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The petrogenesis and tectonic significance of the Early Cretaceous intraplate granites in eastern China: The Laoshan granite as an example



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A R T I C L E I N F O

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ABSTRACT

The Laoshan granite is an example of the widespread intraplate granitoids of early Cretaceous age in eastern continental China. The petrogenesis of these granitoids remains in dispute and we choose the Laoshan granite as the representative case to study these granitoids. Zircons from the Laoshan granite give a crystallization age of ~120 Ma, which is consistent with the emplacement age of ~ 126 Ma given by the bulk-rock Rb-Sr isochron. Representative samples from the granite show a large range of major element compositional variation (e.g., SiO₂/MgO = 64 to 1937), reflecting a varying degree of fractional crystallization of plagioclase, alkali feldspar, amphibole, biotite and accessory phases as observed. The samples are enriched in light rare earth elements, Rb, Th and U, but depleted in Ba and Sr with negative Eu anomalies. The high ⁸⁷Sr/⁸⁶Sr (0.7083 to 1.2265) is largely caused by variably high Rb/Sr (~0.31 to 91 with an average of ~13) due to feldspar fractionation. The low $_{\text{ENd}}(t)$ (-13.8 to -19.5), $\epsilon_{\text{Hf}}(t)$ (-14.6 to -24.4), and $(^{206}\text{Pb}/^{204}\text{Pb})_i$ (16.244 to 17.304) are consistent with significant contributions of the lower continental crust to magmas parental to the Laoshan granite. The origin of the parental magmas is best understood as resulting from anatexis of the lower crust (~20%-25% partial melting of the mafic granulite) triggered by and mixed with the underplating and intruding basaltic magmas. The basaltic magmas were likely derived from melting of the thinning lithosphere being transformed into the asthenosphere as the result of "basal hydration weakening" with the water ultimately coming from dehydration of the stagnant paleo-Pacific slab in the mantle transition zone.

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1. Introduction

The Cretaceous Laoshan granite is one of the widespread Mesozoic granitoid intrusions in eastern continental China (Fig. 1a). The petrogenesis of these granitoids is thought to be related to the paleo-Pacific plate subduction, but debate continues on actual mechanisms (Jahn et al., 1999; Li et al., 2014; Wang et al., 1995, 2001; Wu et al., 2002; Zhou et al., 2006; Zhou and Li, 2000). Niu et al. (2015) argued that all of the Jurassic-Cretaceous granitoids in the interiors of eastern continental China are of intraplate origin genetically associated with the lithosphere thinning beneath the region through basal hydration weakening (Niu, 2005) with the water ultimately coming from dehydration of the paleo-Pacific plate lying stagnant in the mantle transition. To test this

hypothesis, we focus on the petrology and geochemistry of the Laoshan granite, which is on the east coast of continental China but was emplaced within the continental interiors in the Mesozoic (Niu et al., 2015; Niu and Tang, 2016; Tang et al., 2016). There are several studies on the Laoshan granite, but the petrogenesis is still controversial (Wei, 2008; Yan and Shi, 2014; Zhao et al., 1997). These authors mainly focus on the problematic A-type classification that overlaps with highly evolved I-type granitoids (Chappell and White, 2001; King et al., 1997; Whalen et al., 1987). In this paper, we report the results of our detailed petrological, geochronological and geochemical study on the Laoshan granite and discuss its petrogenesis, which offers an effective test on the hypothesis by Niu et al. (2015) as mentioned above.

2. Geological background and Petrography

The Laoshan granite is located in the Jiaodong Peninsula on the east coast of continental China (Fig. 1). Three episodes (i.e., Triassic, Jurassic, and Cretaceous) of Mesozoic magmatism are recognized in



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Fig. 1. (a) Simplified geological framework of eastern continental China. (b) Distribution of the Mesozoic intrusive and eruptive rocks in the Jiaodong Peninsula and the locations of the Laoshan granite and nearby intrusions (modified after the geological map of Shandong Province in 1/1,500,000 scale from the Geological Atlas of China). (c) Geological sketch of the Laoshan granite and sample locations (modified after the Laoshan geological map of 1/200,000 scale).

