheric mantle (and less crustal) contribution. The coastal granitoids plot in the field between the DMM and the SCLM(Fig. 7), suggesting that the underplated basaltic melts must have come from a mantle wedge environment, isotopically resembling basalts and granitoids from subduction settings such as Andean-type continental margin and western Pacific island arcs (Fig. 7). That is, the petrogenesis of the coastal granitoids are more directly related to the active subduction of the paleo-Pacific plate with the mantle wedge derived basaltic melts (the more depleted endmember) intruding/underplating the overlying crust, producing the observed coastal granitoids.

5.3. Geodynamic significance

The granitoids in the continental interiors of eastern China are distributed in a wide zone in excess of >1000 km (Fig. 1, Fig. 8 and Fig. 9), indicating that the Mesozoic lithosphere thinning was not limited to the NCC, but took place throughout the entire eastern continental China as illustrated by Niu (2005) and Niu et al. (2015). This understanding also supports the proposal that the eastern continental China was not an Andean-type margin in the Jurassic-Cretaceous because of lacking a well-defined narrow continental magmatic arc as does along the Andes at present (Niu et al., 2015).

What may have caused the lithospheric thinning and the extensive granitoid magmatism in the Jurassic-Cretaceous Mesozoic? (1) Lithosphere stretching induced asthenosphere upwelling can be ruled out because there are no stretching-related linear magmatism in eastern continental China; (2) thermal mantle plume melting can be ruled out also because of lacking flood basalts, lacking expected space-time pattern of surface magmatism, and because plume melting residues would thicken, not thin, the lithosphere against geological record (Niu et al., 2015); (3) the delamination model can also be ruled out because it is physically not plausible how buoyant SCLM sinks into the dense asthenosphere in such a wide zone (in excess of >1000 km). Some previous studies proposed that these granitoids have something to do with the post-collisional processes (e.g., Wang et al., 2013b) associated with the collision of the South China Block and the North China Craton in the Late Triassic (242–219 Ma, Ames et al., 1993; Li et al., 1993; Okay and Sengo, 1993; Hacker et al., 1996; Zhang et al., 1996a, 1996b; Wan et al., 2005; Liu et al., 2006; Zhao et al., 2006, 2007; Duan et al., 2016; Kong et al., 2017). However, our studied plutons have distinct emplacement time of ~146 to 100 Ma and it is physically and geologically unlikely that these granitoids would have been caused by the continental collision taking place over some ~ 100 Myrs earlier.

Theoretically, there are three basic mechanisms through which a solid rock can partially melt to form magmas: (1) heating; (2) decompression and; (3) water (plus other possible fluids) addition (Niu, 2005). We have precluded the mechanisms of heating (thermal mantle plume melting) and decompression (lithosphere stretching induced asthenosphere upwelling). Thus, water addition is the most likely mechanism that results in lithospheric mantle melting and induced crustal melting. Niu (2005) and Niu et al. (2015) proposed that the basal hydration weakening concept is the common cause resulting in the lithosphere thinning, lithospheric mantle melting and induced crustal melting. This concept is supported by the random distribution of the

