Geochemistry and zircon U–Pb age of subvolcanic rocks in Dajing deposit, NE China: Geodynamic implications

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The Dajing deposit is a large-scale vein-type polymetallic Sn deposit in the southern Great Xing'an Range of North-east China. This study presents new geochronological and geochemical data for subvolcanic rocks associated with the Dajing deposit and discusses the petrogenesis and tectonic setting of these rocks. The subvolcanic rocks associated with the Dajing deposit are felsites, porphyritic andesites, and porphyritic dacites. Laser-ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) U–Pb Zircon dating undertaken during this study indicates that the porphyritic dacite was intruded during the late Permian (265.9 ± 5.4 Ma), whereas both the felsite and the porphyritic andesite were intruded during the Middle Jurassic (168.4 ± 5.0 and 175.5 ± 5.6 Ma, respectively). All of these subvolcanic rocks are of the high-K calc-alkaline series, with high A/CNK ($=(\text{Al}_2\text{O}_3)/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) molecular ratios (>1), and are LREE-enriched relative to the HREEs. The felsite is characterized by relatively high Rb, U, Nd, Zr, and Hf, and relatively low Eu, Ba, Sr, P, and Ti concentrations, and is geochemically similar to highly fractionated I-type granites. In comparison, the porphyritic andesite is characterized by relatively high Rb and K and relatively low Ba concentrations, and is geochemically similar to unfractionated I-type granites. The porphyritic dacite is enriched in Rb, Zr, and Hf, is depleted in Ba, Sr, P, and Ti, and is geochemically similar to A₂-type granites. The regional geological setting and geochemistry of these subvolcanic rocks indicate that both the felsite and porphyritic andesite formed during post-collisional extension within the Xingmeng Orogenic Belt. This extension was a far-field effect of the closure of the Mongol–Okhotsk Ocean and associated lithospheric delamination during the Middle Jurassic. In comparison, the porphyritic dacite was associated with post-collisional slab break-off.

Keywords: Dajing deposit, subvolcanic rocks, U–Pb dating, geochemistry

INTRODUCTION

The southern Great Xing'an Range of NE China is located in the eastern Central Asian Orogenic Belt (Xingmeng Orogenic Belt) and hosts voluminous Mesozoic intrusive and volcanic rocks. Recent research into the petrology and tectonic setting of these rocks indicates that the majority of intrusive and volcanic rocks formed during the Early Cretaceous (Ge *et al.*, 2000; Lin *et al.*, 2004; Wu *et al.*, 2005; Wang, F. *et al.*, 2006; Liu *et al.*, 2005, 2009). However, little research has been undertaken on Jurassic intrusives in this area, meaning that the petrogenesis of the rocks and the tectonic setting in which they formed are poorly understood. This study provides new, precise U–Pb ages for Jurassic subvolcanic rocks in the study area to address these shortcomings.

The Dajing deposit is a large-scale vein-type

polymetallic Sn deposit located in the southern Great Xing'an Range. Previous studies on this deposit have generally focused on the geology (Wang *et al.*, 2001), mineralogy (Wang, Y. W. *et al.*, 2002, 2006), petrology (Zhang *et al.*, 2011), and geochronology (Jiang *et al.*, 2012; Liao *et al.*, 2012), although the majority of these studies have only been published in Chinese. Consequently, an updated and more detailed description of subvolcanic rocks associated with the Dajing deposit and the tectonic setting in which this magmatism occurred is still required.

This study provides new U–Pb isotopic ages and geochemical data for Jurassic and Permian subvolcanic rocks associated with the Dajing deposit that constrain the petrogenesis and tectonic setting of this magmatism.

REGIONAL GEOLOGY

The Paleozoic history of NE China is dominated by the amalgamation of several micro-continental blocks or terranes (Wu *et al.*, 2011), such as the northwestern

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Fig. 1. (a) Tectonic subdivisions of NE China (after Wu *et al.*, 2011); (b) Regional geological map in the Linxi Town of the Southern Great Xing'an Range (after Liu *et al.*, 2001). F1: Mudanjiang; F2: Dunhua-Mishan; F3: Yitong-Yilan; F4: Xilamulun-Changchun; F5: Hegenshan-Heihe; F6: Tanyuan-Xiguitu; F7: Mongol-Okhotsk; (1) Huanggangliang-Ganzhuermiao overturned anticline; (2) Linxi-Taohaiyingzi overturned syncline; (3) Sangmugou-Guandi overturned syncline. 1-Quaternary strata; 2-Upper Cretaceous strata; 3-Upper Jurassic and Middle Jurassic strata; 4-Upper Permian Linxi Formation and Lower Permian Huanggangliang Formation strata; 5-Silurian strata; 6-Mesozoic granitoids; 7-Late Paleozoic granitoids; 8-Unconformity geological boundary; 9-Deep faults; 10-Faults; 11-Overturned anticline; 12-Overturned syncline; 13-Deposit, intrusive location and toponym.

Erguna, the central Xing'an and Songliao, and the south-eastern Liaoyuan terranes (Fig. 1a). The Xing'an terrane contains the northern Great Xing'an Range and the Halar Basin, whereas the Songliao terrane is split into the Lesser Xing'an Range in the north, the Songliao Basin in the center, the Zhangguangcai Range in the east, and the southern Great Xing'an Range in the west. The southern Great Xing'an Range is located in central NE China and is bounded to the north by the Hegenshan-Heihe suture and to the south by the Xilamulun-Changchun suture (Fig.

1a).

Eastern Inner Mongolia, the southern Great Xing'an Range, and the northern margin of the North China Plate, as well as a number of other areas, underwent post-orogenic and intraplate extension after the late Permian (290–260 Ma, Shao *et al.*, 2005; Wu *et al.*, 2002) collision between the North China Plate and the Xingmeng Orogenic Belt; this tectonism also exposes significant volumes of A-type granites along the Hegenshan suture (F5 in Fig. 1a). The Mongol-Okhotsk Ocean ultimately

Fig. 2. (a) Geological sketch map of the Dajing deposit; (b) Geological map of Central ore district; (c) Geological map of East ore district; (d) Geological map of West ore district (a is modified from Wang *et al.*, 2001, b, c, and d are modified from LBGMR, 1976). COD: Central ore district of Dajing deposit; WOD: Western ore district of Dajing deposit; EOD: Eastern ore district of Dajing deposit; NOD: Northern ore district of Dajing deposit; SOD: Southern ore district of Dajing deposit; SEOD: Southeastern ore district of Dajing deposit.

closed during the late Jurassic (~160 Ma, Meng, 2003), an event that was associated with significant magmatism and volcanism within the northern Great Xing'an Range, northeastern Mongolia, the southern margin of the Siberia Plate, and other regions. Middle Jurassic to Early Cretaceous volcanic rocks are widespread throughout the northeastern Great Xing'an Range (Sun *et al.*, 2011). Previous research has indicated that initial subduction of the Paleo-Pacific Plate began in the Early Jurassic, with subduction occurring until the Late Jurassic–Early Cretaceous (~140 Ma). This subduction caused a regional transformation in tectonic setting from compression to extension throughout eastern China, leading to large-scale Early Cretaceous (140–120 Ma) magmatism, volcanism, and mineralization in this area (Mao *et al.*, 2005).

