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High-Mg adakitic rocks in the Dabie orogen, central China: Implications for foundering mechanism of lower continental crust

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ABSTRACT

The late Mesozoic high-Mg adakitic rocks from Eastern and Central China provide important insight into the foundering mechanism of the over-thickened lower continental crust. The Chituling high-Mg adakites (131 ±3 Ma, SHRIMP zircon U–Pb age) from the eastern margin of the Southern Dabie ultrahigh pressure metamorphic zone, adjacent to the Tan–Lu fault, have high Al_2O_3 and Sr contents, high Sr/Y, La/Yb, and Mg# (44–63), but low Y and Yb contents. The samples also have moderately enriched $^{87}Sr/^{86}Sr_i$ (0.70691–0.70775), very low $\varepsilon_{Nd}(T)$ (−20.7 to −24.9), unradiogenic Pb isotopes, enrichment of large ion lithophile elements, and depletion of high field strength elements. These geochemical features indicate that they did not result from melting of young oceanic crust, assimilation and fractional crystallization, or magma mixing. Instead, they were derived from partial melting of delaminated lower continental crust, with subsequent reaction with surrounding mantle peridotites during ascent to crustal depths. The reactions between the adakitic melt and peridotites also generated the enriched mantle source of the post-collisional basaltic rocks in the Dabie orogen. Distribution of the late Mesozoic high-Mg adakites in eastern and central China generally forms a high-Mg adakite belt along the southern Tan–Lu fault. Therefore, we propose that the large strike-slip motion of the Tan–Lu fault in eastern and central China due to the western subduction of the Pacific plate in the early Cretaceous might trigger the foundering of some fragments of the over-thickened lithosphere near the Tan–Lu fault, which caused mantle upwelling and partial melting of the thickened lower crust in the Dabie orogen and eastern boundary of the North China Craton. This further weakened the gravitationally instable lithosphere, consequently resulting in delamination and foundering of the mountain root underneath the Dabie orogen, which could be an important foundering mechanism of lower continental crust.

1. Introduction

Recycling of crustal materials to the mantle has been mainly attributed to recycling of subducted oceanic crust, a process that is important for forming the enriched end members in oceanic basalts (e.g., Hofmann (2003) and references therein). More recently, geochemical evidence indicates that materials from deep continental crust can also be recycled to the mantle, playing an important role in generation of mantle heterogeneities. The possible mechanisms for continental crustal recycling include fore-arc thermal erosion during subduction of oceanic crust (Goss and Kay, 2006), delamination or foundering of dense garnet-bearing rocks (e.g., eclogite and garnet pyroxenite) in mafic lower crust to the mantle during continental orogenesis (Kay and Kay, 1993; Gao et al., 1998,2004; Lee et al., 2007), deep subduction of continental crust (Huang et al., 2007), and return of terrestrial sediments into mantle plume by subduction (Jackson et al., 2007). The key issues include how the continental crustal materials are recycled, how to trace the recycled materials, and to what extent the recycled continental materials contribute to the heterogeneities of the uppermost mantle.

The Dabie orogen is a collisional zone between the North China Block (NCB) and South China Block (SCB) in central China. The ultrahigh pressure metamorphic (UHPM) rocks exposed in the Dabie orogen suggest that the continental crust of the SCB was subducted to the depth of greater than 100 km in the Triassic (e.g., Wang et al., 1989; Okay et al., 1989; Li et al., 1989; Xu et al., 1992; Li et al., 1993, 2000; Ye et al., 2000). However, geophysical investigation shows the absence of a deep mountain root in the Dabie orogen with an average crust thickness of 34 km (Gao et al., 1998). This suggests that the mountain root, as well as the thickened mafic lower continental crust, may have foundered and consequently been recycled into the underlying uppermost mantle. Therefore, the Dabie orogen provides an excellent opportunity to study continental crust recycling by foundering of

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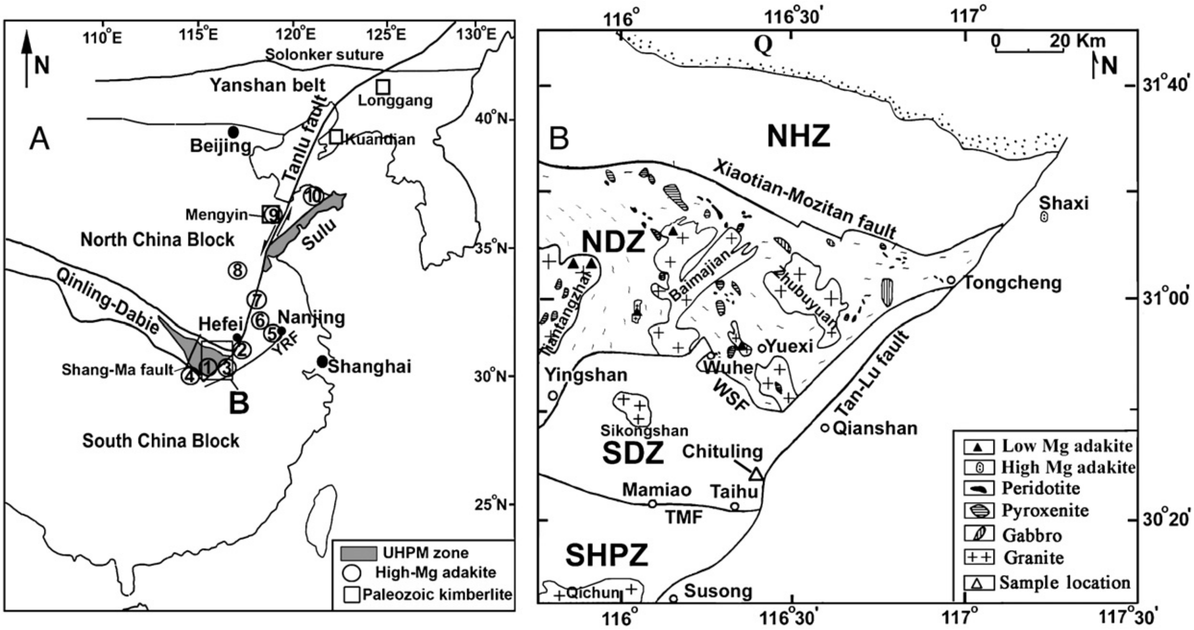


Fig. 1. A, Geological sketch map of Eastern China and distribution of high-Mg adakites in eastern China generally forming a belt along the southern Tan–Lu fault. The localities of high-Mg adakites are referred to Table 1. B, Distribution of adakites in Eastern Dabie orogen. Adakitic rocks inside the Dabie orogen are low-Mg adakites, while the high-Mg adakite (e.g., Chituling) is close to the Tan–Lu fault. The localities of low-Mg adakites are from Wang et al. (2007a) and Xu et al. (2007). Acronyms of faults: YRF, Yangtze River fault; TMF, Taihu–Mamiao fault; and WSF, Wuhe–Shuihou fault.

over-thickened lower continental crust. However, there is still a lack of evidence for the foundering of the lower continental crust underneath the Dabie orogen, which is critical for understanding the mountain root removal, large-scale magmatism in the early Cretaceous, and generation of the enriched mantle source of the post-collisional mafic–ultramafic intrusive rocks in the Dabie orogen.

Adakites, defined by their special geochemical features (i.e., high Al_2O_3 and Sr content, high Sr/Y and La/Yb, and low Y and Yb contents) (Defant and Drummond, 1990), have recently been documented in the North Dabie complex (Wang et al., 2007a; Xu et al., 2007). Adakitic rocks developed in continental collisional zones provide valuable geochemical information about thickened mafic lower continental crust (e.g., Chung et al., 2003). The Dabie orogen adakites reported, however, generally have high SiO_2 content (>65 wt.%) and low Mg# (most of them <45), produced by partial melting of the thickened mafic lower crust and basically indicate no interaction with the upper mantle (Wang et al., 2007a; Xu et al., 2007). Without interaction with peridotite, adakitic melts created through melting experiments of metabasalts and eclogites at 1–4 GPa usually have Mg# lower than 45 (Sen and Dunn, 1994; Rapp and Watson, 1995; Rapp et al., 1999). Therefore, recently reported studies on high-Mg adakites (i.e., adakites with Mg# greater than 45) in the North and South China Block provide important insight into the crust–mantle interaction and the mechanism of continental crust recycling (Fig. 1A) (e.g., Xu et al., 2002; Gao et al., 2004; Xu et al., 2006; Wang et al., 2007b; Xu et al., 2008).

Here we report geochronology, major-trace element and Sr–Nd–Pb isotopic compositions of the early Cretaceous high-Mg adakites from the Chituling diorites in the east margin of the Southern Dabie UHPM zone, adjacent to the Tan–Lu fault. The purposes of this study are to provide (1) evidence for foundering of the lower continental crust in the Dabie orogen, (2) geochemical connections between the recycled lower continental crust, the post-collisional basaltic intrusive rocks, and the high-Mg adakites, and (3) constraints on the foundering mechanism of the lower continental crust and lithospheric thinning processes based on the distribution of the Mesozoic high-Mg adakites along the south Tan–Lu fault.