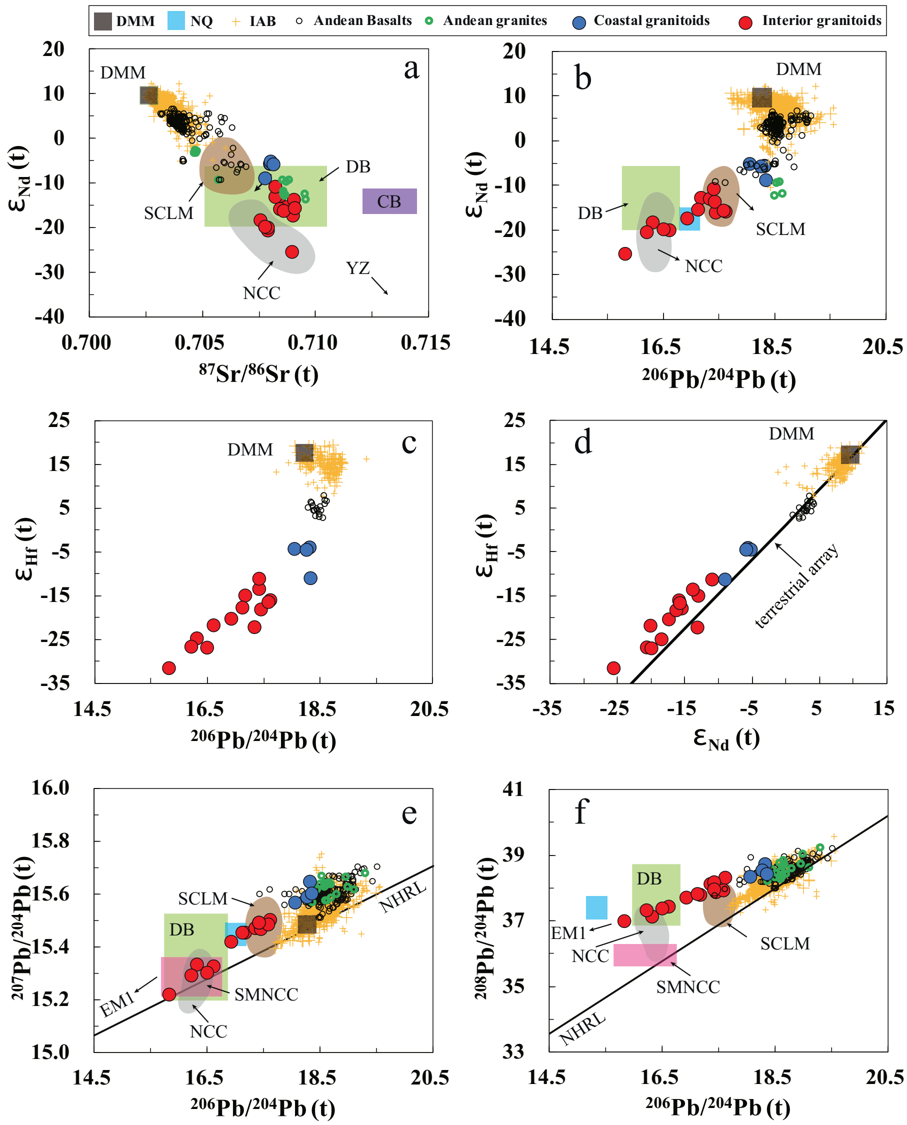

Fig. 7. Sr-Nd-Pb-Hf isotope co-variation diagrams of the plutons/samples we study. The Sr-Nd-Pb isotopic compositions of the lower continental crust from the Dabie (DB), the North China Craton (NCC), the Northern Qinling (NQ), the south margin of the North China Craton (SMNCC), Yangzi Craton (YZ) and Cathaysia Block (CB) are plotted to compare (Wang et al., 2013a; Chen and Jahn, 1998; Liu et al., 2004; Jahn et al., 1999; Ma et al., 2000; Zhang, 1995; Zheng et al., 2000; Zhang et al., 1996a, 1996b; Xu et al., 1997). The subcontinental lithospheric mantle is represented by the Mesozoic basalts in eastern continental China(Guo et al., 2014; Zhang et al., 2002, 2003). Sr, Nd, Pb and Hf isotopes for IAB are from west Pacific arcs (including Kermadec arc, Mariana arc, Izu-Bonin arc, Luzon arc, Ryukyu arc, Yap arc, Tonga arc, Andean arc, Smith et al., 2009; Smith et al., 2006; Ewart et al., 1977; Haase et al., 2002; Smith et al., 2009; Stern et al., 1990; Savov et al., 2005; Stern et al., 2006; Ishizuka et al., 2015a, 2015b; Ishizuka et al., 2011; Marske et al., 2011; Reagan et al., 2013; Tamura et al., 2014; Elliott et al., 1997; Ishizuka et al., 2014; Ishizuka et al., 2015a; Yokoyama et al., 2003; Mukasa et al., 2016; Dufrane et al., 2006; Hoang and Uto, 2006; Shinjo et al., 1999; Hickey-Vargas, 1998; Crawford et al., 1986; Beccaluva, 1980; Turner et al., 1997; Pearce et al., 1994; Taylor and Natland, 2013; Escrig et al., 2013; Béguelin et al., 2015; Chiaradia et al., 2014; Soager et al., 2013; Hickey-Vargas et al., 2016; Holm et al., 2016; Hilton et al., 1993; Hickey-Vargas, 1998; Nyström et al., 2003; Davidson and Silva, 1995; Kramer et al., 2005). Andean granites are from (Lucassen, 1999; Chiaradia, 2004; Chiaradia et al., 2004; Parada et al., 1988; Mamani et al., 2010). The NHRL (north hemisphere reference line) and DMM (Hart, 1984; Workman and Hart, 2005) are shown for comparison.