The Dajing deposit is located in Linxi Town, Inner Mongolia (Fig. 1b). The geology of this area, with the exception of Quaternary cover, is dominated by Permian and Jurassic units with minor Silurian and Cretaceous rocks (Fig. 1b). The Silurian units are the oldest in the

study area and are dominantly gneisses and schists, whereas the Permian units include the lower Huanggangliang Formation and the upper Linxi Formation; the former is dominated by marble, slate, and sandstone, whereas the latter consists of grey-black siltstones intercalated with fine-grained sandstones that contain phosphatic nodules and bands. The Jurassic (Manketouebo Formation) and the Cretaceous units in this area are dominated by rhyolites, volcanoclastic rocks, and rhyolitic tuffs (Liu *et al.*, 2001).

The study area contains a number of well-developed regional-scale faults and folds, including the deep-seated NE–SW-trending Huanggang–Ganzhuermiao Fault in the northwest of the study area, the deep-seated E–W-trending Xinlinzhen and Xilamulun (F4 in Fig. 1b) faults in the north and south of the study area, respectively, and the NW–SE-trending Chaganmulun Fault in the east. The area contains both primary and secondary folds, including the overturned Huanggangliang–Ganzhuermiao anticline ((1) in Fig. 1b) and the overturned Linxi–Taohaiyingzi syncline

Fig. 3. Profile map of exploration line No. 46 in Dajing deposit (Zhang, 1993).

((2) in Fig. 1b). Magmatic rocks, including Mesozoic (e.g., Ma'anzi and Yelaigai intrusions) and late Paleozoic (e.g., Longtoushan intrusion; Fig. 1b) granitoids are widespread throughout the area. Mesozoic granitoids are dominantly K-feldspar granites and porphyritic granites, whereas the rare late Paleozoic granitoids are dominantly quartz diorites and granodiorites (Liu *et al.*, 2001).

DEPOSIT GEOLOGY

The study area is dominated by the late Permian Linxi Formation (P_2l , Fig. 2a) that outcrops in a belt that strikes NW–SW, with some offshoots that strike NE–SW. Research by LBGMR (1976) suggests that these freshwater and lacustrine sedimentary rocks (P_2l) are subdivided from bottom to top into a black silty mudstone member (P_2l^1), a grey fine- to medium-grained sandstone member containing phosphoric nodules or bandings (P_2l^2), a dark grey fine-grained sandstone member with interbedded marl horizons (P_2l^3), and a green or grey siltstone member (P_2l^4). The area is dominated by a weakly folded monoclinical structure, with the exception of the Tulengzigou syncline and the overturned Sangmugou–Guandi syncline (Fig. 2a), which in turn is controlled by the overturned Linxi–Taohaiyingzi syncline ((2) in Fig. 1b) in this area. The area has four distinct fracture sets

that are oriented NE–SW, N–S, NW–SE, and E–W; of these, the NW–SE-trending faults are associated with some of the subvolcanic rocks and mineralized veins (Fig. 2a).

No intrusive are exposed at the surface or have been encountered during drilling within the Dajing deposit, and the nearest intrusives are the granitoids of the Linxi district, namely the Ma'anzi, Longtoushan, and Yelaigai intrusions, which are located some 9 km to the northwest of the study area (Fig. 1b). A number of hypabyssal subvolcanic dykes crosscut the Linxi Formation (P_2l ; Fig. 2a), and three main types of subvolcanic rocks have been identified within the Dajing deposit: a felsite, a porphyritic andesite, and a porphyritic dacite. The felsite is located within the central ore district (COD) in the study area, strikes NW–SE, dips to the NE, outcrops over an area more than 100 m long but only 0.3 m wide (Fig. 2b), and stratigraphically overlies Cu–Sn veins within the deposit. The porphyritic andesite outcrops in the eastern part of the COD, the western ore district (WOD), and the eastern ore district (EOD); this rock outcrops over an area more than 600 m long and several centimeters to several meters wide, strikes NW–SE, and dips to the NE (Figs. 2b and 2c). This rock hosts mineralized Pb–Zn veins within the deposit. The porphyritic dacite generally outcrops in the western COD and the WOD, and is present

Fig. 4. Hand specimens and photomicrographs of subvolcanic rocks. (a) Hand specimen of felsite; (b) Spherulitic texture of felsite; (c) Spherulite is composed of quartz and plagioclase ($Q + Pl$), plagioclase was altered to chlorite ($Pl \rightarrow Chl$), felsite also has some opaque minerals (OM); (d) Hand specimen of porphyritic andesite; (e), (f) Matrix of porphyritic andesite is hyalopilitic in texture, including amphibole (Amp) and plagioclase (Pl); (f) Amphibole was also altered to chlorite ($Amp \rightarrow Chl$); (g) Hand specimen of porphyritic dacite; (h) Amphibole phenocryst, plagioclase matrix was altered to muscovite ($Pl \rightarrow Ms$); (i) Plagioclase phenocryst shows polysynthetic twinning, and quartz phenocryst is xenomorphic-granular.

as a series of 10–800 m long and 2–20 m wide dykes that are split into two groups: one striking $N 40^\circ$ and one striking $N 320^\circ$ (Figs. 2b and 2d).

The Dajing deposit is a vein-type polymetallic Sn deposit that consists of >330 ore veins, the majority of which do not crop out. These veins strike NW–SE or WNW–ESE and dip between 25° and 75° to the north (LBGMR, 1976). The veins crosscut Permian units at low angles ($<20^\circ$) and are present as veins, vein networks, and composite veins within either Permian or subvolcanic rocks. These veins are dominated by chalcopyrite, cassiterite, sphalerite, galena, pyrite, pyrrhotite, arsenopyrite, acanthite, stephanite, and native silver in a siderite, ankerite, calcite, quartz, sericite, chlorite, and fluorite gangue (Wang, Y. W. *et al.*, 2002, 2006). The veins are associated with weak silicification, and with chlorite, carbonate, and sericite alterations that are generally limited to the areas adjacent to individual veins. Ore textures include euhedral-subhedral, xenomorphic-granular, exsolution, replacement remnant, and skeletal minerali-

zation, all of which are within stockwork veins, brecciated, massive, disseminated, and banded ores (Liu *et al.*, 2001).

Crosscutting relationships between ore veins, zonation within ore veins, and paragenetic associations have allowed the identification of three stages of mineralization within the Dajing deposit: (1) a cassiterite–arsenopyrite–quartz stage, (2) a pyrite–chalcopyrite sulfide stage, and (3) a Pb–Zn–Ag–carbonate stage. The mineralization within the Dajing deposit is also zoned (Zhang, 1993), with Cu and Sn enrichments within the felsite-hosted sections of the COD (Figs. 2b and 3), and Pb and Zn enrichments within the porphyritic andesite-hosted periphery of the deposit (e.g., the eastern WOD and the EOD; Figs. 2c, 2d, and 3).