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| Table 1 | |
|-------------|---|
| Petrography | c |

| Sample | Rock Type | GPS | | Mineral composition (%) | | | | | |
|---------|-------------------------|--------------|---------------|-------------------------|----------|------------------|---------------------------|--|--|
| | | Latitude (N) | Longitude (E) | Pl | А | Q | Others | | |
| LS15-06 | alkali-feldspar granite | 36.13 | 120.57 | 2 | 56 | 40 | Mt, Bi, Ap | | |
| LS15-07 | alkali-feldspar granite | 36.15 | 120.52 | 4 | 58 | 35 | Amp, Bi, Mt, Zrn | | |
| LS15-08 | syenogranite | 36.18 | 120.50 | 12 | 45 | 38 | Amp, Bi, Mt | | |
| LS15-11 | alkali-feldspar granite | 36.20 | 120.55 | 6 | 54 | 34 | Amp, Bi, Mt, Zrn, Ap | | |
| LS15-15 | alkali-feldspar granite | 36.25 | 120.62 | 3 | 64 | 28 | Amp, Mt, Sph, Zrn | | |
| LS15-16 | alkali-feldspar granite | 36.27 | 120.60 | 3 | 62 | 30 | Bi, Mt, Sph | | |
| LS15-19 | alkali-feldspar granite | 36.24 | 120.56 | 5 | 55 | 36 | Mt, Amp, Bi, Chl | | |
| LS15-20 | alkali-feldspar granite | 36.24 | 120.57 | 4 | 53 | 40 | Bi, Mt, Amp | | |
| LS15-21 | syenogranite | 36.09 | 120.42 | 20 | 43 | 30 | Amp, Bi, Mt, Sph, Zrn, Ap | | |
| LS15-23 | syenogranite | 36.19 | 120.46 | 20 | 38 | 35 | Bi, Ap, Mt, Zrn, Amp | | |
| LS15-25 | syenogranite | 36.19 | 120.43 | 30 | 40 | 25 | Bi, Amp, Ap, Mt, Zrn,Sph | | |
| LS15-28 | alkali-feldspar granite | 36.11 | 120.37 | 3 | 44 | 48 | Mt | | |
| LS15-30 | alkali-feldspar granite | 36.07 | 120.36 | 5 | 46 | 45 | Bi, Mt, Zrn | | |
| QD15-01 | syenogranite | 36.39 | 120.87 | 15 | 47 | 30 | Amp, Bi, Mt, Zrn, Sph | | |
| QD15-02 | monzonitic granite | 36.39 | 120.87 | 35 | 35 40 20 | | Amp, Bi, Mt, Zrn | | |
| QD15-03 | monzonitic granite | 36.41 | 120.87 35 38 | | 38 | 22 | Amp, Bi, Mt, Zrn | | |
| QD15-04 | syenogranite | 36.49 | 120.86 | 10 | 43 | 40 | Bi, Ap, Mt, Zrn, Chl, Fl | | |
| QD15-08 | alkali-feldspar granite | 36.39 | 120.67 | 3 | 66 | 20 | Bi, Mt, Chl | | |
| QD15-10 | syenogranite | 36.37 | 120.62 | 12 | 42 | 38 | Bi, Ap, Mt, Zrn | | |
| QD15-11 | alkali-feldspar granite | 36.37 | 120.59 | 5 | 53 | 40 | Bi, Ap, Mt, Zrn | | |
| QD15-14 | syenogranite | 36.32 | 120.58 | 20 | 35 | 40 | Bi, Ap, Mt, Zrn | | |
| QD15-17 | monzonitic granite | 36.00 | 120.28 | 35 | 32 | 30 | Bi, Mt | | |
| QD15-24 | syenogranite | 36.03 | 120.04 | 25 | 43 | 30 | Bi, Mt, Ap | | |
| QD15-19 | syenogranite | 35.99 | 120.11 | 13 | 43 | 40 | Bi, Amp, Mt | | |
| QD15-22 | monzonitic granite | 36.03 | 120.11 | 36 | 38 | 20 | Bi, Amp, Mt, Sph | | |
| QD15-25 | syenogranite | 35.94 | 120.10 | 23 52 20 Amp, F | | Amp, Bi, Mt, Chl | | | |
| QD15-27 | syenogranite | 35.94 | 120.06 | 15 | 55 | 25 | Bi, Ap, Mt, Zrn, Amp | | |

Pl = Plagioclase; A = Alkali feldspar; Q = Quartz; Bi = Biotite, Amp = Amphibole, Ap = Apatite, Mt. = Magnetitie, Zrn = Zircon, Fl = Fluorite, Sph = Sphene, Chl = Chlorite.

the Jiaodong Peninsula (Guo et al., 2005; Goss et al., 2010; Liu et al., 2008; Yang et al., 2005a, 2005b; Zhao et al., 2017; Fig. 1b). The Cretaceous mafic rocks include the Jimo basalts and numerous mafic dikes of 130–67 Ma age (Cai et al., 2015; Liang et al., 2017; Ma et al., 2014, 2016; Yang et al., 2005a, 2005b; Ying et al., 2006; Zhang et al., 2011; Zhang et al., 2012). The Laoshan pluton is an early Cretaceous granitoid intrusion, which is termed the Laoshan granite for discussion convenience. It is exposed in an area of ~ 600 km² (Fig. 1c) and belongs to the 500 km long so-called Early Cretaceous A-type granite belt (from Taolin in Jiangsu, towards NEE, to Rizhao, Jiaonan, Qing-dao, Laoshan, Haiyang, Rushan, and Weihai; Wang et al., 1995). It intruded the Cretaceous volcanic, Jurassic-Cretaceous sedimentary and