2. Geological setting and sample description

The Dabie orogen is part of the Qinling–Dabie–Sulu orogen, a Triassic collision zone between the North and South China Blocks. On the eastern end of the Dabie orogen, the Tan–Lu fault displaced the Sulu orogen northward by ~500 km (Fig. 1A). The Dabie orogen is

Table 1
Locations of the mid- to late-Mesozoic high-Mg adakites along Southern Tanlu fault and Yangtze River fault in Eastern China

Location	Rock type	Age (Ma)	Dating method	Mg#	Reference
Chituling, Dabie (1)	Diorite	131±3	SHRIMP zircon U–Pb	44–63	This study
Shaxi–Luzong (2)	Quartz diorite	136±3	SHRIMP zircon U–Pb	45–60	Wang et al., (2006a)
Yueshan–Zongpu (3)	Diorite, monzodiorite, granodiorite, granite	132–133	Biotite and hornblende K–Ar	46–55	Chen et al., 1991; Qiu and Dong, (1993); Wang et al., (2004)
Tongshankou, Daye (4)	Porphyry granodiorite	147±3	SHRIMP zircon U–Pb	46–50	Wang et al., (2007b)
Ningzhen (5)	Diorite	106–123	Whole rock K–Ar	40–60	Xia, 2000; Xu et al., (2002)
Chuzhou (6), Sulu belt	Porphyritic andesite	~114	Whole rock K–Ar	52–58	Guo et al., (2006)
Guandian, Jiashan (7)	Granite, granodiorite	119–132	Whole rock K–Ar	56–59	Niu et al., (2002)
Xuzhou–Suzhou (8)	Diorite, monzodiorite	131–132	SHRIMP zircon U–Pb	49–61	Xu et al., (2006)
Laiwu (9)	Diorite	131–134	LA-ICP-MS zircon U–Pb	63–67	Yang et al., 2006; Xu et al., (2008)
Jiaonan (10)	Potassic volcanic rocks	98.1–106.2	Zircon U–Pb	~60	Ling et al., (2007)

Table 2
SHRIMP U–Pb isotopic data for zircons from the Chituling diorite, Southern Dabie orogen

Spot	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	Th/U	$^{207}Pb^*/^{206}Pb^*$	± %	$^{207}Pb^*/^{235}U$	± %	$^{206}Pb^*/^{238}U$	± %	$^{206}Pb^*/^{238}U$ age (Ma)	
05LJW11	11.22	102.07	190.97	1.93	–	–	–	–	0.0138	15	88	±13
05LJW12	5.45	95.72	200.67	2.17	0.034	54	0.094	54	0.01998	4.2	127.5	±5.4
05LJW13	1.68	115.94	214.11	1.91	0.0575	15	0.169	16	0.02126	3.8	135.6	±5.1
05LJW14	3.62	150.32	389.46	2.68	0.041	28	0.112	28	0.01985	3.7	126.7	±4.6
05LJW15	1.56	157.41	320.38	2.10	0.0485	12	0.139	12	0.02081	3.5	132.8	±4.6
05LJW16	8.13	117.89	276.72	2.43	–	–	–	–	0.01671	4.5	106.8	±4.8
05LJW17	1.71	163.27	370.59	2.35	0.0468	9.9	0.133	10	0.02067	3.4	131.9	±4.4
05LJW18	2.17	163.04	354.12	2.24	0.0415	21	0.117	21	0.02055	3.5	131.1	±4.6
05LJW19	6.42	119.84	226.74	1.95	0.021	94	0.06	93	0.02098	4.3	133.9	±5.8
05LJW110	6.64	100.78	193.36	1.98	0.046	47	0.128	47	0.0203	4.5	129.6	±5.8
05LJW111	1.87	143.59	282.95	2.04	0.0491	16	0.144	17	0.02125	3.5	135.6	±4.7
05LJW112	3.03	159.34	326.46	2.12	0.041	27	0.115	27	0.02035	3.7	129.9	±4.7

Pb_c and Pb* indicate the common and radiogenic portions respectively. Common Pb was corrected using measured ^{204}Pb. 05LJW11 and 05LJW16 are eliminated for age calculating as outliers. Errors on individual spots are at the 1σ level, but the uncertainty of average weighted age is 2σ or 95% confidence.

further divided by the Shang–Ma fault into the eastern and western portions. The eastern Dabie orogen is composed of four major units from north to south (Li et al., 2001): (1) the North Huaiyang zone (NHZ), a low grade metamorphic terrane in the Dabie orogen which was scraped from subducting crust of the SCB (Zheng et al., 2005); (2) the Northern Dabie high P/T metamorphic zone (NDZ), where high temperature Triassic eclogites have been observed (Liu et al., 2000; Xu et al., 2000); (3) the Southern Dabie UHPM zone (SDZ) with coesite and diamond-bearing eclogites (Wang et al., 1989; Xu et al., 1992); and (4) the Susong lower temperature UHPM zone (SHPZ) containing "cold" coesite-bearing eclogite (Li et al., 2004). Intrusive igneous rocks are abundant and widely distributed in the eastern Dabie orogen at the early Cretaceous (Fig. 1B), while a smaller volume of igneous rocks occurs in the western Dabie orogen. The predominant igneous rocks in the Dabie orogen are granites, which cover ~50% of area of the NDZ (e.g., Tiantangzhai, Baimajian, and Zhubuyuan) (Chen et al., 2002; Zhao et al., 2004). Lesser volumes of granites are developed in the SDZ, SHPZ, and NHZ regions, with Sikongshan, Qichun, and Shangcheng being the largest granitic plutons in the SDZ, SHPZ and NHZ, respectively. Some of the older granitic plutons (143–130 Ma) have adakitic geochemical features with low Mg# (Wang et al., 2007a; Xu et al., 2007), while granites younger than 120 Ma generally have a higher Yb and Y concentration relative to those in adakites (Zhang et al., 2002; Wang et al., 2007a). The 123–130 Ma mafic intrusions are mainly pyroxenite-gabbros and basaltic diabases distributed in the NDZ (Jahn et al., 1999; Li et al., 1999; Wang et al., 2005; Zhao et al., 2005). Intermediate diorites mainly occur as small intrusions like the Xiaozhai pluton (Ma et al., 1998). Due to slight deformation, intermediate diorites were normally named as gneisses with ages of about 130 Ma (Hacker et al., 1998). Late Mesozoic volcanic rocks (basaltic trachyandesite, trachyandesite, and trachyte) mainly occur within the NHZ (Fan et al., 2004).

The samples of interest were collected from the Chituling dioritic intrusion, located in the northeast of Taihu county, Anhui province, close to the Tan–Lu fault in the SDZ with latitude of 30.48 N and longitude of 116.32 E (Fig. 1A and B). This intrusion is also considered as the dioritic portion of the Liujiawa complex in the literature (e.g., Ma et al., 1998, 2003). The ~1 km^2 outcrop of the intrusion is mainly composed of equigranular diorites absent of enclaves or deformation. The Chituling diorites intrude into Neoproterozoic granitic gneisses (with protolith ages of ~750 Ma), which had undergone ultrahigh pressure metamorphism in the Triassic (Zheng et al., 2004). Petrographic observations by optical microscope show that the samples are mainly composed of <2 mm amphibole and plagioclase crystals with a minor amount of opaque minerals. Modes of plagioclase are generally greater than 60%, and no quartz or pyroxene was observed in the samples.

3. Analytical procedures

Samples were treated by the same methods as described in Huang et al. (2007) in order to avoid metal contamination. In brief, fresh rock

Table 3
Major element compositions (wt.%) of the Chituling diorites

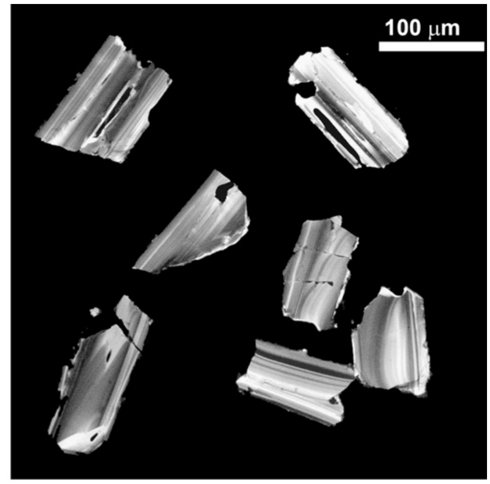
Sample no.	00CT-1	00CT-2	00CT-3	00CT-4	00CT-5	00CT-6	00CT-6*	04CTL-1	04CTL-2	GBW07104**		GBW07105**	
										Meas. (n=2)	True	Meas. (n=2)	True
SiO_2	61.65	58.81	57.18	57.4	59.65	59.31	59.52	57.92	63.56	60.59(36)	60.62	44.76 (32)	44.64
TiO_2	0.66	0.92	0.97	0.89	0.59	0.63	0.64	0.85	0.65	0.51(1)	0.52	2.35(0)	2.36
Al_2O_3	16.27	15.85	15.75	15.51	14.38	14.75	14.87	15.94	16.18	16.10(10)	16.17	13.39(16)	13.83
Fe_2O_3	2.39	3.01	2.96	2.96	2.25	2.16	2.21	7.09	4.98	2.26(15)	2.20	4.60(4)	4.96
FeO	2.82	3.5	3.95	4.07	2.69	3.13	3.10	–	–	2.34(1)	2.39	7.75(10)	7.60
MnO	0.1	0.1	0.11	0.12	0.08	0.09	0.09	0.13	0.14	0.08(1)	0.08	0.17(1)	0.17
MgO	2.13	3.51	3.81	3.73	4.4	4.55	4.96	4.03	2.26	1.69(6)	1.72	7.66(9)	7.77
CaO	4.64	5.52	6.09	6.17	4.03	4.66	4.72	5.18	3.87	5.18(2)	5.20	8.82(2)	8.81
Na_2O	3.23	3.75	3.28	3.84	3.55	3.09	3.43	3.69	4.18	3.74(10)	3.86	3.46(9)	3.38
K_2O	3.35	3.13	2.82	2.5	3.04	3.15	3.12	2.55	3.48	1.88(1)	1.89	2.33(1)	2.32
P_2O_5	0.31	0.37	0.38	0.35	0.22	0.24	0.23	0.38	0.3	0.23(1)	0.24	0.88(1)	0.95
Total	99.42	100.17	99.81	99.45	99.4	99.49	99.99	99.59	100.26				
Na_2O/K_2O	0.97	1.2	1.16	1.54	1.17	0.98	1.10	1.45	1.2				
Mg#	44	50	51	50	63	62	64	53	48				

* Duplicate analysis.
** GBW07104 and GBW07105 are Chinese national standards for andesites and basalts, respectively. 60.59(36) reads as 60.59±0.36. The errors stand for 1σ of 2 duplicated analyses.