SAMPLES AND ANALYTICAL METHODS

Sample description

Three felsite, seven porphyritic andesite, and two

Table 1. Zircon U-Pb isotopic data of subvolcanic rocks in Dajing deposit

Sample number	^{204}Pb		Th	U	$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$		ρ		$^{207}\text{Pb}/^{206}\text{Pb}$		$^{207}\text{Pb}/^{235}\text{U}$		$^{206}\text{Pb}/^{238}\text{U}$	
	ppm		ppm	ppm	Ratio	1σ	Ratio	1σ	Ratio	1σ			Age (Ma)	1σ	Age (Ma)	1σ	Age (Ma)	1σ
DI-1-1 Felsite																		
DI-1-1-01	0.00	77	291	0.27	0.0536	0.0048	0.1834	0.0141	0.0253	0.0006	0.3026		354	202	171	12	161	4
DI-1-1-02	1.55	177	580	0.31	0.0494	0.0036	0.1870	0.0125	0.0274	0.0005	0.2825		165	163	174	11	174	3
DI-1-1-03	0.00	309	488	0.63	0.0509	0.0035	0.2024	0.0118	0.0291	0.0006	0.3434		239	156	187	10	185	4
DI-1-1-05	0.00	315	866	0.36	0.0480	0.0030	0.1709	0.0105	0.0253	0.0004	0.2897		98	141	160	9	161	3
DI-1-1-06	0.00	237	669	0.35	0.0492	0.0032	0.1847	0.0110	0.0271	0.0005	0.3064		167	131	172	9	172	3
DI-1-1-07	0.00	267	818	0.33	0.0452	0.0026	0.1678	0.0095	0.0264	0.0004	0.2752		200	168	158	8	168	3
DI-1-1-10	0.00	379	973	0.39	0.0501	0.0032	0.1883	0.0115	0.0271	0.0005	0.2799		211	144	175	10	172	3
DI-1-1-11	1.47	396	1014	0.39	0.0510	0.0029	0.1807	0.0104	0.0253	0.0004	0.2949		243	131	169	9	161	3
DI-1-1-12	0.00	341	927	0.37	0.0508	0.0034	0.1887	0.0116	0.0270	0.0004	0.2663		232	149	176	10	172	3
DI-1-1-14	1.99	1000	797	1.25	0.0488	0.0032	0.1746	0.0110	0.0258	0.0004	0.2590		139	148	163	10	164	3
DI-1-1-09	2.97	502	984	0.51	0.0512	0.0024	0.3567	0.0167	0.0493	0.0007	0.2988		256	77	310	12	310	4
ZX-9 Porphyritic andesite																		
ZX-9-03	0.00	941	1599	0.59	0.0484	0.0042	0.1892	0.0162	0.0283	0.0006	0.2304		117	193	176	14	180	3
ZX-9-04	5.30	804	1722	0.47	0.0486	0.0036	0.1879	0.0137	0.0278	0.0005	0.2545		128	172	175	12	177	3
ZX-9-06	4.29	560	1103	0.51	0.0578	0.0048	0.2132	0.0158	0.0279	0.0007	0.3416		520	183	196	13	178	4
ZX-9-08	1.78	621	1401	0.44	0.0534	0.0043	0.1960	0.0146	0.0273	0.0006	0.2892		346	183	182	12	173	4
ZX-9-09	0.00	831	1407	0.59	0.0491	0.0048	0.1959	0.0185	0.0292	0.0008	0.2737		154	215	182	16	185	5
ZX-9-11	1.17	941	1421	0.66	0.0490	0.0038	0.1982	0.0150	0.0289	0.0006	0.2857		150	170	184	13	183	4
ZX-9-14	0.00	559	1314	0.43	0.0533	0.0042	0.1917	0.0146	0.0264	0.0007	0.3342		343	178	178	12	168	4
ZX-9-12	0.00	1075	1755	0.61	0.0490	0.0038	0.1807	0.0142	0.0261	0.0005	0.2491		146	170	169	12	166	3
TH-12 Porphyritic dacite																		
TH-12-01	1.41	827	1572	0.53	0.0518	0.0037	0.2953	0.0200	0.0412	0.0008	0.2735		276	165	263	16	260	5
TH-12-02	0.00	446	807	0.55	0.0560	0.0049	0.2985	0.0253	0.0401	0.0010	0.2965		450	196	265	20	254	6
TH-12-04	0.00	773	1197	0.65	0.0555	0.0039	0.3165	0.0210	0.0416	0.0010	0.3615		435	125	279	16	263	6
TH-12-06	0.00	545	1145	0.48	0.0526	0.0043	0.2937	0.0241	0.0412	0.0009	0.2551		309	181	261	19	260	5
TH-12-07	0.00	797	1213	0.66	0.0527	0.0035	0.3076	0.0208	0.0419	0.0009	0.3193		322	145	272	16	265	6
TH-12-10	0.00	450	1125	0.40	0.0538	0.0044	0.3258	0.0250	0.0442	0.0009	0.2619		365	216	286	19	279	5
TH-12-11	5.81	523	1327	0.39	0.0526	0.0042	0.3132	0.0243	0.0430	0.0008	0.2395		322	183	277	19	271	5
TH-12-12	6.32	994	1134	0.88	0.0540	0.0043	0.3249	0.0240	0.0441	0.0009	0.2675		369	175	286	18	278	5
TH-12-13	1.43	370	842	0.44	0.0544	0.0047	0.2966	0.0247	0.0398	0.0008	0.2437		387	190	264	19	251	5
TH-12-14	2.32	617	1124	0.55	0.0516	0.0037	0.2967	0.0207	0.0414	0.0009	0.3007		333	167	264	16	262	5
TH-12-16	4.58	1490	1405	1.06	0.0508	0.0038	0.3030	0.0228	0.0428	0.0008	0.2469		232	168	269	18	270	5
TH-12-17	0.00	609	851	0.72	0.0535	0.0040	0.3207	0.0235	0.0440	0.0009	0.2795		350	168	282	18	278	6
TH-12-19	0.76	225	661	0.34	0.0530	0.0047	0.3007	0.0246	0.0421	0.0011	0.3118		328	197	267	19	266	7

Fig. 5. (a) Selected zircon CL images, dating point, and data of DJ-1-1 for felsite; (b) Selected zircon CL images, dating point, and data of ZX-9 for porphyritic andesite; (c) Selected zircon CL images, dating point, and data of TH-12 for porphyritic dacite.

porphyritic dacite samples were collected from the various ore districts within the Dajing deposit (Figs. 2b–d). The felsite is greyish-white, has felsitic and spherulitic textures, and is massive (Fig. 4a). It contains plagioclase (50%), quartz (40%), and opaque minerals (10%), in addition to spherulitic aggregates of plagioclase and quartz that were generated during devitrification (Figs. 4b and 4c), present as small (<2 μm) xenomorphic granular crystals that are partially altered to chlorite, whereas the quartz is xenomorphically granular but is generally <1.5 μm in size and is unaltered and free of inclusions.

The porphyritic andesite is dark grey, porphyritic, and massive (Fig. 4d). It contains plagioclase (2–5 mm; 2%–3% abundance) and amphibole (4–6 mm; 1%–2%) phenocrysts in a hyalopilitic matrix (Figs. 4e and 4f) that has a 0.5–1 mm grain size, and contains amphibole ($\geq 65\%$), plagioclase (20%–25%), biotite (2%–3%), quartz (5%), and magnetite (2%–3%). The plagioclase is euhedral to subhedral and tabular, whereas the amphibole is subhedral, cylindrical, and is slightly altered to chlorite (Fig. 4f), the biotite is scaly, and the quartz is generally present as interstitial crystals between plagioclase.