Fig. 2. Photograph in the field and photomicrographs in cross-polarized light. (A) shows the sharp contact of mafic magmatic enclave with the host granite (QD15-03); (B) shows the mineral assemblage and the granophyric texture of alkali feldspar granite (LS15-15); (C) shows the mineral assemblage of monzonitic granite (LS15-21); (D) shows fluorite in QD15-04. Afs = alkali feldspar; Pl = plagioclase; Qtz = quartz; Am = amphibole; Bi = biotite; Ap = apatite; Sph = sphene; Fl = Flourite.

| Table 2 |
|--|
| LA-ICPMS zircon U-Pb data of Laoshan granites. |

| Spot | Content (ppm) | | | | Ratios | | | | | Age (Ma) | | | | |
|--------------|---------------|--------|--------|------|--------------------------------------|--------|-------------------------------------|--------|-------------------------------------|----------|-------------------------------------|------|-------------------------------------|-----|
| | Pb | Th | U | Th/U | ²⁰⁷ Pb/ ²⁰⁶ Pb | 1σ | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ | ²⁰⁷ Pb/ ²³⁵ U | 1σ | ²⁰⁶ Pb/ ²³⁸ U | 1σ |
| QD15-22-1 | 7.42 | 301.55 | 224.15 | 1.35 | 0.0485 | 0.0025 | 0.1222 | 0.0063 | 0.0184 | 0.0006 | 117.1 | 5.7 | 117.8 | 3.5 |
| QD15-22-3 | 5.45 | 213.24 | 163.04 | 1.31 | 0.0469 | 0.0027 | 0.1198 | 0.0073 | 0.0186 | 0.0006 | 114.9 | 6.6 | 118.8 | 3.6 |
| QD15-22-4 | 9.85 | 438.03 | 260.53 | 1.68 | 0.0481 | 0.0022 | 0.1223 | 0.0062 | 0.0182 | 0.0006 | 117.2 | 5.6 | 116.4 | 3.5 |
| QD15-22-5 | 7.52 | 302.49 | 208.86 | 1.45 | 0.0506 | 0.0029 | 0.1236 | 0.0066 | 0.0184 | 0.0006 | 118.4 | 6.0 | 117.5 | 4.0 |
| QD15-22-6 | 7.13 | 275.54 | 200.57 | 1.37 | 0.0514 | 0.0025 | 0.1257 | 0.0057 | 0.0182 | 0.0006 | 120.2 | 5.2 | 116.5 | 3.6 |
| QD15-22 = 7 | 47.08 | 723.63 | 336.87 | 2.15 | 0.0479 | 0.0017 | 0.1226 | 0.0042 | 0.0187 | 0.0003 | 117.4 | 3.8 | 119.3 | 1.9 |
| QD15-22 = 8 | 6.74 | 105.83 | 48.56 | 2.18 | 0.0518 | 0.0050 | 0.1255 | 0.0117 | 0.0188 | 0.0005 | 120.1 | 10.5 | 120.2 | 3.3 |
| QD15-22 = 10 | 17.72 | 254.67 | 149.43 | 1.70 | 0.0491 | 0.0024 | 0.1263 | 0.0056 | 0.0190 | 0.0004 | 120.8 | 5.1 | 121.1 | 2.3 |
| QD15-22 = 13 | 20.01 | 287.18 | 219.96 | 1.31 | 0.0497 | 0.0022 | 0.1252 | 0.0058 | 0.0184 | 0.0004 | 119.8 | 5.2 | 117.4 | 2.3 |
| QD15-22 = 14 | 14.84 | 215.50 | 205.53 | 1.05 | 0.0471 | 0.0024 | 0.1188 | 0.0056 | 0.0187 | 0.0003 | 114.0 | 5.0 | 119.3 | 2.2 |
| QD15-22 = 15 | 15.67 | 215.90 | 175.35 | 1.23 | 0.0483 | 0.0026 | 0.1255 | 0.0061 | 0.0193 | 0.0005 | 120.1 | 5.5 | 123.3 | 2.9 |
| QD15-22 = 16 | 22.67 | 318.67 | 234.56 | 1.36 | 0.0487 | 0.0019 | 0.1267 | 0.0049 | 0.0191 | 0.0003 | 121.1 | 4.4 | 121.8 | 2.1 |
| QD15-22 = 17 | 27.88 | 421.41 | 251.20 | 1.68 | 0.0467 | 0.0023 | 0.1156 | 0.0051 | 0.0184 | 0.0003 | 111.0 | 4.6 | 117.4 | 2.0 |
| QD15-22 = 18 | 16.07 | 223.96 | 197.61 | 1.13 | 0.0513 | 0.0026 | 0.1269 | 0.0056 | 0.0185 | 0.0004 | 121.3 | 5.0 | 118.4 | 2.3 |
| QD15-22 = 20 | 20.91 | 322.50 | 174.28 | 1.85 | 0.0523 | 0.0031 | 0.1302 | 0.0070 | 0.0192 | 0.0006 | 124.3 | 6.3 | 122.8 | 3.6 |