granitoids in space and time in the continental interiors in a wide zone in excess of >1000 km, contrary to the arguments and ideal model expectation in the literature that there is a systematic NW-to-SE granitoid age decrease, which actually does not exist (see Fig. 9, Niu et al., 2015). In the Mesozoic, the source of water or "water reservoir" was most probably the stagnant paleo-Pacific slab in the mantle transition zone that laterally extended far to the west in excess of 1000 km from the coast as is the case observed in the Cenozoic (Karason and van der Hilst, 2000; Zhao and Ohtani 2009). Water released from the stagnated slab in the form of hydrated melts that rises, weakens and converts the basal lithosphere into asthenosphere while producing basaltic melts from the being-converted mantle lithosphere. These basaltic melts rise, underplate and intrude the crust causing mature crustal melting to form the voluminous Jurassic-Cretaceous granitoids in the interiors of eastern continental China. This concept is illustrated schematically in Fig. 10. Therefore, the interior granitoids were formed in the intraplate setting rather than an active subduction setting nor post-collisional products of the ~ 220 Ma Qinling-Dabie Orogen as interpreted by some.

6. Summary

(1) The Jurassic-Cretaceous granitoids (~ 146–100 Ma) in the interiors of eastern continental China (e.g., Xiaoqinling area) have distinct isotopic compositions from those of coastal granitoids, indicating their different sources and petrogenesis.
(2) The interior granitoids show isotopically two-component mixing trends with the "enriched endmember" well represented by the