The porphyritic dacite is greyish-green, porphyritic, and massive (Fig. 4g), and contains plagioclase (0.1–0.3 mm, 30%), amphibole (0.1–0.3 mm, 20%), and quartz (0.1–0.25 mm, 20%) phenocrysts. Plagioclase within the unit is euhedral, tabular, contains polysynthetic twins (Fig. 4i), and is partially altered to muscovite, whereas the amphibole is reddish brown and xenomorphic (Fig. 4h),

and the quartz is xenomorphic and granular. This unit has a cryptocrystalline matrix that contains plagioclase (10%), quartz (10%), biotite (5%), and amphibole (5%).

Zircon LA-ICP-MS U–Pb dating

Zircons were separated from three subvolcanic rock samples during this study, namely samples DJ-1-1 (felsite), ZX-9 (porphyritic andesite), and TH-12 (porphyritic dacite), using conventional heavy liquid and magnetic techniques at the Langfang Regional Geological Survey, Hebei Province, China. Representative zircons were handpicked under a binocular microscope, were mounted in an epoxy resin disc, and then polished and coated with gold film prior to analysis. Zircons were imaged under transmitted and reflected light and cathodoluminescence using a JXA-8100 instrument fitted with a MonoCL3 setup, employing an acceleration voltage of 1–30 kV and with a 200–900 nm spectrum to reveal external and internal structures. These zircons were analyzed using laser ablation (LA) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan, China, using an Agilent 7500a inductively coupled plasma-mass spectrometer (ICP-MS), equipped with a 193 nm excimer laser. Ages were calibrated using a zircon 91500 standard (Wiedenbeck *et al.*, 1995), and an NIST 610 standard was used to optimize trace element concentrations. The analyses used a 24 μm diameter spot and followed Liu *et al.* (2008, 2010). No common lead correction was applied

Fig. 6. (a) LA-ICP-MS U–Pb concordia diagrams and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for zircon grains DJ-1-1 (felsite); (b) LA-ICP-MS U–Pb concordia diagrams and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for zircon grains ZX-9 (porphyritic andesite); (c) LA-ICP-MS U–Pb concordia diagrams and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age for zircon grains TH-12 (porphyritic dacite).

to the data because of the very low ^{204}Pb counts obtained during analysis and poor analytical precision of ^{204}Pb . Ages were calculated using ICPMSDataCal software (ver9.0; China University of Geosciences; Liu *et al.*, 2008), and Concordia diagrams were constructed using Isoplot/Ex ver3.7 (Ludwig, 2003). Zircon trace element composition was calibrated using a GSE-1G standard combined with internal standardization using ^{29}Si (Liu *et al.*, 2010). Errors on individual LA-ICP-MS analyses are quoted at the 95% (1σ) confidence level. Measured isotopic ratios and calculated ages for individual analyses are given in Table 1, and representative CL images of the zircons are shown in Fig. 5. The zircons are generally euhedral, colorless, transparent, and elongate to prismatic, and are up to 240 μm in diameter. They contain clear oscillatory zoning, and some zircons have clear core-rim textures with dark sector-zoned cores (Fig. 5). Concordia diagrams and weighted mean ages are shown for each sample in Figs. 6a–c.

Major and trace elemental analyses

The major and trace element compositions of 10 subvolcanic rock samples were determined during this study. Prior to analysis, whole-rock samples were trimmed to remove altered surfaces, before being crushed and then powdered in an agate mill.

Major elements were analyzed using a PAN analytical Axios X-ray fluorescence spectrometer (XRF) at ALS Chemex Co. Ltd. in Guangzhou, China. Before analysis, 0.9 g of ignited sample was added to 9.0 g of lithium borate flux (50%–50% $\text{Li}_2\text{B}_4\text{O}_7$ – LiBO_2) before being mixed and fused in an auto-fluxer at temperatures between 1050°C and 1100°C, yielding the melt carried in a flat molten glass disc, and then was analyzed by XRF. The precision of the XRF analyses was better than 5%.

Trace element concentrations were determined using an Elan 9000 ICP-MS instrument at the same lab as was used for XRF analysis. Before analysis, 0.2 g of sample was added to a lithium metaborate flux (0.9 g) before the

sample was mixed and then fused in a furnace at 1000°C. The resulting melt was then cooled and dissolved in 100 ml of 4% HNO_3 /2% HCl_3 solution, which was then analyzed by ICP-MS. The precision of the ICP-MS analysis at ALS Chemex was better than 10% for all elements. Major element concentrations are reported as weight percent (wt.%) and trace element concentrations are reported in ppm.

RESULTS

Zircon cathodoluminescence images and U–Pb data

The zircons analyzed during this study have Th and U concentrations as follows: felsite sample DJ-1-1 contains zircons with Th and U concentrations of 77–1000 and 291–1014 ppm, respectively, yielding an average Th/U ratio of 0.47; porphyritic andesite sample ZX-9 contains zircons with Th and U concentrations of 559–1075 and 1103–1755 ppm, respectively, yielding an average Th/U ratio of 0.54; and porphyritic dacite sample TH-12 contains zircons with relatively high Th concentrations (225–1490 ppm), relatively low U concentrations (661–1572 ppm), and an average Th/U ratio of 0.59. Wu and Zheng (2004) determined that magmatic zircons have Th/U that are generally >0.4 ; this means that the oscillatory zoning and average Th/U ratios (0.47 to 0.59) of the zircons analyzed during this study are indicative of a magmatic origin.

Zircons from sample DJ-1-1 are concordant within error and yield a weighted $^{206}\text{Pb}/^{238}\text{U}$ mean age of 168.4 ± 5.0 Ma ($n = 10$; Fig. 6a), interpreted to be the crystallization age of the felsite. Zircon DJ-1-1-9 yielded an older $^{206}\text{Pb}/^{238}\text{U}$ age of 310 Ma (Table 1), although this zircon has a sector zoned core that is much darker than the surrounding magmatic rims (Fig. 5), indicating that this zircon was inherited from the source of the magma that formed this unit or from the surrounding wall rocks during intrusion. Samples ZX-9 and TH-12 have weighted $^{206}\text{Pb}/^{238}\text{U}$ mean ages of 175.5 ± 5.6 ($n = 8$; Fig. 6b) and