| QD15-22 = 22 | 23.43 | 362.75 | 194.34 | 1.87 | 0.0529 | 0.0024 | 0.1314 | 0.0061 | 0.0193 | 0.0007 | 125.4 | 5.5 | 123.3 | 4.4 |
| LS15-15-3 | 9.49 | 403.35 | 290.85 | 1.39 | 0.0504 | 0.0027 | 0.1278 | 0.0072 | 0.0187 | 0.0008 | 122.1 | 6.4 | 119.6 | 5.0 |
| LS15-15-4 | 10.32 | 436.27 | 305.70 | 1.43 | 0.0487 | 0.0023 | 0.1256 | 0.0062 | 0.0192 | 0.0008 | 120.1 | 5.6 | 122.3 | 4.9 |
| LS15-15 = 7 | 14.24 | 185.48 | 197.24 | 0.94 | 0.0537 | 0.0024 | 0.1362 | 0.0060 | 0.0186 | 0.0004 | 129.7 | 5.3 | 118.7 | 2.3 |
| LS15-15 = 8 | 27.67 | 427.90 | 256.87 | 1.67 | 0.0529 | 0.0025 | 0.1319 | 0.0063 | 0.0182 | 0.0003 | 125.8 | 5.6 | 116.5 | 1.8 |
| LS15-15 = 10 | 12.12 | 168.76 | 140.59 | 1.20 | 0.0524 | 0.0029 | 0.1319 | 0.0068 | 0.0189 | 0.0004 | 125.8 | 6.1 | 120.5 | 2.4 |
| LS15-15 = 11 | 25.04 | 366.40 | 250.10 | 1.47 | 0.0512 | 0.0022 | 0.1331 | 0.0056 | 0.0191 | 0.0004 | 126.9 | 5.1 | 122.2 | 2.7 |
| LS15-15 = 12 | 35.49 | 485.57 | 294.23 | 1.65 | 0.0516 | 0.0017 | 0.1375 | 0.0047 | 0.0195 | 0.0004 | 130.8 | 4.2 | 124.3 | 2.4 |
| LS15-15 = 13 | 19.94 | 283.03 | 241.36 | 1.17 | 0.0483 | 0.0024 | 0.1252 | 0.0056 | 0.0191 | 0.0004 | 119.8 | 5.1 | 122.2 | 2.4 |
| LS15-15 = 14 | 43.81 | 655.64 | 439.44 | 1.49 | 0.0491 | 0.0017 | 0.1251 | 0.0044 | 0.0187 | 0.0004 | 119.7 | 4.0 | 119.5 | 2.2 |
| LS15-15 = 17 | 21.92 | 320.47 | 224.55 | 1.43 | 0.0495 | 0.0026 | 0.1246 | 0.0059 | 0.0190 | 0.0005 | 119.2 | 5.3 | 121.6 | 3.2 |
| LS15-15 = 18 | 16.42 | 242.23 | 195.54 | 1.24 | 0.0485 | 0.0025 | 0.1256 | 0.0071 | 0.0196 | 0.0007 | 120.1 | 6.4 | 125.1 | 4.3 |
| LS15-15 = 19 | 22.61 | 343.31 | 256.66 | 1.34 | 0.0517 | 0.0026 | 0.1331 | 0.0066 | 0.0200 | 0.0007 | 126.9 | 5.9 | 127.4 | 4.4 |
| LS15-15 = 20 | 16.05 | 214.84 | 206.54 | 1.04 | 0.0565 | 0.0027 | 0.1514 | 0.0072 | 0.0208 | 0.0008 | 143.2 | 6.4 | 132.9 | 5.0 |
| LS15-15 = 21 | 16.64 | 225.52 | 182.64 | 1.23 | 0.0480 | 0.0026 | 0.1341 | 0.0069 | 0.0213 | 0.0007 | 127.8 | 6.1 | 135.9 | 4.5 |

Precambrian metamorphic rocks of the Jiaonan group (Fig. 1c). Our samples include monzogranite, syenogranite and alkali-feldspar granite in terms of modal mineralogy and the petrographic details (Table 1). The samples are light grey to pink in colour and medium to fine in grain size. Most of the samples are relatively uniform with mafic magmatic enclaves (MMEs) present in places (e.g., QD15-03;Fig. 2A). Both the MMEs and host have the same mineralogy but the MMEs have greater modal amphibole and biotite. The main mineral phases of monzogranites (Fig. 2B) are feldspar, plagio-clase and quartz. The alkali-feldspar granite (Fig. 2C) is dominated by alkali-feldspar and quartz. The alkali feldspars are mainly perthitic potassium feldspar. Mafic minerals (1%~10%) are biotite and amphibole. Mafic alkali minerals like aegirine (Zhao et al., 1997) is not

observed in our samples. Accessory phases (<1%) include apatite, sphene, magnetite, zircon and fluorite (Fig. 2D).