Table 4
Trace element compositions (ppm) of the Chituling high-Mg adakites

Sample	00CT-1	00CT-2	00CT-3	00CT-4	00CT-5	00CT-6	04CTL-1	04CTL-2
Sc	8.6	13.8	6.9	16.2	12.6	13.6	16.0	8.4
V	82	123	138	117	93	99	126	76
Cr	36	66	76	85	228	246	85	38
Co	12	19	22	22	20	21	21	11
Ni	15	33	44	39	86	87	27	19
Rb	72	75	63	53	81	82	76	91
Sr	740	760	780	750	570	580	650	750
Y	17	20	18	20	13	14	21	15
Zr	*120*	*240*	*220*	*220*	*160*	*160*	200	210
Nb	9.3	9.2	8.8	8.1	8.2	8.3	9.6	11.6
Cs	2.1	1.7	1.8	1.5	7.4	6.4	3.3	2.4
Ba	1740	1690	1780	1340	1340	1310	1270	1640
La	57	61	56	47	33	34	42	53
Ce	102	114	110	89	61	63	79	97
Pr	11	13	13	11	7	7	9	11
Nd	41	49	48	41	26	27	35	38
Sm	5.9	7.2	7.5	6.4	4	4.3	6.0	5.9
Eu	1.6	1.9	1.9	1.8	1.1	1.3	1.8	1.7
Gd	4.3	5.3	5.3	5.1	3.1	3.3	5.2	4.7
Tb	0.63	0.78	0.77	0.72	0.47	0.5	0.72	0.59
Dy	3.2	3. 8	3.8	3.6	2.4	2.6	3.8	2.9
Ho	0.58	0.69	0.68	0.69	0.46	0.50	0.75	0.53
Er	1.6	1.9	1.8	1.8	1.3	1.4	2.0	1.4
Tm	0.23	0.26	0.25	0.27	0.19	0.21	0.29	0.19
Yb	1.5	1.7	1.6	1.7	1.2	1.3	1.9	1.2
Lu	0.24	0.27	0.25	0.27	0.21	0.21	0.29	0.18
Hf	*2.9*	*5.3*	*5.1*	*5.1*	*4.0*	*3.9*	4.8	5.5
Ta	0.6	0.56	0.52	0.48	0.58	0.58	0.57	0.75
Pb	18	15	17	14	23	22	8	25
Th	6.6	6.5	3.9	4.5	4.2	4.1	5.2	9.0
U	1.2	0.9	0.8	0.7	1.5	1.4	1.1	1.8
∑REE	232	262	250	210	141	147	188	219
Eu/Eu*	0.95	0.92	0.94	0.95	0.97	1.01	1.00	0.95
La/Yb	37	37	36	29	27	26	22	44
Sr/Y	43	38	45	38	42	40	31	49
δSr	0.79	0.72	0.78	0.89	1.02	0.99	0.88	0.86

$Eu^* = Eu_N/(Sm_N \times Gd_N)^{1/2}$, N is the chondrite normalization value. $\delta Sr = 2Sr_n/(Ce_n + Nd_n)$, n is the primitive normalization value (Sun and McDonough, 1989). Zr and Hf contents of 00CT-1, -2, -3, -4, -5, and -6 are likely in error because zircons in these samples may not be digested in Savillex Teflon screw-top beakers.



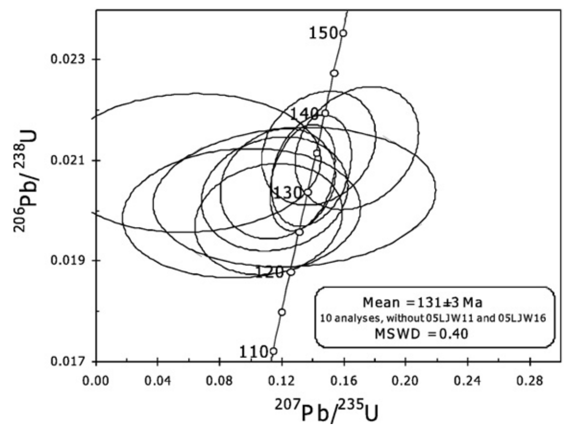


Fig. 2. SHRIMP zircon U–Pb concordia diagram for the Chituling diorites and representative CL images for single zircons. Data are from Table 2. The uncertainty of average weighted age is 2σ or 95% confidence.

chunks were cut using a diamond saw, and trace iron was removed from the surface by silicon carbide sandpaper. The rock slices were then wrapped in a cloth and crushed into pieces of ~1 cm using a plastic coated hammer. After rinsing three times with distilled water, the samples were pulverized in an agate mortar in the Institution of Regional Geology and Mineral Investigation of Hebei, China, where zircons were also extracted and selected from crushed rock samples by handpicking under a binocular microscope.

Zircon U–Pb dating for the Chituling diorite was conducted using the SHRIMP II at Beijing SHRIMP center in the Chinese Academy of Geological Sciences (Table 2), following the conventional method described in Compston et al. (1992) and Williams (1998). Common Pb correction was based on measured ^{204}Pb. Zircon U–Pb ages were calculated using the ISOPLOT program (Ludwig, 2001).

Major elements of all samples except 04CT-1 and 04CT-2 were analyzed XRF spectrometry at the Institute of Geophysical and Geochemical Exploration, Langfang, Hebei, China (Table 3). FeO

Table 5
Sr–Nd–Pb isotopic compositions of the Chituling high-Mg adakites

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ (±2δ)	$^{87}Sr/^{86}Sr_i$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (±2δ)	ε_{Nd} (*T*)	T_{DM} (Ga)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb_i$	$^{207}Pb/^{204}Pb_i$	$^{208}Pb/^{204}Pb_i$	Δ7/4	Δ8/4
00CT-1	72.01	771.2	0.2702	0.707745±35	0.70725	5.714	35.54	0.09717	0.511354±22	−23.4	2.34	16.00	15.23	36.74	15.92	15.23	36.74	1.33	186.4
00CT-2	73.07	802.8	0.2634	0.708181±23	0.70769	7.213	42.91	0.1016	0.511309±12	−24.4	2.49	15.98	15.23	36.81	15.91	15.23	36.81	1.44	194.6
00CT-3	62.83	844.3	0.2153	0.708147±23	0.70775	7.606	45.41	0.10124	0.511281±22	−24.9	2.52								
00CT-4	53.86	816.5	0.1909	0.707379±19	0.70703	6.405	36.85	0.10503	0.511313±23	−24.3	2.56	15.87	15.17	36.62	15.81	15.17	36.62	−3.5	187.7
00CT-5	83.64	582.5	0.4155	0.707682±25	0.70691	4.513	26.77	0.10191	0.511494±20	−20.7	2.25	15.96	15.24	36.81	15.88	15.24	36.81	2.76	198.3
00CT-6	83.18	658.9	0.3653	0.707905±23	0.70723	5.709	33.02	0.10448	0.511467±23	−21.3	2.34	15.94	15.25	36.81	15.86	15.25	36.81	3.98	200.7
04CTL-1												16.46	15.31	37.35	16.29	15.3	37.35	4.32	202.7
04CTL-2												16.11	15.25	36.95	16.02	15.25	36.95	2.24	195.3

Initial isotopic ratios are calculated to 130 Ma. Initial Pb isotopic ratios are calculated using the whole rocks U, Th, Pb contents by ICP-MS. Chondritic uniform reservoir (CHUR): $^{147}Sm/^{144}Nd = 0.1967$; $^{143}Nd/^{144}Nd = 0.512638$. Depleted mantle (DM): $^{147}Sm/^{144}Nd = 0.2137$; $^{143}Nd/^{144}Nd = 0.51315$. $\Delta 7/4 = (^{207}Pb/^{204}Pb_i - ^{207}Pb/^{204}Pb_{NHRL}) \times 100$; $\Delta 8/4 = (^{208}Pb/^{204}Pb_i - ^{208}Pb/^{204}Pb_{NHRL}) \times 100$; $^{207}Pb/^{204}Pb_{NHRL} = ^{206}Pb/^{204}Pb_i \times 0.1084 + 13.491$; $^{208}Pb/^{204}Pb_{NHRL} = ^{206}Pb/^{204}Pb_i \times 1.209 + 15.627$ (Hart, 1984).

content was determined by wet chemistry and Fe_2O_3 was from subtraction of FeO from total Fe. Repeated analyses of Chinese national basalt and andesite standards show that the precision for major elements is better than 3%. Duplicate analyses of 00CT-6 show good reproducibility. Major elements of 04CT-1 and 04CT-2 were analyzed by X-ray fluorescence (XRF) spectrometry (RIX-2100) in the Key Laboratory of Continental Dynamics in the Department of Geology of the Northwest University, Xi'an, China. After digestion in Teflon bombs, trace elements of 04CT-1 and 04CT-2 were measured by inductively coupled plasma mass spectrometry (ICP-MS) in the Key Laboratory of Continental Dynamics in the Department of Geology of the Northwest University, Xi'an, China. Analytical details and results of reference materials in Northwest University, Xi'an, were reported in Rudnick et al. (2004). The other six samples were dissolved in distilled HF-HNO_3 in Savillex Teflon screw-top beakers at 150 °C four more than four days for trace element analyses by the ICP-MS at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS) (Table 4). Repeated analyses for USGS standards BHVO-1 and W-2 show precision for rare earth elements (REE) and high field strength elements (HFSE) of ~5% (Xu, 2002). Analytical procedures and analyses of reference materials at the GIGCAS have been described in Xu (2002) and Yang and Li (in press).

The Rb, Sr, Sm, and Nd data are measured by isotope dilution method in the Chemical Geodynamics Laboratory of the University of Science and Technology of China using MAT-262 mass spectrometry following the procedure of Foland and Allen (1991) (Table 5). Total procedure blank is Sr = 0.4 ng and Nd = 50 pg. Sr, Sm, and Nd isotope fractionations were calibrated using $^{86}Sr/^{88}Sr = 0.1194$, $^{149}Sm/^{152}Sm = 0.516858$, and $^{146}Nd/^{144}Nd = 0.7219$. The Pb isotope data were analyzed using a MAT-262 mass spectrometry in the Laboratory for Radiogenic Isotope Geochemistry of Institute of Geology and Geophysics, Chinese Academy of Science (Table 5). Pb was purified by conventional anion-exchange method (AG1-X8, 200–400 resin) using HBr as an eluant. The whole procedure blank for Pb is 0.05–0.1 ng. Fractionation of Pb isotopes during mass spectrometry analysis was calibrated against the standard NBS981. The NBS981 average measured during the course of this study was $^{206}Pb/^{204}Pb = 16.9376 \pm 0.0015$ (2σ), $^{207}Pb/^{204}Pb = 15.4939 \pm 0.0014$ (2σ), and $^{208}Pb/^{204}Pb = 36.7219 \pm 0.0033$ (2σ). The precision of Pb isotope data on the mass spectrometry is better than 0.1%.