Table 2. Chemical compositions of subvolcanic rocks in Dajing deposit

Sample number	DJ-3	DJ-11	DJ-14	DJ10-1	DJ10-3	DJ-2-1	DJ-24	DJ-1-3	ZX-55	ZX-62	TH-13	TH-12	DI-36	YX-15	YX-17	YX-18	YX-20	WT-2
Rock types	Felsite				Porphyritic andesite				Porphyritic dacite									
SiO ₂	76.64	75.17	74.69	76.39	76.25	59.78	61.00	58.83	61.93	59.15	60.23	70.28	69.53	69.59	70.29	69.49	69.53	68.63
Al ₂ O ₃	12.73	12.95	13.82	13.73	13.13	14.56	14.57	17.43	18.71	16.95	16.12	15.10	15.76	15.16	16.57	16.30	15.47	14.99
Fe ₂ O ₃	1.62	0.68	0.03	0.27	0.74	0.19	1.37	0.62	0.55	0.31	0.49	0.42	0.75	0.03	0.03	0.02	0.01	0.03
FeO	2.60	5.60	6.12	5.00	4.60	8.79	11.05	10.05	8.18	10.15	8.50	4.62	6.35	7.79	5.22	4.61	5.14	6.59
MgO	0.69	0.77	0.57	0.30	0.42	5.77	3.29	4.02	1.67	2.62	4.25	1.02	1.41	0.96	0.82	1.01	1.19	2.75
CaO	0.18	0.08	0.22	0.19	0.14	5.14	3.99	4.39	1.93	2.88	5.34	0.89	0.23	0.28	0.27	0.33	0.42	0.45
Na ₂ O	0.14	0.13	0.10	0.15	0.15	5.70	0.12	0.04	0.20	0.27	0.08	1.74	0.18	0.09	0.29	0.89	0.87	0.13
K ₂ O	2.96	3.29	3.19	3.43	3.52	2.97	2.57	2.92	3.40	3.38	2.29	4.05	3.92	3.96	4.45	4.10	4.31	4.25
MnO	0.16	0.10	0.20	0.07	0.08	0.30	0.17	0.18	0.13	0.49	0.13	0.27	0.04	0.13	0.12	0.14	0.04	0.06
TiO ₂	0.10	0.08	0.06	0.09	0.08	0.94	0.93	1.11	0.41	1.37	1.12	0.34	0.58	0.40	0.35	0.42	0.41	0.53
P ₂ O ₅	0.02	0.02	0.01	0.02	0.02	0.44	0.32	0.36	0.13	0.40	0.36	0.08	0.12	0.15	0.16	0.18	0.14	0.22
LOI	0.99	0.62	0.31	0.25	0.74	0.75	0.47	0.15	1.84	1.60	1.12	0.93	0.54	0.68	0.93	1.07	1.12	0.94
Total	98.83	99.48	99.32	99.88	99.86	100.33	99.85	100.10	99.07	99.57	100.03	99.73	99.41	99.22	99.50	98.56	98.65	99.57
Fe ₂ O ₃ ^T	4.51	6.90	6.83	5.83	5.85	9.96	13.65	11.79	9.64	11.59	9.94	5.55	7.81	8.69	5.83	5.14	5.72	7.35
FeO ^T	4.06	6.21	6.15	5.24	5.27	8.96	12.28	10.61	8.67	10.43	8.94	7.82	7.03	7.82	5.25	4.63	5.15	6.62
FeO ^T /MgO	5.88	8.06	10.78	17.48	12.54	1.55	3.73	2.64	5.19	3.98	2.10	4.90	4.98	8.14	6.40	4.58	4.33	2.41
Na ₂ O + K ₂ O	3.10	3.42	3.29	3.58	3.67	3.67	2.69	2.96	3.60	3.65	2.37	5.79	4.10	4.05	4.74	4.99	5.18	4.38
A/CNK	1.54	3.37	3.62	3.32	3.14	1.61	2.21	2.41	3.25	2.52	2.16	1.87	3.32	3.23	2.99	2.63	2.39	2.87
La	11.50	24.80	12.00	27.80	20.20	15.60	18.00	24.40	24.20	18.70	30.40	30.30	31.90	32.00	35.00	29.00	28.00	35.00
Ce	21.90	46.40	21.00	50.10	38.20	34.30	41.50	50.10	46.80	44.20	58.80	63.20	67.80	61.00	65.00	54.00	50.00	65.00
Pr	2.36	4.68	2.20	5.34	4.06	4.54	5.13	6.21	5.39	6.25	6.77	6.95	7.14	6.80	7.10	5.90	5.40	7.20
Nd	8.30	15.50	7.70	18.10	14.40	19.80	22.60	25.90	18.70	26.70	25.50	26.40	26.50	25.00	26.00	21.00	21.00	27.00
Sm	1.65	2.50	1.10	2.96	2.38	4.43	5.48	5.14	3.40	5.80	4.46	4.75	5.18	4.10	4.10	3.60	3.60	4.70
Eu	0.30	0.42	0.20	0.62	0.35	1.35	1.42	1.50	0.92	1.52	1.38	1.12	1.44	1.10	1.20	0.70	0.70	1.10
Gd	1.53	2.14	1.20	2.20	1.88	4.42	5.15	4.56	3.15	5.30	3.72	3.80	4.70	3.30	3.72	2.80	3.00	4.00
Tb	0.25	0.31	0.20	0.38	0.34	0.69	0.77	0.68	0.44	0.78	0.53	0.57	0.73	0.50	0.40	0.40	0.40	0.60
Dy	1.68	1.83	1.60	2.27	1.92	4.02	3.89	3.77	2.03	3.77	2.97	3.26	4.03	2.20	2.20	1.90	2.20	3.00
Ho	0.33	0.36	0.30	0.42	0.37	0.90	0.69	0.82	0.37	0.71	0.64	0.72	0.80	0.40	0.40	0.30	0.40	0.60
Er	1.10	1.10	1.10	1.19	1.13	2.45	1.99	2.14	1.04	1.98	1.67	1.99	2.50	1.00	1.00	1.00	1.20	1.70
Tm	0.17	0.16	0.20	0.21	0.18	0.36	0.27	0.31	0.13	0.26	0.23	0.30	0.35	0.10	0.10	0.10	0.20	0.30
Yb	1.18	1.08	1.30	1.43	1.33	2.17	1.76	1.86	0.84	1.55	1.41	1.90	2.40	0.80	0.90	0.90	1.10	1.50
Lu	0.18	0.16	0.20	0.23	0.20	0.36	0.26	0.29	0.13	0.24	0.22	0.31	0.36	0.10	0.10	0.10	0.20	0.20
ΣREE	52.43	101.44	50.30	113.24	86.94	95.39	108.91	127.68	107.54	117.76	138.70	145.57	155.83	138.40	146.90	121.70	117.40	151.90
LREE/HREE	7.17	13.21	7.25	12.61	10.83	5.21	6.37	7.85	12.23	7.07	11.18	10.33	8.82	15.48	16.28	15.23	12.49	11.76
(La/Lu) _N	6.85	16.61	6.43	13.18	10.99	4.64	7.42	9.02	19.95	8.35	14.81	10.48	9.50	34.30	37.51	31.08	15.00	18.76
(Gd/Lu) _N	1.05	1.65	0.74	1.20	1.18	1.52	2.45	1.94	2.99	2.73	2.09	1.52	1.61	4.08	4.20	3.46	1.85	2.47
δEu	0.57	0.54	0.53	0.71	0.49	0.92	0.80	0.93	0.84	0.82	1.01	0.78	0.88	0.89	0.95	0.65	0.63	0.76
Rb	277.00	310.00	211.00	212.00	251.00	59.60	125.00	215.00	208.00	277.00	128.50	171.00	175.00	310.00	402.00	311.00	462.00	219.00
Ba	413.00	174.50	338.00	327.00	225.00	256.00	245.00	344.00	228.00	247.00	247.00	575.00	447.00	174.00	1577.00	254.00	991.00	1148.00
Th	10.10	11.65	11.30	11.10	12.00	5.01	3.67	3.94	12.40	2.23	7.07	10.70	10.65	13.00	13.70	12.10	14.60	11.10
U	4.88	3.80	6.93	5.46	5.67	1.71	2.37	1.74	2.95	0.63	1.73	2.75	2.86	3.34	3.54	3.26	4.38	2.67
K	24571	27311	26481	28473	29220	24654	21334	24239	28224	28058	19010	33620	32540	32872	36940	34035	35778	35280
Ta	1.60	2.00	2.30	1.95	2.02	0.80	0.80	1.00	0.80	0.60	1.60	1.40	1.40	1.02	1.16	1.12	1.36	1.36
Nb	15.20	16.00	18.34	16.78	16.22	9.60	12.00	14.60	9.60	9.80	22.80	17.60	19.20	11.98	12.70	13.02	12.08	16.96
Sr	22.10	15.90	28.20	34.30	14.20	625.00	69.80	304.00	60.50	112.50	392.00	139.50	20.20	61.80	88.30	53.30	177.00	116.00
P	96.00	74.18	43.64	87.28	78.55	1906.99	1392.06	1579.70	545.48	1732.43	1575.34	340.38	523.66	654.57	698.21	785.49	610.93	960.04
Zr	66.00	63.00	146.00	101.00	79.20	137.00	118.00	159.00	184.00	151.00	232.00	168.00	191.00	440.00	476.00	486.00	634.00	258.00
Hf	2.50	2.60	5.50	3.50	3.36	3.70	3.10	4.20	4.80	3.80	5.50	4.70	5.30	9.88	11.00	10.80	6.81	12.70
Ti	599.50	479.60	359.70	515.57	479.60	5635.29	5575.34	6654.44	2457.95	8213.14	6714.39	2038.30	3477.10	2398.00	2098.25	2517.90	2457.95	3177.35
Y	21.40	20.60	20.00	25.00	21.20	47.20	37.80	44.80	21.20	35.80	33.20	38.80	44.40	22.00	21.40	19.08	23.4	35.8
Ga	17.80	17.60	16.40	-	-	16.80	20.60	24.70	18.60	22.60	20.80	19.10	18.90	19.40	20.00	20.40	21.20	21.20
10000 Ga/Al	2.64	2.57	2.24	-	-	2.18	2.67	2.68	1.88	2.52	2.44	2.39	2.27	2.42	2.28	2.36	2.44	2.67
Zr+Nb+Ce+Y	124.50	146.00	205.34	192.88	154.82	228.10	209.30	268.50	261.60	240.80	346.80	287.60	322.40	534.98	575.10	572.10	343.48	725.38
Y+Nb	36.60	36.60	38.34	41.78	37.42	56.80	49.80	59.40	30.80	45.60	56.00	56.40	63.60	33.98	34.10	32.10	35.48	52.76
Yb+Ta	2.78	3.08	3.60	3.38	3.35	2.97	2.56	2.86	1.64	2.15	3.01	3.30	3.80	1.82	2.06	2.02	2.46	2.86