3. Analytical methods

3.1. Zircon U-Pb dating

Zircon separation was done in the Laboratory of the Langfang Institute of Regional Geological Survey using a combined method of heavy liquid, magnetic and manual selection under a binocular. The selected zircons were set in an epoxy mount before polished to expose zircon interiors. Cathodoluminescence(CL)images were taken at Beijing



Fig. 3. The Concordia diagrams show zircon U-Pb ages and representative CL images of zircons with analytical spots as indicated with yellow circles for LS15-15 and QD15-22. See Table 2 for analytical data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



Fig. 4. Portion of the total alkali versus silica (TAS) diagram (Cox et al., 1979; Maitre et al., 1989; Wilson, 1989) shows the compositional variation of samples. The curved solid line subdivides the alkalic (above) from sub-alkalic (below) rock types (Maitre et al., 1989; Wilson, 1989). The A-type granite and I-type granite are literature data of Laoshan granitoid rocks (Yan and Shi, 2014; Zhao et al., 1997).

GeoAnalysis CO. Ltd. to examine the internal structure of individual zircon grains needed for spot analysis. Zircon U-Pb dating was done using LA-ICP-MS in the Ocean Lithosphere and Mantle Dynamics Laboratory, Institute of Oceanology, Chinese Academy of Sciences (OLMDL-IOCAS). We used an Agilent 7900 ICP-MS instrument coupled with 193 nm Photon Machines Excite Laser for analysis. Helium was applied as a carrier gas. The laser spot size was 35 µm. Zircon 91500 was used as the external standard for U-Pb dating (Wiedenbeckliu et al., 1995), and analyzed twice between every five unknowns. NIST 610 glass was used as an external standard for trace element analysis (Xiao et al., unpublished). The age calculation was done using the method of Liu et al. (2010) and the Concordia diagrams were plotted using Isoplot (Ludwig, 2003).

3.2. Major and trace elements

The bulk-rock major and trace element analysis was done in OLMDL-IOCAS. Bulk-rock major elements were analyzed using Agilent 5100 ICP-OES following the method of Kong et al. (unpublished). Trace element analysis was done using ICP-MS (Agilent 7900) following Chen et al. (2017). The bulk-rock major (Appendix 1) and trace (Appendix 2) elements of USGS reference materials analyzed together with our samples agree well with reference values within error (GeoREM, http://georem. mpch-mainz.gwdg.de/).

3.3. Bulk-rock Sr-Nd-Pb-Hf isotopes

Bulk-rock Sr-Nd-Pb-Hf isotopes analysis was done in the Radiogenic Isotope Facility at the University of Queensland, Australia. The rock powders were dissolved in a mixture of double-distilled concentrated HNO₃ and HF, and dried on a hot plate at 80 °C. After converting any fluoride to nitrate, the dried residue was dissolved with 3 ml 2 N HNO₃ and 1.5 ml was loaded onto a stack of Sr-spec, Thru-spec and LN-spec resin columns to separate Sr, Nd, Pb, and Hf from the matrix, using a streamlined procedure modified after Míková and Denková (2007) and Yang et al. (2010).



Fig. 5. Bivariate plots of the major element oxides and ratios (e.g., A/NK = molar Al₂O₃ /[Na₂O + K₂O], A/CNK = molar Al₂O₃ /[CaO + Na₂O + K₂O]) as a function of SiO₂//MgO show a large range of major element compositional variation, reflecting a varying degree of fractional crystallization of plagioclase, alkali feldspar, amphibole, biotite and accessory phases as observed. The A-type granite and I-type granite are the literature data as Fig. 4.