4. Results

4.1. Geochronology

SHRIMP U–Pb dating of zircons from the Chituling diorite (05LJW) defines a weighted mean average $^{206}Pb/^{238}U$ age of 131 ± 3 Ma (Fig. 2). In the CL images, the Chituling zircons have oscillatory and rhythmic zoning, which are typical features of magmatic zircon. Analysis 05LJW11 was not used for age calculation because of the high common ^{204}Pb during the analysis. Analysis 05LJW16 (106.8 Ma) is similar to the late granitic rocks in the Dabie orogen (Wang et al., 2007a), indicating that late granitic magmatism may have caused slight recrystallization of some zircons from the Chituling samples. Accordingly, we infer that the age of 131 ± 3 Ma given by weighted average of 10 out 12 spots in Table 2 is the best estimate of the emplacement age of the Chituling diorite. This age is consistent with the zircon U/Pb age of the granite near the Chituling diorite (135.4 ± 2.7 Ma) (2δ) (Ma et al., 2003) and the zircon U/Pb ages for low-Mg adakites observed at the Dabie orogen within error, such as the early stage deformed granitoids (e.g., Duzunshan and Yinshanjian bodies) (132.4 ± 1.8 Ma) (Xu et al., 2007) and other low-Mg adakitic granitoids

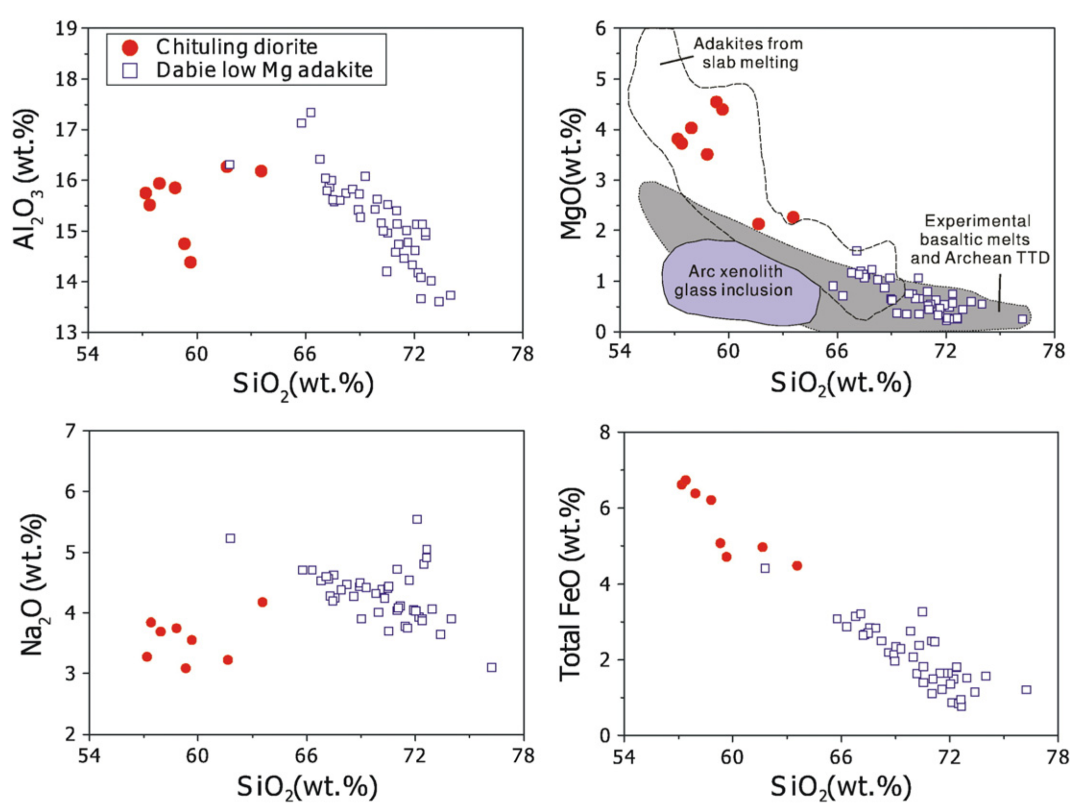


Fig. 3. Comparison of the major element correlations of the Chituling samples with low-Mg adakites from the Dabie orogen (Wang et al., 2007a; Xu et al., 2007). The Chituling samples have significant higher MgO and total FeO contents than the Dabie low-Mg adakites. The fields of slab-derived adakites, experimental basaltic melts, Archean TTD, and arc xenolith glass inclusion are after Defant and Kepezhinskas (2001).

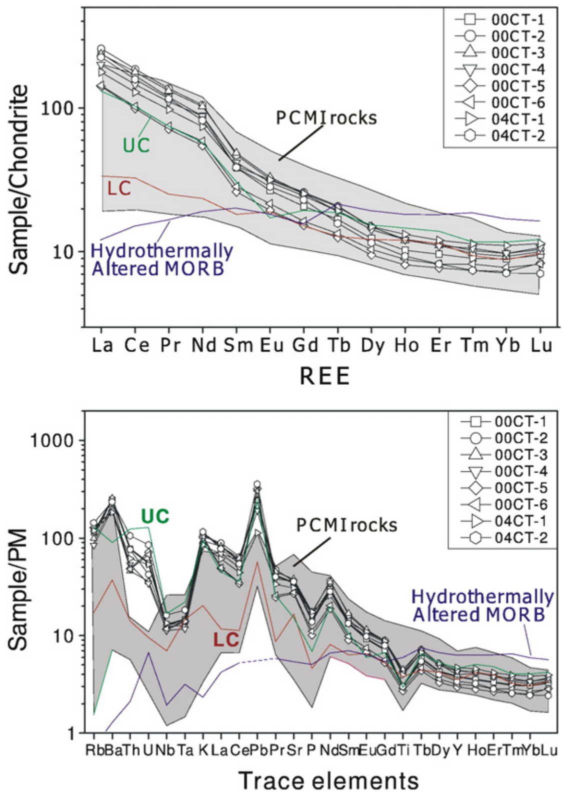


Fig. 4. Chondrite-normalized REE (A) and primitive mantle (PM) normalized trace elements patterns (B). The Chituling samples are enriched in the LREE relative to the HREE as shown by comparison with the post-collisional mafic–ultramafic (PCMI) rocks and the hydrothermally-altered MORB (Nakamura et al., 2007). Note that the Chituling samples clearly show enrichments of LILE (e.g., U and Ba) and depletions of HFSE (e.g., Nb and Ta), similar to the features of continental crust (Rudnick and Gao, 2003) and PCMI rocks (Jahn et al., 1999; Wang et al., 2005; Huang et al., 2007). Chondrite and PM data are from Sun and McDonough (1989). PCMI rocks are from Jahn et al. (1999) and Huang et al. (2007).

from the NDZ (143–129 Ma) (Wang et al., 2007a). The age is slightly older than the post-collisional mafic–ultramafic intrusive rocks (123–130 Ma) (Jahn et al., 1999; Li et al., 1999; Wang et al., 2005; Zhao et al., 2005) and significantly older than granitic dikes (118–105 Ma) (Wang et al., 2007a).

4.2. Major and trace elements

The Chituling samples have intermediate composition with SiO_2 contents ranging from 57.2 to 63.6 wt.% (Table 3). The whole alkali contents (Na_2O+K_2O) vary from 6.1 to 7.7 wt.%. Na_2O/K_2O of the Chituling samples ranges from 0.97 to 1.54, lower than the values of adakitic rocks with trondhjemitic affinities and liquid from melting experiment of basalts (~2, see the compilation of adakite data in Martin, 2005). The MgO contents vary from 2.13 to 4.55 wt.% and Al_2O_3 from 14.3 to 16.3 wt.% with six out of eight samples having >15 wt.%. Mg# of the Chituling samples ranges from 44 to 63, which are similar to those of high-Mg# adakites in eastern China (e.g., Xu et al., 2002; Gao et al., 2004; Xu et al., 2006; Wang et al., 2007b; Xu et al., 2008), but considerably higher than those (most of them <45) of experimental melts from hydrous basalt in the garnet stability field (Sen and Dunn, 1994; Rapp and Watson, 1995; Rapp et al., 1999). As shown in the major element plot (Fig. 3), the Chituling diorites have lower SiO_2 and higher MgO and total FeO contents than the low-Mg adakite from the Dabie orogen (Wang et al., 2007a; Xu et al., 2007). The Chituling samples also have higher Ni (16–87 ppm) and Cr contents (36–246 ppm) than the low-Mg adakites from the Dabie orogen.

The Chituling samples have Sr/Y ranging from 30.5 to 48.9 with five out of eight samples higher than 40, including the two samples with high Mg#, 00CT-5 and 00CT-6 (Table 4). Chondrite-normalized REE patterns (Fig. 4A) show that the Chituling samples are enriched in light REE (LREE) and depleted in heavy REE (HREE). $(La/Yb)_N$ (15.9–31.6) is higher than the values of upper (15.5) and lower continental crust (5.3) (Rudnick and Gao, 2003), indicating strong fractionation of the REE in the Chituling diorites. The Chituling diorites have only slight negative Eu anomalies with Eu/Eu* ranging from 0.92 to 1.01, while they show moderately negative to slightly positive anomaly of Sr with δSr varying from 0.76 to 1.13. Although there is no obvious correlation between Sr/Y and δSr, the negative Eu and Sr anomalies may still suggest slight fractional crystallization of plagioclase, which could decrease Sr/Y of the Chituling samples. In the primitive mantle normalized figure (Fig. 4B), all samples are enriched in Pb and large ion lithophile elements (LILE, e.g., Ba and Th), but depleted in HFSE (e.g., Nb and Ta). Ba is enriched relative to Rb and Th. These features are similar to those in the lower continental crust (Rudnick and Gao, 2003) and the post-collisional mafic–ultramafic rocks from the Dabie–Sulu orogen (Jahn et al., 1999; Wang et al., 2005; Huang et al., 2007), but different with the pattern of hydrothermally-altered mid-ocean ridge basalt (MORB) (Nakamura et al., 2007).