Data from DJ-3 to DJ-11, DJ-2-1 to DJ-36 are after this paper; data from DJ1-4, YX-15 to WT-2 are after Zhang et al. (2011); data from DJ10-1 to DJ10-3 are after Jiang et al. (2012). “—” entries indicate undetected element concentrations.

Fig. 7. (a) $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs. SiO_2 plots (after Le Bas *et al.*, 1986; IR series is from Irvine and Baragar, 1971); (b) K_2O vs. SiO_2 plots (solid line is from Peccerillo and Taylor, 1976; dotted line is from Middlemost, 1985).

265.9 ± 5.4 Ma ($n = 13$; Fig. 6c), respectively, interpreted to be the crystallization ages of the porphyritic andesite and the porphyritic dacite, respectively.

Major elements

This study focuses on the major and trace element compositions of 18 samples, including some data from earlier studies (e.g., Zhang *et al.*, 2011; Jiang *et al.*, 2012) in this area (Table 2). The sampling locations for the samples of subvolcanic rocks associated with the Dajing deposit are shown in Figs. 2b–d, and are discussed below.

The felsite samples have higher A/CNK values (3.14 to 3.62) than samples from the porphyritic andesite (1.61 to 3.25) and the porphyritic dacite (1.87 to 3.32), with the three A/CNK values indicative of aluminum oversaturation. The porphyritic dacite samples have K_2O concentrations (3.92wt.%–4.45wt.%) that appear to correlate with loss on ignition (LOI) values (0.54wt.%–1.12wt.%; Table 2), indicating that these samples may have undergone muscovite alteration, a hypothesis that was confirmed by petrographic observation (Fig. 4h). The MgO concentrations of the porphyritic andesite samples (1.67wt.%–5.77wt.%) correlate with LOI values (0.15wt.%–1.84wt.%; Table 2), indicating that these samples may have undergone chlorite alteration, again a hypothesis that is corroborated by petrographic observations (Fig. 4f). The felsite samples have FeO concentrations (2.60wt.%–6.12wt.%) that correlate with the LOI values (0.25wt.%–0.99wt.%; Table 2), indicating that these samples have undergone partial chlorite alteration, as confirmed by petrography (Fig. 4c).

The felsite, porphyritic andesite, and porphyritic dacite samples plot in the rhyolite, andesite, and dacite fields of a SiO_2 vs. $\text{K}_2\text{O} + \text{Na}_2\text{O}$ diagram, respectively (Fig. 7a). In addition, the felsite samples are transitional between

high-K calc-alkaline and calc-alkaline in a SiO_2 vs. K_2O diagram (Fig. 7b), whereas the porphyritic andesite and porphyritic dacite samples are dispersed within the high-K calc-alkaline field. Harker diagrams (Fig. 8) indicate that the Al_2O_3 , CaO , MgO , and FeO^T concentrations of these samples negatively correlate with SiO_2 concentrations, whereas K_2O concentrations positively correlate with SiO_2 . In addition, the high K_2O concentrations of the porphyritic dacite samples are indicative of the influence of muscovite, meaning that these samples do not follow linear trends.

Trace elements

Although the samples of all three subvolcanic rocks have somewhat similar REE patterns that are characterized by enrichments in the LREE relative to HREE (Figs. 9a, 9c, and 9e), there are also some differences in the REE systematics of these samples (Table 2).

The felsite samples are characterized by low ΣREE (50.30–113.24 ppm), $(\text{La}/\text{Lu})_N$ (6.43–16.61), and $(\text{Gd}/\text{Lu})_N$ (0.74–1.65) values compared with ΣREE (95.39–138.70 ppm), $(\text{La}/\text{Lu})_N$ (4.64–19.95), and $(\text{Gd}/\text{Lu})_N$ (1.52–2.99) values for samples of the porphyritic andesite. The porphyritic dacite samples have the highest ΣREE (117.40–155.83 ppm), $(\text{La}/\text{Lu})_N$ (9.50–34.30), and $(\text{Gd}/\text{Lu})_N$ (1.52–4.20) values. In addition, the felsite samples have more significantly negative Eu anomalies ($\delta\text{Eu} = 0.49$ to 0.71) than the porphyritic andesite ($\delta\text{Eu} = 0.80$ to 1.01) and porphyritic dacite ($\delta\text{Eu} = 0.63$ to 0.95) samples.