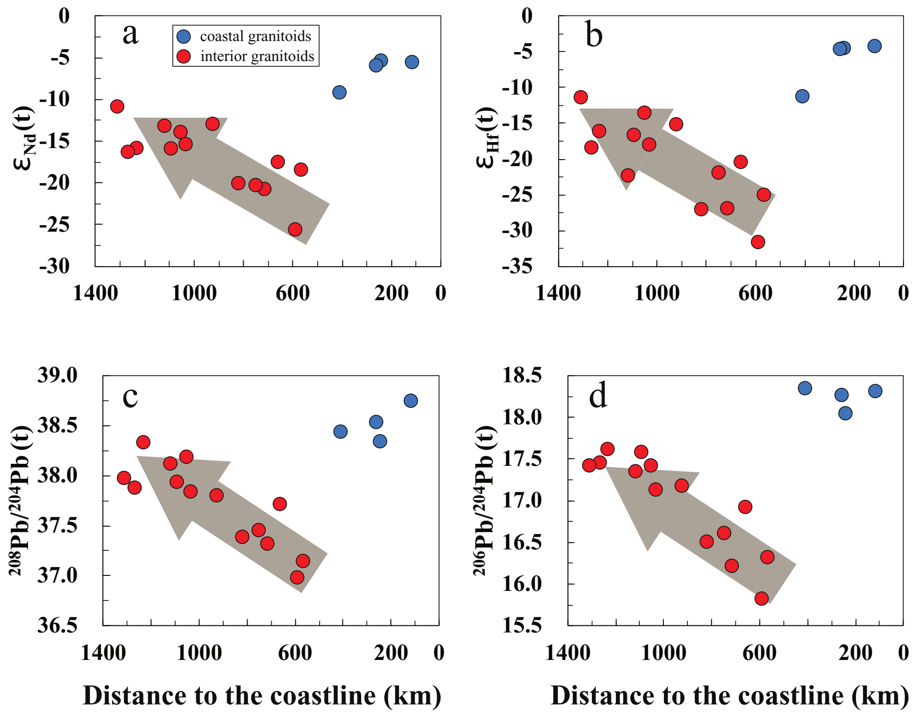

Fig. 8. Spatial variation of isotopic compositions, apparently showing that coastal granitoids (blue circles) are Nd (Hf) less enriched and Pb more enriched than interior granitoids (red circles). The interior granitoids show first-order spatial variation as a function of distance to the coastline of the southeast continental China, showing the location of the boundary of the coastal granitoids and the interior granitoids is ~400 km away from the southeastern coastline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

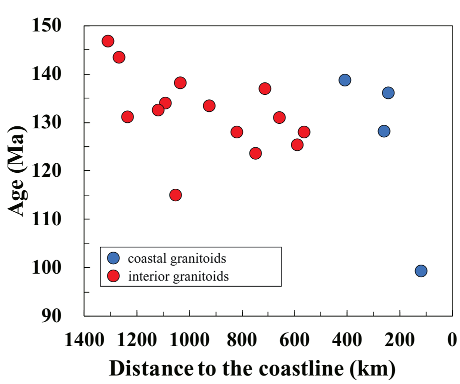

Fig. 9. Showing that the plutons/samples we study have no correlation in space and time. This supports the prediction that except for the coastline plutons, most of these inland plutons are not associated with the active subduction of the paleo-Pacific plate, but are genetically and ultimately associated with dehydration of the paleo-Pacific plate lying stagnantly in the mantle transition zone (Niu, 2014; Niu et al., 2015).

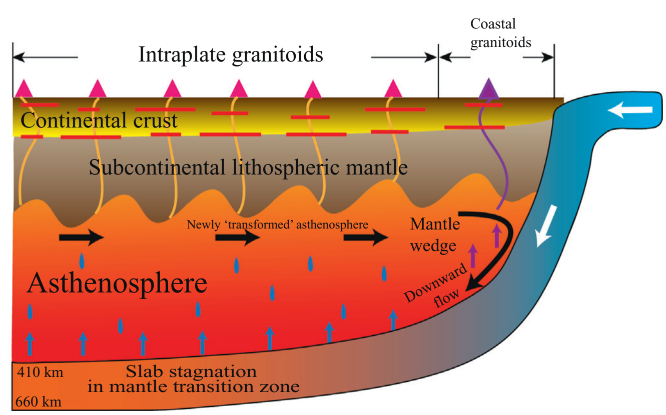

Fig. 10. Cartoon illustrating the concept of paleo-Pacific plate subduction-related coastal granitoids and subducted stagnant paleo-Pacific slab dehydration related widespread Jurassic-Cretaceous granitoids in the interior of continental China, with the latter involving re-working of mature lower continental crust.

LCC (mature lower continental crust) because they both consistently have high radiogenic Sr, and low radiogenic Nd-Hf-Pb isotopes. The "depleted" or "less enriched" endmember is best represented by the SCLM (metasomatized mantle lithosphere) (Fig. 7).

(3) We conclude from "(2)" above that the interior granitoids result from partial melting of the LCC, triggered by underplating/intruding of basaltic melts derived from the SCLM undergoing basal hydration weakening and lithosphere thinning (Niu, 2005; Niu et al., 2015).

(4) The coastal granitoids show higher radiogenic Nd-Hf-Pb isotopes, approaching isotopic compositions of basalts and granitoids from subduction settings such as the Andean-type continental margin and western Pacific island arcs. That is, the coastal granitoids are best interpreted as resulting directly from subduction slab dehydration induced mantle wedge melting and resultant crustal anatexis. This offers material evidence supporting the proposal for the exotic origin of Chinese continental shelf (Niu et al., 2015).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lithos.2018.10.027.

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