Most of the Chituling samples have geochemical features similar to those of adakites: high SiO_2 (>57.9 wt.%), Al_2O_3 (most >15 wt.%), and Sr contents (>650 ppm), high Sr/Y (>40) and La/Yb (>20), and low Yb (<1.9 ppm) and Y contents (<19 ppm) (Defant and Drummond, 1990; Kay and Kay, 1993; Martin, 1999; Martin et al., 2005). As shown in Fig. 5, most of the Chituling samples are located in the adakite field with high Sr/Y and low Y content similar to the Mesozoic adakites observed in eastern China, e.g., Xuzhou–Suzhou (Xu et al., 2006), Ningzhen (Xu et al., 2002), Xinglonggou (Gao et al., 2004), and low-Mg adakite from the Dabie orogen (Wang et al., 2007a; Xu et al., 2007), while the NHZ andesites with higher Y content are in the normal andesite and dacite field. The lower Na_2O/K_2O of the Chituling samples than the typical adakites from oceanic subduction zone settings (Martin et al., 2005) is a common feature for the adakitic rocks developed within continental crust. Na_2O content was not used as a defining characteristic of adakites in the original definition in Defant and Drummond (1991) and numerous following studies on adakites (e.g., see Wang et al., 2007a for detailed discussion). Therefore, given the high Mg# (44–63), the Chituling diorites can be classified as high-Mg adakites.

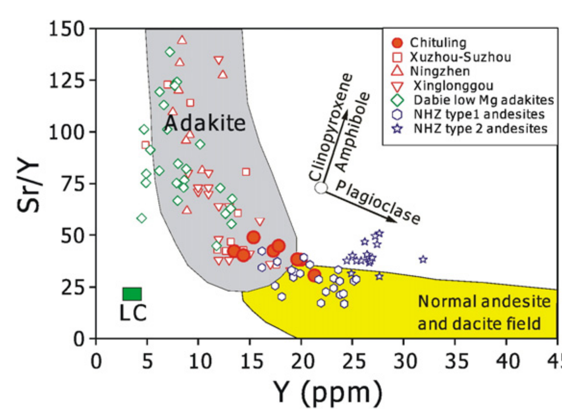


Fig. 5. Sr/Y versus Y diagram after Defant et al. (2002). The Chituling samples have high Sr/Y and (La/Yb) but low Y contents similar to typical adakites, while the NHZ andesites have relatively higher Y content and lower Sr/Y (Fan et al., 2004). Mesozoic adakitic rocks from Eastern China include Xuzhou–Suzhou (Xu et al., 2006), Ningzhen (Xu et al., 2002), Xinglonggou (Gao et al., 2004), and Dabie low-Mg adakites (Wang et al., 2007a). Lower crust (LC) values are from Rudnick and Gao (2003). The arrows stand for the trend of fractional crystallization of plagioclase, clinopyroxene, and amphibole.

4.3. Sr–Nd–Pb isotopes

Whole rock Sr–Nd–Pb isotopic compositions of the Chituling diorites are quite different from the depleted mantle and MORB, but resembling the typical features of the EM-I component or lower continental crust in the Dabie orogen (Table 5). The initial Sr–Nd–Pb isotopic ratios are calculated back to 130 Ma based on the SHRIMP zircon U–Pb dating. The Chituling samples have very low $\varepsilon_{Nd}(T)$ ranging from −20.7 to −24.9 (Fig. 6), comparable to the values of the NHZ andesites (Fan et al., 2004) and Mesozoic granites from the Dabie orogen (Chen et al., 2002; Zhang et al., 2002), but lower than the post-collisional mafic–ultramafic intrusive rocks from the Dabie–Sulu orogen (Li et al., 1998; Jahn et al., 1999; Wang et al., 2005), Dabie low-Mg adakites (Wang et al., 2007a), NDZ gneisses (Li et al., 1998), and exhumed UHPM eclogites (Li et al., 1993; Jahn, 1998; Li et al., 2000). $^{87}Sr/^{86}Sr_i$ of the Chituling samples vary from 0.70691 to 0.70775, lower than the NHZ andesites but within the ranges of other terrestrial rocks from the Dabie–Sulu orogen.

The Pb isotopic compositions of the Chituling high-Mg adakites are similar to the Dabie–Sulu Mesozoic granites, which have generally been considered as a result of melting of the lower-middle crust of the Dabie–Sulu orogen (Fig. 7) (Zhang, 1995; Zhang et al., 2002, 2004). The samples have unradiogenic Pb isotopes with $^{206}Pb/^{204}Pb_i$ ranging from 15.86 to 16.44 and $^{207}Pb/^{204}Pb_i$ from 15.17 to 15.25, obviously lower than the values of the post-collisional mafic–ultramafic intrusive rocks from the Dabie orogen (Wang et al., 2005; Huang et al., 2007), andesites from the NHZ (Wang et al., 2005), gray gneisses from the NDZ (Li et al., 2003), and UHPM rocks from the SDZ (Zhang et al., 2002) and Chinese Continental Scientific Drilling (CCSD) projects (Li et al., submitted for publication). Notably, $^{208}Pb/^{204}Pb_i$ of the Chituling samples is higher than that of the post-collisional mafic–ultramafic intrusive rocks given the same $^{206}Pb/^{204}Pb_i$ (Fig. 7). Δ7/4 of the Chituling diorites vary from −3.5 to 4.32, while Δ8/4 (186.4–202.7) are even higher than the values of the mafic–ultramafic intrusive rocks from the Dabie orogen (159–180) (Wang et al., 2005; Huang et al., 2007). Given the recent observation that the subducted continental crust from the SCB has higher thorogenic Pb isotopes than the deep lithosphere of the NCB with Δ8/4 < 160, the high Δ8/4 of the Chituling diorites clearly indicates its geochemical resemblance to the SCB (Huang et al., 2007). The trace element and Sr–Nd–Pb isotopic compositions of the Chituling adakites suggest a derivation from the old lower continental crust of the subducted SCB, not the subducted oceanic crust.

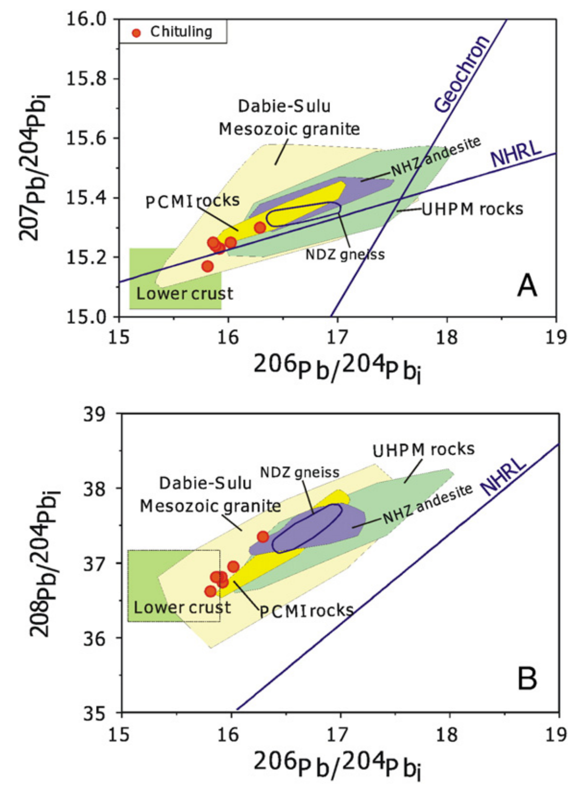


Fig. 7. Initial Pb isotope ratios of the Chituling high-Mg adakites. The Chituling high-Mg adakites have lower $^{206}Pb/^{204}Pb_i$ and $^{207}Pb/^{204}Pb_i$ than the post-collisional mafic–ultramafic intrusive (PCMI) rocks, while the $^{208}Pb/^{204}Pb_i$ of the Chituling samples are higher than those of the PCMI rocks given the same $^{206}Pb/^{204}Pb_i$. The unradiogenic Pb isotopes of the Chituling samples indicate the derivation from the lower continental crust. Data source: NHZ andesites, Wang et al. (2005); NDZ gray gneisses, Wang and Li (unpublished data); PCMI rocks, Wang et al. (2005) and Huang et al. (2007); UHPM rocks, Zhang et al. (2002) and Li et al. (2007); and Dabie–Sulu granites, Zhang (1995), Zhang et al. (2002, 2004). $(^{207}Pb/^{204}Pb)_{NHRL} = 0.1084 \times (^{206}Pb/^{204}Pb)_i + 13.491$; $(^{208}Pb/^{204}Pb)_{NHRL} = 1.209 \times (^{206}Pb/^{204}Pb)_i + 15.627$ (Hart, 1984). The lower crust field is represented by the unradiogenic Pb isotopes of the Dabie–Sulu Mesozoic granitoids, which are generally explained as a result of partial melting of the lower-middle continental crust of the Dabie orogen (e.g., Zhang, 1995; Chen et al., 2002; Zhang et al., 2004).

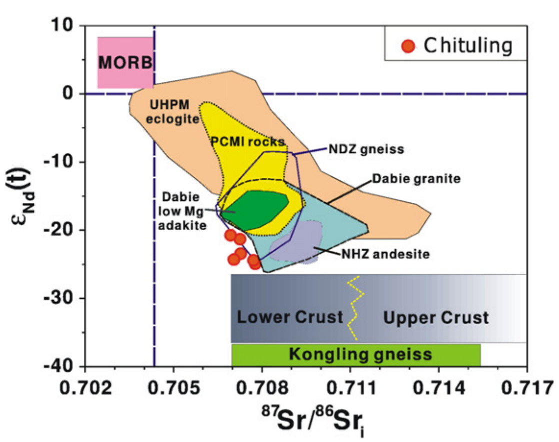


Fig. 6. Comparison of the initial Sr–Nd isotopic compositions of the Chituling high-Mg adakites with terrestrial rocks from the Dabie–Sulu orogen. Data source: the UHPM rocks, Jahn (1998); gray gneisses from the NDZ, Li et al. (1998); Mesozoic igneous rocks from the Dabie–Sulu orogen including low-Mg adakites, Wang et al. (2007a); granites, Chen et al. (2002) and Zhang et al. (2002); PCMI rocks, Jahn et al. (1999), Wang et al. (2005), and Huang et al. (2007); and NHZ andesites, Fan et al. (2004). Note that the Chituling high-Mg adakites have moderately enriched Sr isotopes and very low $\varepsilon_{Nd}(T)$ comparable to the lowest values of the Dabie granites, similar to the features of the lower continental crust (e.g., Liu et al., 2004). The fields of Kongling gneisses and upper–lower crust are from Jahn et al. (1999).