All the measured ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd, ¹⁷⁶Hf/¹⁷⁷Hf ratios were normalized to 86 Sr/ 88 Sr = 0.1194, 146 Nd/ 144 Nd = 0.7219 and 179 Hf/ 177 Hf = 0.7325, respectively. Analyses of NBS987 standard run during the same period gave ${}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.710249 \pm 9$ (*n* = 22, 2 σ). In the course of ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf analysis, the in-house Nd standard, Ames Nd Metal and 10 ppm Hf ICP solution from Choice Analytical were used as instrument drift monitors, respectively. This in-house Nd Metal and Hf standards were cross-calibrated against the JNdi-1 Nd international standard and the JMC-475 Hf international standard, respectively. Analyses of in-house Nd standard gave 143 Nd/ 144 Nd = 0.511965 \pm 6 (*n* = 12, 2 σ). Analyses of in-house Hf standard yielded a mean 176 Hf/ 177 Hf of 0.282147 \pm 5 ($n = 39, 2\sigma$). Pb isotope ratios were normalized for instrumental mass fraction relative to NBS/SRM 997 203 Tl/ 205 Tl = 0.41891, which were then normalized against NBS981 (see Sun et al., 2017). The values of USGS reference materials run with our samples are given in Appendix 3, which agree with the reference values (GeoREM, http://georem.mpch-mainz.gwdg.de/). Procedures for Sr, Nd, Pb and Hf elemental column separation and analytical details are given in Guo et al. (2014) and Sun et al. (2017).

4. Results

4.1. Zircon U-Pb ages

Zircons from LS15-15 and QD15-22 have been dated (Table 2). The zircons are mostly euhedral, transparent, ranging from 100 to 200 µm in size with length-to-width ratios of 1:1–2:1. The cathodoluminescence (CL) images show oscillatory zoning of magmatic origin. The zircons have varying U (48.46 to 439.44 ppm) and Th (105.83 to 723.63 ppm) concentrations with varied Th/U ratio of 0.94–2.18. After rejecting discordant analyses, we obtain zircon crystallization age of ~ 120 Ma within error (Fig. 3). This age is similar to the youngest ages of the granitoids in the region (Fig. 1; Guo et al., 2005; Goss et al., 2010). Captured zircon cores exist in both samples, plot along or close to the Concordia. Their age is around 140–130 Ma (Table 2), similar to the ages of Cretaceous granitoids in the region (Guo et al., 2005).

4.2. Bulk-rock major and trace elements

4.2.1. Major elements

The samples (Fig. 4) are compositionally alkali rich ($Na_2O + K_2O$ = 7.82–10.63 wt.%) and calc-alkaline (Rittmann Serial Index σ $[= (K_2O + Na_2O)^2 / (SiO_2-43), units in wt.\%] < 9; in Appendix$ 6) without excess alkalis (A/NK>1; Fig. 4). Previous classification of the Laoshan granite is largely based on SiO₂ content (Fig. 4; Yan and Shi, 2014). The so-called A-type granites are actually highly evolved ones with high SiO₂ (Fig. 4) and low Al₂O₃ (Fig. 5). Our samples span a larger range of SiO₂ than the data in the literature (Yan and Shi, 2014). Thus, the changes in alkali content between the Itype granite and the A-type granite in the literature can be observed (Fig. 4). The changes of samples in alkali content was most likely controlled by fractional crystallization in consistence with the petrography. Because the liquidus temperature is inversely correlated with SiO₂ but positively correlated with MgO during magma evolution, the ratio of SiO₂/MgO can be an effective parameter to describe the extent of magma differentiation (see Fig. 5). For example, magma cooling and mineral crystallization lead to increasing $SiO_2/$ MgO in the residual melts. Thus, the most evolved granite experienced highest extent of crystallization and thus have the highest SiO₂/MgO. Note that by using the combined parameter SiO₂/MgO, we emphasize that these samples represent products of varying extent of fractional crystallization (Fig. 5) despite the fact that the granitoid rocks are not pure liquids, but mixtures of liquids with incompletely segregated crystals (both liquidus and residual phases).

4.2.2. Trace elements

Fig. 6a shows chondrite-normalized rare earth element (REE) patterns of the samples. They are enriched in light REEs (Appendix 6, Fig. 6a) and have varying negative Eu anomalies (Eu/Eu* = 0.05–0.77, Fig. 7a). Four samples have low abundances from Sm to Tm, which can also be found in some highly fractional granites (Fig. 6, Qiu et al., 2008). Fig. 6b shows that the samples are enriched in Rb, Th and U, but depleted in Ba and Sr. This is consistent with the negative Eu anomalies due to feldspar fractionation. Like most granites, our samples are characteristically depleted in Nb, Ta and Ti. The P depletion results from apatite fractionation.