Primitive-mantle-normalized trace element variation patterns for the samples vary somewhat (Figs. 9b, 9d, and 9f), with felsite samples having positive Rb, U, Nd, Zr, and Hf anomalies, and negative Ba, Sr, P, and Ti anomalies, whereas porphyritic andesite samples are character-

Fig. 8. Harker diagrams of the subvolcanic rocks in Dajing deposit, Southern Great Xing'an Range, NE China.

ized by positive Rb and K anomalies and a negative Ba anomaly. In comparison, the porphyritic dacite samples are characterized by positive Rb, Zr, and Hf anomalies, and negative Ba, Sr, P, and Ti anomalies. In addition, felsite, porphyritic andesite, and porphyritic dacite samples plot in fractionated I-type, unfractionated I-type, and A-type granite fields, respectively, in Zr vs. $10000\text{Ga}/\text{Al}$ and FeO^T/MgO vs. $\text{Zr} + \text{Nd} + \text{Ce} + \text{Y}$ diagrams (Figs. 10a and 10b), and the porphyritic dacite samples plot in the A₂-type granitoid field of a Nb vs. Y vs. Ce diagram (Fig. 10c).

DISCUSSION

Granite geochronology in the Dajing deposit and surrounding region

The zircon U–Pb ages of the felsite (168.4 ± 5.0 Ma) and the porphyritic andesite (175.5 ± 5.6 Ma) determined

during this study, combined with earlier LA-ICP-MS zircon U–Pb ages for samples from the Dajing deposit (162 ± 1 and 170.7 ± 1.4 Ma; Liao *et al.*, 2012; Jiang *et al.*, 2012) indicate that the magmatism in this area was simultaneous with the formation of 190–160 Ma Middle Jurassic granitoids in the Zhangguangcai Range and the Erguna Massif (Fig. 1a; Wu *et al.*, 2011). In addition, numerous other Middle Jurassic granitoids were emplaced in the southern Great Xing'an Range (Table 3), including granitoids in the Chifeng City, Xing'anmeng City, and Xilinguolemeng City areas (e.g., granitoids within the Naoniushan, Lianhuashan, Budunhua, Mengentaolegai, Baiyinnuor, Dashizhai, Jingyang, Ma'anzi, Zhangwuying, and Manketouebo formations), which have ages that cluster around 182 to 160 Ma.

The U–Pb age of 265.9 ± 5.4 Ma for the porphyritic dacite in the study area indicates that this unit formed during the late Permian, and is the equivalent of 290–260

Fig. 9. (a) Chondrite-normalized REE patterns for the felsite in Dajing deposit; (b) Primitive mantle-normalized spider diagrams for the felsite in Dajing deposit; (c) Chondrite-normalized REE patterns for the porphyritic andesite in Dajing deposit; (d) Primitive mantle-normalized spider diagrams for the porphyritic andesite in Dajing deposit; (e) Chondrite-normalized REE patterns for the porphyritic dacite in Dajing deposit; (f) Primitive mantle-normalized spider diagrams for the porphyritic dacite in Dajing deposit; Abundances for Chondrite and Trace element abundances for primitive mantle are after Sun and McDonough (1989).

Ma Permian A-type granites (Wu *et al.*, 2002) of the Lesser Xing'an Range and Inner Mongolia along the Hegenshan–Heihe suture (Fig. 1a).

In summary, the Dajing deposit and adjacent areas underwent three stages (Fig. 11) of magmatism: (1) Late Permian magmatism (280–266 Ma) that formed intrusions such as the Ma'anzi biotite monzogranite to the NW of the Dajing deposit (Fig. 1b; 279.7 Ma; Jiang *et al.*, 2012) and the porphyritic dacite within the Dajing deposit was dated during this study (265.9 ± 5.4 Ma); (2) Middle

Jurassic magmatism (176–162 Ma), including the formation of the felsite (170.7–162 Ma, Liao *et al.*, 2012; Jiang *et al.*, 2012; this paper) and the porphyritic andesite (175.5 ± 5.6 Ma) that were dated during this study, both of which are within the Dajing deposit; and (3) Early Cretaceous magmatism (146–125 Ma), including the formation of the Ma'anzi, Longtoushan and Yelaigai intrusions (Fig. 1b; 146–125 Ma, Liu *et al.*, 2009) to the NW of the Dajing deposit.

Fig. 10. (a) Zr vs. 10000Ga/Al classification diagrams (Whalen *et al.*, 1987); (b) FeO^T/MgO vs. Zr + Nb + Ce + Y classification diagrams (Whalen *et al.*, 1987); (c) The A₁ and A₂ subgroup discriminations of A-type granites (Eby, 1992); FG: Fractionated felsic granites; OGT: unfractionated M-, I- and S-type granites; A₁ suggest a post-orogenic tectonic setting; A₂ show an anorogenic environment.

Source and petrogenesis of the subvolcanic rocks

The majority of granites in northeast China were emplaced between the late Paleozoic and the late Mesozoic. These granites have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.705 ± 0.001), positive $\epsilon_{\text{Nd}}(T)$ values (+4 to 0), and fairly young T_{DM} model ages (1300–500 Ma). Jurassic basalts within the Manketouebo Formation of the southern Great Xing'an Range have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70489–0.70499), low $\epsilon_{\text{Nd}}(T)$ values (–0.1 to 0.7), and young $T_{\text{DM}2}$ ages (830–770 Ma) (Fan *et al.*, 2008). Liu *et al.* (2005) reported that Linxi granitoids (Ma'anzi, Yelaigai, and Longtoushan intrusions in Fig. 1b) have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.701764–0.707654 and $\epsilon_{\text{Nd}}(T)$ values of –2.89 to +5.60. In addition, Huang *et al.* (1986) used geophysical data and mathematical modeling to suggest that the Linxi granitoids are linked at depth and form a single granitic stock under the Dajing deposit, with Liu *et al.* (2001) using geochemical data to suggest that the Linxi granitoids and subvolcanic rocks in this area have a common source. This indicates the existence of genetic relationships be-

tween the Linxi granitoids and subvolcanic rocks within the Dajing deposit. In addition, the porphyritic dacite in the study area has a positive $\epsilon_{\text{Nd}}(T)$ value (+3.45) and a young T_{DM} model age (562.8 Ma, e.g., Xiao *et al.*, 2004), similar to the Sr–Nd compositions of rocks in the surrounding area (e.g., Linxi granitoids). Previously published data suggest that the subvolcanic rocks in this area were derived from partial melting of depleted lithospheric mantle or depleted mantle that contained crustal material.