5. Discussion

5.1. Petrogenesis of the Chituling high-Mg adakite

Adakites were originally considered to be the result of partial melting of young and hot subducted oceanic crust (Defant and Drummond, 1990). They can also be produced by alternative means, e.g., basaltic magma differentiation (Castillo et al., 1999), melting of hydrous peridotites (e.g., Stern and Hanson, 1991; Martin et al., 2005), mixing between basaltic and crustal-derived felsic magmas (e.g., Guo et al., 2007), and partial melting of thickened or delaminated continental lower crust (e.g., Xu et al., 2002; Chung et al., 2003; Wang et al., 2007a).

Given the typical "lower continental crust"-like Sr–Nd–Pb isotopic features and the fact that there was no subduction of oceanic slabs in the Dabie orogen during the early Cretaceous, the partial melting of oceanic slabs cannot form the Chituling adakite. The lower $\varepsilon_{Nd}(T)$ and initial Pb isotopes of the Chituling samples than the Mesozoic mafic–ultramafic intrusive rocks from the Dabie orogen also argue against generation of the Chituling high-Mg adakites by basaltic magma differentiation.

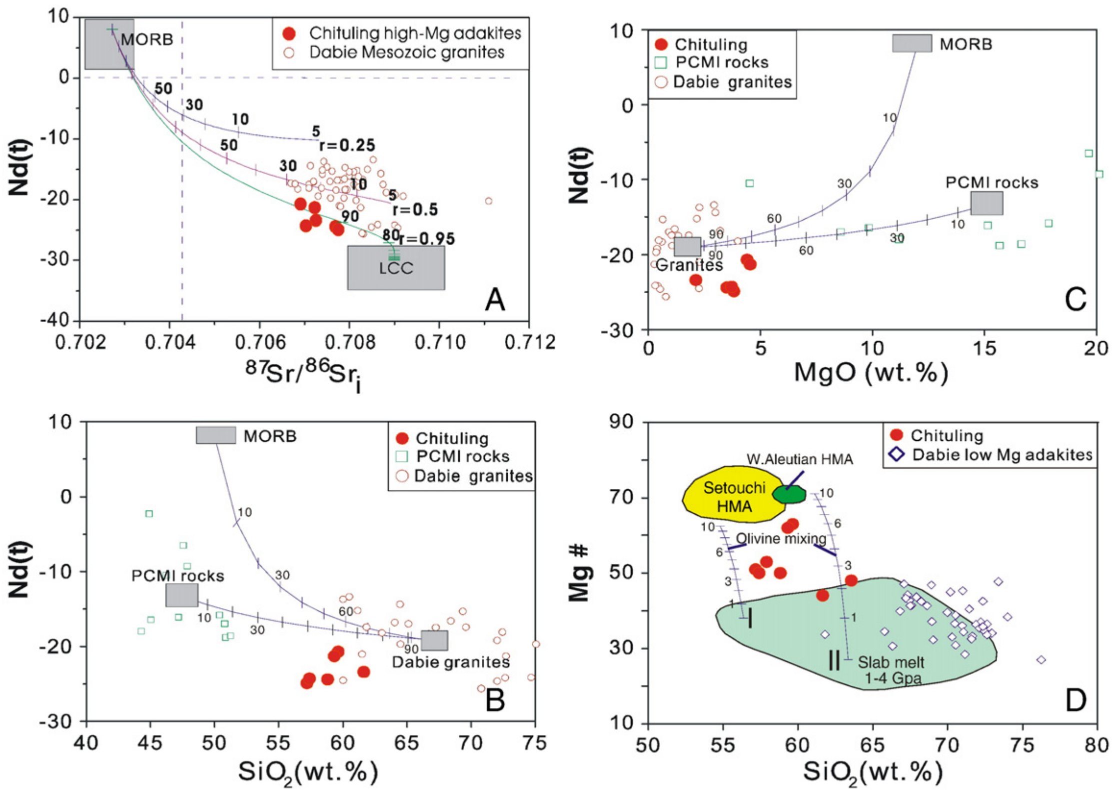


Fig. 8. A, AFC processes with an initial magma of a slab-melt with MORB-like Sr–Nd isotopic compositions and assimilant from the lower continental crust. The AFC curve passes the Chituling data only for a large assimilation rate (r=0.95). B–C, SiO_2 and MgO versus $\varepsilon_{Nd}(T)$ diagrams showing that mixing between basaltic (MORB and PCMI rocks) and granitic magmas from the Dabie–Sulu orogen cannot explain the geochemical features of the Chituling high-Mg adakites. D, assimilation of less than 8 wt.% mantle olivine by slab-derived melts (I and II) can increase the Mg# but does not change SiO_2 content significantly. Data source: PCMI rocks, Jahn et al. (1999) and Huang et al. (2007); Dabie granites, Chen et al. (2002) and Zhang et al. (2002); Dabie low-Mg adakites, Wang et al. (2007a); slab-derived melts, Setouchi high-Mg andesite (HMA), and W. Aleutian HMA, Rapp et al. (1999). The parameters for the AFC model and mixing end members are shown in Table 6.

High-Mg adakites/andesites can be produced by melting of hydrous peridotite (e.g., Stern and Hanson, 1991). However, a quantitative model for simulation of the AFC process shows that it is highly unlikely that the Chituling adakites were derived from slab melts from hydrous peridotites via assimilation of the lower continental crust and fractional crystallization of mafic minerals (e.g., clinopyroxene and orthopyroxene) and plagioclase. The AFC trend can pass through the Chituling data only for a high assimilation rate (r=0.95) (Fig. 8A). Following the approach in Gao et al. (2004), a slab-melt with high Cr (636 ppm) and Ni contents (132 ppm) (the highest Cr and Ni contents in Aleutian high-Mg andesites and adakites, Yogodzinski and Volynets (1994)) is used to represent the primary high-Mg adakitic melt before crustal assimilation (Table 6). We use low-Mg adakites in the Dabie orogen to represent the

Table 6
Parameters used in the models in Fig. 8

AFC model parameters	Sr	Nd	Cr	Ni
Magma initial concentration (ppm)	502	10.7	636	132
Magma initial $^{87}Sr/^{86}Sr_i$ and $\varepsilon_{Nd}(T)$	0.702725	8	–	–
Bulk partition coefficient (Bulk D)	1.12	0.13	>2	>2
Assimilant concentration (ppm)	336	25	11.5	5.2
Assimilant $^{87}Sr/^{86}Sr_i$ and $\varepsilon_{Nd}(T)$	0.709	−30	–	–

	$\varepsilon_{Nd}(T)$	Nd (ppm)	SiO_2 (wt.%)	MgO (wt.%)	Mg#	References
Average granites	−19.3	47.7	67.05	1.43	–	Average of 29 granites from the Dabie orogen (Chen et al., 2002; Zhang et al., 2002).
Average PCMI rocks	−13.3	20.0	47.49	15.15	–	Average of samples from the Zhujiapu intrusion (Jahn et al., 1999; Huang et al., 2007).
MORB	8	7.3	50	12	–	Sun and McDonough (1989), Jahn et al. (1999).
Slab-melt I	–	–	56.37	2.57	37.9	Melt in experiment No1 at 1025 °C and 2.2 GPa in Rapp and Watson (1995).
Slab-melt II	–	–	63.36	0.7	26.9	Melt in experiment No. 1 at 1075 °C and 2.2 GPa in Rapp and Watson (1995).
Mantle olivine	–	–	40.8	49.4	90.0	Calculated based on the formula $(Mg_{0.9}Fe_{0.1})_2SiO_4$

Note to AFC model: This model is used for AFC process of slab-melt from hydrous mantle peridotite. Low-Mg adakites from the Dabie orogen are used as the assimilant from the lower continental crust. Assuming that the crystallized minerals contain 50% plagioclase (plg), 25% clinopyroxene (cpx), and 25% orthopyroxene (opx), bulk D of Sr and Nd are calculated by $50\%^{plg/melt}D+25\%^{cpx/melt}D+25\%^{opx/melt}D$. $^{opx/melt}D_{Sr-Nd}$ is negligible relative to $^{plg/melt}D_{Sr-Nd}$ and $^{cpx/melt}D_{Sr-Nd}$ (see Bédard, 2007 for a recent review). $^{plg/melt}D_{Sr-Nd}$ and $^{cpx/melt}D_{Sr-Nd}$ are from Blundy et al. (1998). Bulk D of Cr and Ni depend on $^{opx/melt}D$ and $^{cpx/melt}D$, which mainly is a function of mineral and melt composition. Given the high compatibility of Ni and Cr in cpx and opx, we simply assume the bulk D of Cr and Ni is greater than 2. Sr–Nd compositions are from Gao et al. (2004) except that Sr–Nd isotopic compositions of the lower continental crust are based on the values used in Jahn et al. (1999). Initial Cr–Ni contents the slab-melt are same as the values used in Gao et al. (2004), which are from the highest Cr and Ni contents in Aleutian high-Mg andesites/adakites (Yogodzinski and Volynets, 1994). Cr and Ni contents of the melt from lower continental crust are from average of 42 low-Mg adakites from the Dabie orogen from Wang et al. (2007a).

assimilant from the lower continental crust (e.g., Wang et al., 2007a). Given the high compatibility of Cr and Ni in the crystallized minerals, the AFC process with a high assimilation rate dramatically decreases Cr and Ni contents in the adakitic melt to as low as a few ppm, which is lower than the Cr (36–246 ppm) and Ni (16–87 ppm) contents in the Chituling high-Mg adakites.