4.3. Bulk-rock Sr-Nd-Pb-Hf isotopes

Bulk-rock Sr-Nd-Pb-Hf isotopic data are given in Appendix 7. The $\epsilon_{\rm Nd}$ (t), $\epsilon_{\rm Hf}(t)$, $(^{206}{\rm Pb}/^{204}{\rm Pb})_i$, $(^{207}{\rm Pb}/^{204}{\rm Pb})_i$ and $(^{208}{\rm Pb}/^{204}{\rm Pb})_i$ are calculated at 120 Ma. Samples have variably high $^{87}{\rm Sr}/^{86}{\rm Sr}$ (0.7083 to1.2265; Fig. 7b) because of feldspar fractionation-reduced low Sr in the samples, hence the high Rb/Sr and high radiogenic $^{87}{\rm Sr}$ as manifested by the correlated negative Sr/Sr* and Eu/Eu* anomalies (Fig. 7a; Halliday et al., 1991; Sallet et al., 2000; Shao et al., 2015). Calculation of initial $^{87}{\rm Sr}/^{86}{\rm Sr}$ for such high Rb/Sr samples would become



Fig. 6. Chondrite-normalized rare earth element and primitive mantle normalized incompatible element patterns for the Laoshan granite. For comparison, the literature data (A-type granite, I-type granite; see Fig. 4) are also plotted. Chondrite and primitive mantle values are from Sun and McDonough (1989). Samples show various Eu anomalies as the result of plagioclase and alkali feldspar fractionation as Fig. 7a. The lower values of middle rare earth elements from Sm to Tm in the four samples is mainly controlled by fractionation of amphibole, apatite and plagioclase.



Fig. 7. (a) The correlation between Eu/Eu^{*} and Sr/Sr^{*} (R² = 0.7593; Fig. 7a) indicates the consequence of plagioclase-dominated fraction (Niu and O'Hara, 2009; Shao et al., 2015). (b) Rb/Sr isochron defined by Laoshan granite samples give a significant and consistent emplacement age of ~ 126 Ma, which is, expectedly, slightly older than the zircon crystallization ages (Fig. 3). Importantly, the isochron gives a tight and significant initial ⁸⁷Sr/⁸⁶Sr of 0.7061, pointing to uniform source (or mixed source) composition for the Laoshan granite.

problematic (Cavazzini, 1994; Mahood and Halliday, 1988; Sallet et al., 2000), but the bulk-rock isochron gives a unique initial 87 Sr/ 86 Sr = 0.7061 and significant isochron age of ~126 Ma (Fig. 7b), representing the magma emplacement age and is consistent with the zircon crystallization ages (Fig. 3; also see Section 5.3). Our samples have enriched $\epsilon_{Nd}(t)$ (-13.8 to -19.5) and $\epsilon_{Hf}(t)$ (-14.6 to -24.4), defining a trend that is on the extension of the mantle array (Fig. 8). Both Nd-Hf and Pb isotopes ((206 Pb/ 204 Pb) $_i$ = 16.244 to 17.304) indicate a trend of magma mixing, with the enriched endmember and the less enriched endmember (Fig. 8, Fig. 9).

5. Discussion

5.1. Intra-plate setting

Previous studies (Zhao et al., 1997) used the tectonic discrimination plots to classify the calc-alkali granites into volcanic arc granite (VAG) and within plate granite (WPG). Here we emphasize that the intraplate tectonic setting of Laoshan granites in Mesozoic is already



Fig. 8. Hf-Nd isotope diagram illustrates that magmas parental to the Laoshan granite are derived from anatexis of the lower continental crust induced by and mixed with lithospheric mantle-derived basaltic magmas beneath eastern continental China. Binary isotope mixing calculations with the number of basaltic melts contribution use the lithosphere mantle-derived melts data from Guo et al. (2013) and Liang et al. (2017) and the lower continental crust (LCC) data from Jahn et al. (2008), in 5% intervals. Hf isotope of the literature data is inferred from Nd isotope following the equation ($\epsilon_{Hf} = 1.36\epsilon_{Nd} + 2.95$) given by Vervoort and Patchett (1996). The coastal granitiods are from Xue et al. (2018).

known (see above and below). It is thus unnecessary to use tectonic discrimination plots to interpret tectonic settings that are geologically incorrect. The Korean Peninsula has long been thought to be part of the North China Craton (once called Sino-Korean para-platform) with similar Precambrian basement (Zhai et al., 2005, 2007, 2016). Recent studies have been able to correlate the lithologies between the Jiaodong Peninsula and the Korean Peninsula (Hu et al., 2012; Oh and Kusky, 2007; Zhai et al., 2005, 2007, 2016). Besides, the paleomagnetic data analysis (Zhao et al., 1999), the combined method of seismic tomography and gravity data (Hu et al., 2012) confirm the traditional view. That is, the North China Craton and the Korean Peninsula have been a single coherent block since the early Paleozoic. However, how the Jiaodong Peninsula and Korean Peninsula may have actually correlated has not been explained until recently when Niu and Tang (2016) and Tang et al. (2016) elaborated the origin of the Yellow Seas as a continent-rifted basin since ~56 Ma. This means the Laoshan granite was emplaced in an intra-plate setting before the opening of the Yellow Sea. This is consistent with the contemporaneous granitoid magmatism in the Russian Far East (as young as ~56 Ma), South Korea and Southwest Japan (as young as 71 Ma; Tang et al., 2016).