Tectonic setting

Late Paleozoic to Mesozoic intrusive rocks are widespread throughout northeast China. These magmatic events have been the focus of a significant amount of geological, petrological, and geochronological research, but the tectonic setting of these events remains controversial. Four main models have been proposed to explain these magmatic events: (1) magmatism associated with a mantle plume or other intraplate process (Ge *et al.*, 2000;

Table 3. The Middle Jurassic magmatic and volcanic activities events in the Southern Great Xing'an Range

Location	Intrusives/volcanic rocks	Lithology	Age (method)	References
Linxi, Chifeng	Dajing	Felsite, porphyritic andesite	162–175 Ma (LA-ICP-MS zircon U–Pb)	Jiang <i>et al.</i> , 2012; Liao <i>et al.</i> , 2012; this paper
Linxi, Chifeng	Ma'anzi	Biotite syenogranite	165 Ma (Inherited zircon SHRIMP U–Pb)	Liu <i>et al.</i> , 2009
Linxi, Chifeng	Zhangwuying	Diabase	170.4 Ma (K–Ar)	Shao <i>et al.</i> , 1998a
Lingcheng, Chifeng	Banqiaogou	K-feldspar granite	167 Ma (Rb–Sr)	Shao <i>et al.</i> , 1998b
Duolun, Xilinguolomeng	Erdaogou	Andesite	178.79 ± 7.6 Ma (Rb–Sr)	Shao <i>et al.</i> , 1998b
Wulanhaote, Xing'anmeng	Dashizhai	Biotite granite	182 ± 3 Ma (Zircon LA-ICP-MS U–Pb)	Ge <i>et al.</i> , 2005
Wulanhaote, Xing'anmeng	Jingyang	Biotite granodiorite	174 ± 4 Ma (Zircon LA-ICP-MS U–Pb)	Ge <i>et al.</i> , 2005
Maoshandong and Manitu, Chifeng	Manketoubo Formation	Rhyolite	174 ± 4 Ma, 160–165 Ma (Zircon LA-ICP-MS U–Pb)	Zhang <i>et al.</i> , 2010
Tuquan, Xing'anmeng	Naoniusan	Dioritic porphyrite	161.8 Ma (Rb–Sr)	Zhao and Zhang, 1997
Tuquan, Xing'anmeng	Lianhuashan	Dioritic porphyrite	161 Ma (U–Pb)	Kang <i>et al.</i> , 2004
Kerqinyuizhongqi, Xing'anmeng	Budunhua	Plagiogranite porphyry, dioritic porphyrite	151–154 Ma (Zircon SHRIMP U–Pb)	Feng, 2010
Kerqinyuizhongqi, Xing'anmeng	Mengentaolegai	Biotite plagiogranite, Muscovite plagiogranite	179.0 ± 1.5 Ma (Muscovite Ar–Ar)	Zhang <i>et al.</i> , 2003
Balinzuqi, Chifeng	Baiyinnuor	Dioritic porphyrite	171 Ma (Rb–Sr)	Zhang <i>et al.</i> , 1991

Fig. 11. Histogram of the three magmatic stages in this area and adjacent areas. Zircon U–Pb age data in the Late Permian magmatism are after Jiang *et al.* (2012) and this paper. Zircon U–Pb age data in the Middle Jurassic magmatism are after Liao *et al.* (2012), Jiang *et al.* (2012) and this paper. Zircon U–Pb age data in the Early Cretaceous magmatism are after Liu *et al.* (2009).

Shao *et al.*, 2005), (2) magmatism associated with subduction of the Paleo-Mongol–Okhotsk Ocean or post-orogenic extension after the closure of this ocean (Meng, 2003; Lin *et al.*, 2004), (3) magmatism associated with an active continental margin related to the Mesozoic subduction of the Paleo-Pacific Plate (Wu *et al.*, 2005), or (4) magmatism associated with lithospheric delamination (Wang, F. *et al.*, 2006).

These conflicting models for the tectonic setting of this area must also incorporate spatial variations in tectonic stress, including the tectonic stress caused by the post-orogenic extension of the Xingmeng Orogenic Belt, tectonic stress associated with closure of the Mongol–Okhotsk Ocean, and tectonic stress caused by westward subduction of the Paleo-Pacific Plate (Wu *et al.*, 2002, 2011; Meng, 2003).

As stated above, numerous late Permian (290–260 Ma) A-type granites formed in this area during post-orogenic extension, including the 265.9 ± 5.4 Ma (late Permian) porphyritic dacite within the Dajing deposit. This unit is classified as an A₂-type granitoid and is associated with post-orogenic extension of the Xingmeng Orogenic Belt, and the majority of samples from this unit plot in post-collisional fields of Rb vs. (Y + Nb) and Rb vs. (Yb + Ta) discrimination diagrams (Figs. 12a and 12b). In addition,

Fig. 12. (a) Rb vs. Y + Nb diagrams; (b) Rb vs. Yb + Ta diagram; (a) and (b) are from Pearce, 1996. VAG, Volcanic arc granite; ORG, ocean ridge granite; WPG, within-plate granite; Syn-COLG, Syn-collision granite.

Wu *et al.* (2002) suggested that the post-orogenic tectonic setting could be explained by a slab break-off model, suggesting that the magmatism that formed this porphyritic dacite was associated with post-collisional slab break-off.

The felsite and the porphyritic andesite in the Dajing deposit are I-type granitoids that were intruded at 168.4 ± 5.0 and 175.5 ± 5.6 Ma, respectively, both of which formed prior to the initiation of large-scale westward subduction of the Paleo-Pacific Ocean (140 Ma). This indicates that the westward subduction of the Paleo-Pacific Ocean had no effect on the study area. In addition, the Dajing deposit is located in the southern Great Xing'an Range, far from the Mongol–Okhotsk Ocean, indicating that this area was minimally affected by the closure of this ocean at ~ 160 Ma. These findings indicate that both the felsite and the porphyritic andesite formed during the post-orogenic extension of the Xingmeng Orogenic Belt in an area that was influenced by far-field effects associated with the closure of the Mongol–Okhotsk Ocean. This inference is supported by the fact that the majority of samples from these intrusions plot in post-collisional fields of Rb vs. (Y + Nb) and Rb vs. (Yb + Ta) discrimination diagrams (Fig. 12a and 12b), suggesting that the post-orogenic tectonic setting of this area was related to lithospheric delamination (Wu *et al.*, 2002).

CONCLUSIONS

The geochronological and geochemical data presented here allow the following conclusions to be reached.

(1) Felsite, porphyritic andesite, and porphyritic dacite subvolcanic rocks are associated with the Dajing deposit. Zircon LA-ICP-MS U–Pb dating of these units indicates

that the porphyritic dacite was intruded at 265.9 ± 5.4 Ma (late Permian) in a tectonic setting associated with post-collisional slab break-off. The felsite and the porphyritic andesite were intruded at 168.4 ± 5.0 and 175.5 ± 5.6 Ma, respectively, and both most likely formed in a post-collisional extensional setting within the Xingmeng Orogenic Belt that was influenced by far-field effects of the closure of the Mongol–Okhotsk Ocean.

(2) The subvolcanic rocks associated with the Dajing deposit are high-K and calc-alkaline, and have high A/CNK ratios ($A/CNK > 1$). They are all preferentially enriched in LREE compared with HREE, and the felsite is characterized by relatively high concentrations of Rb, U, Nd, Zr, and Hf, and relatively low concentrations of Ba, Sr, P, and Ti, similar to highly fractionated I-type granites. The porphyritic andesite contains relatively high concentrations of Rb and K, and relatively low concentrations of Ba, similar to unfractionated I-type granites. The porphyritic dacite is enriched in Rb, Zr, and Hf, is depleted in Ba, Sr, P, and Ti, and is compositionally similar to A_2 -type granites.

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