It is also unlikely that mixing between basaltic and granitic magmas generated the Chituling high-Mg adakites. The Chituling samples have very low ε_{Nd}(T) (up to −24.9), close to the lowest values observed at the Dabie granites (−25) (Chen et al., 2002; Zhang et al., 2002), much lower than that of the PCMI rocks (−2.3 to −19.2) (Li et al., 1998; Jahn et al., 1999; Wang et al., 2005). Mixing of granitic magma with a significant amount of mafic magma cannot produce such low $\varepsilon_{Nd}(T)$ of the Chituling high-Mg adakites. Moreover, we use the average composition of 29 Dabie granitic rocks from Chen et al. (2002) and Zhang et al. (2002) with SiO_2 of 67 wt.% and ε_{Nd}(130 Ma) of −19.2 as the felsic end member to simulate possible magma mixing in Fig. 8 (Table 6). Mixing between granites and basalts (such as MORB or the post-collisional mafic–ultramafic intrusive rocks) shows that 30–50 wt.% mafic magma is required to form the intermediate SiO_2 content of the Chituling samples (Fig. 8B). However, the resultant MgO content is much higher than that of the Chituling adakites due to the large contribution of basalts (Fig. 8C). Because most granites with low ε_{Nd}(130 Ma) (−25) have SiO_2>70 wt.% (Chen et al., 2002; Zhang et al., 2002), mixing involving such high silica magma requires a higher proportion of basaltic magma, resulting in even higher MgO content. Additionally, mafic enclaves or orthopyroxene phenocrysts are usually considered as evidence for magma mixing (e.g., Guo et al., 2007). However, none of these has been observed in the Chituling intrusion. Therefore, mixing between granitic and basaltic magma cannot generate the Chituling high-Mg adakites.

Finally, recently reported early Cretaceous adakites in the Dabie orogen have low MgO contents and were interpreted as the product of partial melting of thickened lower continental crust containing amphibole or rutile (Wang et al., 2007a; Xu et al., 2007). Considering the "lower continental crust"-like Sr–Nd–Pb isotopic compositions, trace element features, and high MgO, Cr, and Ni contents, the Chituling high-Mg adakites are more likely to be produced by reaction between partial melts from delaminated eclogitic lower continental crust and mantle peridotite. Experimental studies show that SiO_2-rich melt can assimilate peridotite when the melt/rock ratio is greater than two, which could produce high-Mg silicic melts (Rapp et al., 1999, 2005). Simple calculation shows that addition of less than 8 wt.% of olivine (Fo_{90}) to melts derived from slabs at 1–4 GPa can enhance the Mg# (from less than 40 to 60) and Ni–Cr contents (not shown) without decreasing the SiO_2 content significantly (Fig. 8D).

5.2. Interaction between recycled deeply-subducted continental crust and the upper mantle

As mentioned above, the Chituling high-Mg adakites have high thorogenic Pb isotopes similar to the UHPM rocks and post-collisional mafic–ultramafic intrusive rocks of the Dabie orogen, but quite different from that of the deep lithosphere of the NCB. This clearly shows the close relationship of subducted lower continental crust from the SCB with the early Cretaceous high-Mg adakites and basaltic rocks in the Dabie orogen. Interaction between adakitic melt derived from the foundering lower continental crust and uppermost mantle is an appropriate explanation for the isotopic similarity between them. Experimental studies about reactions between silicic melts and mantle peridotites show that a small amount of slab-derived melts with low Mg# can be completely consumed by peridotites to form pyrope-rich garnet and orthopyroxene (Rapp et al., 1999). Therefore, small-scale adakitic melts could react with peridotite to form enriched mantle with "marble-cake" structure (e.g., Allègre and Turcotte, 1986) or modally and cryptically metasomatized mantle. Partial melts from such enriched mantle could still preserve some typical "continental" geochemical features related to the incompatible elements (Rapp et al., 1999), e.g., enrichments of LILE, depletions of HSFE, and "lower continental crust"-like Sr–Nd–Pb isotopic compositions. Thus, geochemical features of the recycled deeply-subducted continental crust from the SCB can be inherited and observed at the post-collisional intra-plate basaltic intrusions from the Dabie–Sulu orogen (e.g., the Zhujiapu intrusion) (Huang et al., 2007).

On the other hand, when the amount of adakitic melts or local melt/rock ratio is large enough, the silicic melt cannot be fully consumed by the surrounding mantle peridotite. Assimilation of mantle minerals by the adakitic melt could significantly increase the MgO, Cr, and Ni contents and produce high-Mg adakitic melts such as the Chituling diorite. A following question is whether such interaction can significantly influence other aspects of geochemical composition of the adakitic melts such as Nd isotopes. Some authors have proposed the assimilation of whole peridotite to explain the high $\varepsilon_{Nd}(T)$ (−2 to +2) of high-Mg adakites, which were suggested to be originally derived from partial melting of subducted slabs (Stern and Kilian, 1996) or lower continental crust ($\varepsilon_{Nd}(T)<-10$) (Gao et al., 2004; Wang et al., 2006b). However, as mentioned above, the Chituling high-Mg adakitic rocks have the lowest $\varepsilon_{Nd}(T)$ ranging from −20.7 to −24.9 among the terrestrial samples from the Dabie orogen (Fig. 6), which suggests that the interaction between the crust-derived melts and the upper mantle may not significantly change the Nd isotopic compositions of high-Mg adakitic melt. Experimental studies show that it is most likely that olivine (not whole peridotite, clinopyroxene, or orthopyroxene) is preferentially assimilated by the silicic melt because it is undersaturated in SiO_2 (Rapp et al., 1999, 2005). Given the extremely high incompatibility of Nd in Fo-rich olivine (e.g., $^{olivine/melt}D_{Nd}=7\times10^{-5}$ in Suhr et al. (1998)), assimilation of olivine should not significantly change Nd isotopic composition of adakitic melts. Experimental studies also show that while the trace element contents may change during the melt–rock interaction with consumption of melt, assimilation of olivine, and mineralogical variation in peridotite, the relative ratios between those trace elements in the melt do not change (Rapp et al., 1999, 2005). Similarly, slightly adding mantle olivine to the Chituling adakites cannot either change incompatible element ratios (e.g., LILE/HFSE) or Sr–Pb isotopic compositions. In all, Sr–Nd–Pb isotopic and incompatible trace element compositions of high-Mg adakites more likely reflect the features of the basaltic protolith, while high Mg#, Cr, and Ni contents might result from interaction with mantle peridotite. This explains the "lower continental crust"-like geochemical features of the Chituling high-Mg adakites. This conclusion is also consistent with the geochemical features of the high-Mg diorites (enrichment of LILE, depletion of HFSE, and negative $\varepsilon_{Nd}(T)$ (up to −13.3)) from Western Shandong in the North China Craton, which contains mantle xenoliths with good evidences for adakitic melt–peridotite interactions (Xu et al., 2008).

It is important to note that the thorogenic Pb isotope features have only been observed in mantle-derived rocks from the Dabie orogen, not in the mafic samples from the adjacent SCB and North China Craton (Huang et al., 2007). This may suggest that recycling of lower continental crust only changes the geochemical properties of the upper mantle close to the Dabie–Sulu orogen. Recycling of delaminated lower continental crust into the upper mantle might provide an alternative to "ancient metasomatic events" as an explanation for the presence of enriched mantle components intra-plate basalts (Lustrino and Dallai, 2003; Anderson, 2006).

5.3. Role of the Tan–Lu fault in lower crustal foundering and lithospheric thinning

In contrast to the Sulu orogen, most of the post-collisional plutonic rocks from the Dabie orogen show a limited age range from 143 to 110 Ma (Hacker et al., 1998; Jahn et al., 1999; Li et al., 1999; Zhao et al., 2004, 2005; Wang et al., 2005; Xie et al., 2006; Xu et al., 2007). Although Jurassic ages of granitoids from the Dabie orogen have been reported in older literature summarized in Ma et al. (1998), recent accurate U–Pb zircon ages dated by SHRIMP and TIMS exclusively show early Cretaceous ages (Wang et al., 2007a; Xu et al., 2007). The narrow age range argues against any significant extension or thinning of the Dabie lithosphere in the Jurassic. As a sharp thermal response to a removal of a thickened mountain root (Kay and Kay, 1993), the post-collisional igneous activity provides important information on processes governing the evolution of the lithosphere beneath the Dabie orogen.

The coincidence between the rapid uplifting of the Luotian dome and a voluminous igneous intrusions in the Dabie orogen suggests that the thickened mountain root of the Dabie orogen was removed by lithospheric delamination and foundering in the early Cretaceous (Li et al., 2002; Hou et al., 2005; Huang et al., 2007; Wang et al., 2007a). It is also well accepted that the mafic lower continental crust underneath over-thickened lithosphere can metamorphose to denser eclogite resulting in negative buoyancy and gravitational instability (e.g., Kay and Kay, 1993; Lustrino, 2005). Numerical modeling shows that the timescale for the foundering of a denser lithosphere to underlying asthenosphere is ~10 Ma (Jull and Kelemen, 2001), much shorter than the time interval (100 Ma) between the peak metamorphism and post-collisional magmatism of the Dabie–Sulu orogen. Thus a trigger is required for the abrupt foundering of the thickened lithosphere and intensive magmatism of the Dabie orogen in the early Cretaceous. Such a trigger could be the addition of hydrous fluids from the subducted Pacific oceanic slab to the mantle wedge of eastern China (Niu, 2005) or underplating of magma from upwelling asthenosphere (Deng et al., 2007). However, the Sr–Nd–Pb isotopic compositions of the post-collisional basaltic rocks from the Dabie orogen rule out any significant contribution of materials from subducted oceanic slabs (Li et al., 1998; Jahn et al., 1999; Wang et al., 2005; Huang et al., 2007). Despite the small overlap between the ages of the adakites (143–129 Ma) and basaltic rocks (123–130 Ma) from the Dabie orogen (Li et al., 1999; Zhao et al., 2005; Wang et al., 2007a; Xu et al., 2007), the earliest adakites are significantly older than most basaltic intrusive rocks and the thermal event caused by mantle upwelling indicated by the basaltic underplating and metamorphic ages of the Huilanshan granulite (Hou et al., 2005). This suggests that the large-scale partial melting of the upper mantle and mantle upwelling might occur later than the earliest melting of thickened lower crust. Therefore, the trigger mechanism of the initial partial melting of the thickened lower crust and lithospheric delamination for the Dabie orogen still remains unclear.

One of the most important geological events occurring in eastern China from late Jurassic to early Cretaceous is the development of the Tan–Lu fault (Xu et al., 1987; Xu and Zhu, 1994; Zhu et al., 2005). The Tan–Lu fault was recently suggested to be critically associated with lithospheric weakening and thinning of the North China Craton in the Mesozoic (Menzies et al., 2007). Adakites observed inside the Dabie orogen have low Mg content (Wang et al., 2007a; Xu et al., 2007), while high-Mg adakite has only been reported from the Chituling, adjacent to the Tan–Lu fault. Distributions of the late Mesozoic high-Mg adakitic rocks generally follow the Tan–Lu fault (Fig. 1A), forming a high-Mg adakitic rock belt from the eastern Dabie orogen to Sulu orogen along the eastern boundary of the NCB. Notably, the high-Mg adakitic rock belt and the Tan–Lu fault are also spatially coincident with the area where the thinnest lithosphere–asthenosphere boundary (LAB) in the NCB has recently been revealed by seismic tomographic study in Chen et al. (2007). Finally, the coupling between the age of adakitic rocks and the large-scale strike-slip of the Tan–Lu fault (see Table 1 for details) may also suggest the key role of the trans-lithospheric fault in lithospheric delamination and thinning processes.

The possible processes for the mountain root removal of the Dabie orogen are shown in an east–west cross-section from the eastern Dabie orogen to the northeastern part of the SCB (Fig. 9). The sinistral strike-slip Tan–Lu fault was formed by the fast and oblique subduction of the northwestern Pacific plate toward eastern China in the earliest Cretaceous (Xu et al., 1987; Xu and Zhu, 1994; Zhu et al., 2005). Subduction of the Pacific plate could also result in eastward mantle corner flow due to the coupling between subducted slab and mantle wedge. The age of the Shang–Ma fault is not quite clear yet, but it is generally considered to form at the same time of the Tan–Lu fault (Xu et al., 1993). During 143–130 Ma, the sinistral motion of the Sulu orogenic belt and SCB relative to the Dabie orogen triggered the foundering of some fragments of brittle thickened lithosphere and upwelling of asthenosphere in the area close to the Tan–Lu fault (Fig. 9A). Melting of the over-thickened lower continental crust inside the Dabie orogen caused by upwelling mantle produced the low-Mg adakites (Wang et al., 2007a; Xu et al., 2007), while melting of the foundered lower crust resulted in high-Mg adakites due to the reaction with mantle peridotite (e.g., Chituling). Most importantly, partial melting of the lower crust could further weaken the over-thickened lithosphere and produce eclogite restite, consequently resulting in the large-scale delamination of lithospheric mantle, asthenosphere mantle upwelling, and foundering of the eclogite

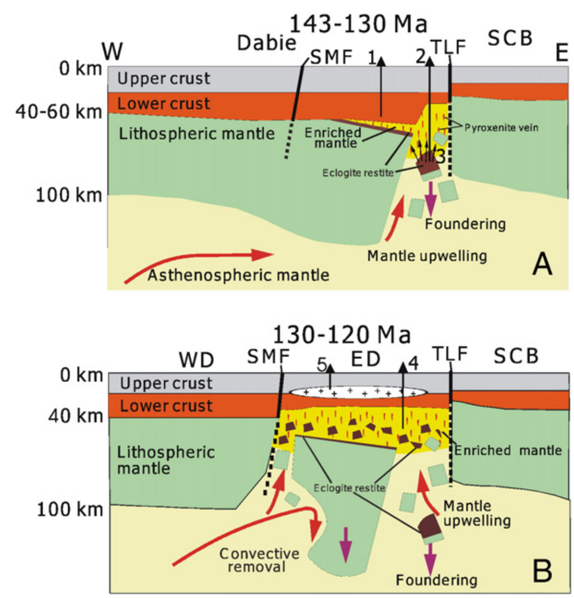


Fig. 9. Cartoons showing foundering mechanism of the lower continental crust and removal process of the thickened mountain root of the Dabie orogen. A, the Tan–Lu fault (TLF) and Shang–Ma fault (SMF) controlled the removal of Eastern Dabie mountain root. The TLF was developed at late Jurassic to early Cretaceous (Xu et al., 1987, 1992). The strike-slip motion of the Tan–Lu fault broke some lithospheric fragments near the fracture zone, which triggered the delamination and foundering of the over-thickened lithosphere and mantle upwelling in the area close to the Tan–Lu fault. Partial melting of the thickened lower continental crust inside the Dabie orogen caused by upwelling mantle generated the low-Mg adakites with ages ranging 143–129 Ma (1), while partial melting of the foundered lower continental crust generated the Chituling high-Mg adakites (2) with age of 131 Ma near the Tan–Lu fault. The adakitic melts (3) could be consumed by the uppermost mantle forming pyroxenite veins (if melts percolate through a fracture), or they could uniformly and modally react with mantle creating cryptically metasomatism (if melts transport by porous flows). Subduction of the Pacific plate could cause eastward flow of asthenospheric mantle. B, adakitic melts (1) produced in Fig. 9A further weakened lithosphere, resulting in the large-scale delamination of lithospheric mantle and removal of mountain root by convective mantle flow, followed by the large-scale mantle upwelling and foundering of eclogite restite. Interaction between the silicic melts from foundering eclogite restite and upwelling mantle formed enriched mantle with garnet pyroxenite veins. Partial melting of such enriched mantle and crust produced PCMI rocks (4) (Li et al., 1998; Jahn et al., 1999; Wang et al., 2005; Huang et al., 2007) and granites (5) slightly later (Wang et al., 2007a; Xu et al., 2007), respectively. ED and WD stand for Eastern and Western Dabie, respectively.

restite, which further caused intensive magmatism in the area between the Shang–Ma and Tan–Lu faults (Fig. 9B).

We should emphasize that although the density of eclogitic lower continental crust (up to 3.8 g/cm^3) could be greater than the asthenospheric mantle, it is highly unlikely that the average density of lithosphere is large enough to result in delamination of the whole rigid lithosphere. The presence of Archean peridotite xenoliths in Ordovician kimberlites (e.g., Mengyin, Fig. 1A) but lack of them in Cenozoic basalts may imply the loss of original Archean lithospheric mantle in the area close to the Tan–Lu fault (Zhang et al., 2008). However, Re–Os ages of peridotite xenoliths from Cenozoic basalts in the NCB indicate that the current sub-continental lithospheric mantle beneath the NCB still has ancient melt depletion ages from the Paleoproterozoic to Phanerozoic (Rudnick et al., 2004; Wu et al., 2006; Zhang et al., 2008). This indicates that the ancient lithospheric mantle was not completely delaminated and replaced. Instead, the bottom of the lithospheric mantle was most likely removed by the convective flow of asthenosphere (Fig. 9B) (Houseman et al., 1981; England and Houseman, 1989; Platt and England, 1994). Partial melting of eclogitic lower crust could produce adakitic melt and eclogite restite (i.e., garnet clinopyroxenite) (Lustrino, 2005). Therefore, we propose that lithospheric foundering may only happen to small fragments, which is produced by a large-scale strike-slip fault and a relatively large proportion of denser eclogitic restite is attached. Since the recycled lower continental crust only changes the geochemical properties of the upper mantle close to the Dabie orogen as mentioned above, the foundering eclogite restites could be restricted in the upwelling mantle underneath the Dabie orogen (Fig. 9B).

As discussed above, interaction of mafic lower crust-derived melts with mantle peridotites could result in enriched mantle with pyroxenite veins (Fig. 9A) (Rapp et al., 1999; Xu et al., 2008) or a modally and cryptically metasomatized mantle. Melting of such enriched mantle and lower crust by heat from the upwelling mantle produced abundant basaltic rocks (e.g., Zhujiapu, Jiaoziyan, and Shacun intrusions) (Li et al., 1998; Jahn et al., 1999; Zhao et al., 2005; Huang et al., 2007) and granitoids (Chen et al., 2002; Zhao et al., 2004), respectively (Fig. 9B).

6. Conclusions

The Chituling diorites have adakite-like major and trace element features, including high Al_2O_3 and Sr contents, high Sr/Y and La/Yb, but low Y and Yb contents. The high Mg# (44–63) and high Cr and Ni contents indicate that the Chituling diorite are high-Mg adakites. The Chituling high-Mg adakites show typical “lower continental crust” signatures, such as enrichments in LILE and depletions in HFSE, moderately enriched $^{87}Sr/^{86}Sr_i$, very low $\varepsilon_{Nd}(T)$, and unradiogenic Pb isotopes. Such chemical features argue against the derivation of the Chituling high-Mg adakites from melting of young and hot oceanic slabs, basaltic magma differentiation, AFC process of slab-melt at shallow crustal level, or mixing between basaltic and granitic magmas. Instead, it is more likely that the Chituling samples were derived from partial melts of delaminated and foundered lower continental crust with slight assimilation (<8 wt.%) of mantle olivine. The Sr–Nd–Pb isotopic compositions of the Chituling diorites suggest that such reactions do not change the Sr–Nd–Pb isotopic compositions of the adakitic melt, but can significantly increase the MgO, Cr, and Ni contents, producing the high-Mg adakites. Small-scale silicic melts from delaminated lower continental crust can be completely consumed by mantle peridotite, forming the enriched mantle source of the post-collisional basaltic rocks from the Dabie orogen.

Observation of the high-Mg adakitic rock belt along the southern Tan–Lu fault provides important insights into the foundering mechanism of the lower continental crust and removal process of the thickened mountain root. Development of the Tan–Lu trans-lithospheric fault in eastern and central China might trigger the earliest delamination, foundering, and sequentially partial melting of over-thickened lithosphere in the Dabie orogen. This further weakened the gravitationally instable lithosphere and resulted in the massive removal of the mountain root and large-scale magmatism in the Dabie orogen, which could be an important foundering mechanism of lower continental crust.

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