5.2. Origin of the Laoshan granite

Several models have been proposed for the origin of the Laoshan granite in the literature, including (1) partial melting of residual basaltic lower crust that had been previously melted to produce I-type granites (Zhao et al., 1997), (2) low degree melting of intermediate to felsic lower crust under granulite facies (Wei, 2008), and (3) mixing of the asthenosphere-derived basaltic melt and the lower continental crust - derived melt (Yan and Shi, 2014). We evaluate these scenarios and propose our explanation that is consistent with the geological, petrological and geochemical data.

5.2.1. Assessing the model of lower continental crust anatexis

Several experimental studies on partial melting of intermediate to felsic crustal rocks (Patiño Douce, 1997; Skjerlie and Johnston, 1992) have been proposed to explain the origin of granite similar to the Laoshan granite with high ^TFe₂O₃, K₂O and low Al₂O₃, CaO, MgO, Sr, and Eu. All the existing models (Wei, 2008; Yan and Shi, 2014; Zhao et al., 1997) require melting of the lower continental crust for magmas parental to the Laoshan granite. Thus, it is necessary to test whether melting of the mafic lower continental crust can indeed produce magmas parental to the Laoshan granite. To quantify and assess the partial melting interpretation, we choose a mafic granulite (90DA1, SiO₂ = 51.6 wt.%, MgO = 10.8 wt.%; Na₂O + K₂O = 2.52 wt.%; Zhou et al., 2002) and the average composition of the granulite of the Yangtze

craton (YC-LCC, $SiO_2 = 65.7$ wt.%, MgO = 2.3 wt.%; Gao et al., 1998) as the source rocks to model partial melting of the mafic and intermediate lower continental crust separately. The MELTS (Ghiorso and Sack, 1995) used for the model is set at 10 kbars with the temperature range of 1200-700 °C at 20 K intervals (Fig. 10d). The calculation shows that 20%–28% partial melting of the mafic granulite can produce melts that match the least evolved (low SiO₂/MgO) composition of the Laoshan granite (Fig. 10d). This corresponds to temperature condition of 900-1040 °C, consistent with the least evolved compositions of the Laoshan granite. Varying extents of fractional crystallization from such least evolved samples can effectively explain the entire data range (e.g., SiO₂/MgO) of the Laoshan granite. This is consistent with the major and trace element data as discussed below. Obviously, melting of the intermediate or felsic YC-LCC cannot produce melts parental to the Laoshan granite. This model provides a conceptual clue to the feasibility of mafic crustal melting and provides clue to the hypothesis of lower continental crust melting for the granitoids in the continental interiors (Niu et al., 2015).

5.2.2. Constraints on the source

The model above shows that magmas parental to the Laoshan granite can be generated by anatexis of the lower continental crust, which is consistent with isotope data. The isotope compositions of the lower crust beneath the Jiaodong Peninsula vary greatly (Fig. 8; Jahn et al., 2008), and some values coincide with the Laoshan granite. In other words, some samples can be formed directly through anatexis. The lower continental crust with a normal geothermal gradients is seldom able to melt and anatexis requires excess heat source (e.g., Huppert and Sparks, 1988). Although minor volumes of partial melt can be



Fig. 9. (a) Initial ²⁰⁷Pb/²⁰⁴Pb vs. initial ²⁰⁶Pb/²⁰⁴Pb and (b) initial ²⁰⁶Pb/²⁰⁴Pb vs. initial ²⁰⁸Pb/²⁰⁴Pb diagrams show the Laoshan granites differ distinctly from those of the coastal granitoids (Hong et al., 2018). The North Hemisphere Reference Line (NHRL) refers to what from Hart (1984). EM2 fields after Zindler and Hart (1986) are also shown.

produced by fluid-present melting at high water fugacity (Bergantz, 1989), because the Laoshan granitoid magmatism occurred in an "intra-plate" setting away from any known paleo-subduction zone (Fig. 11), the excess heat required for the anatexis must have come from mantle-derived basaltic melts (Niu, 2005; Niu et al., 2015; Zhou et al., 2006). Isotopically, the $\varepsilon_{Nd}(t)$ (-13.8 to -19.5) and ε_{Hf} (t) (-14.6 to -24.4) values (Fig. 8) of the Laoshan granite lie between the range of the lower crust of the Jiaodong Peninsula (Jahn et al., 2008) and the Mesozoic lithospheric mantle-derived melts (basalts from Guo et al., 2013; dolerite from Liang et al., 2017). The isotopic range of samples provide evidence for the crustal anatexis induced by mantlederived basaltic melts. That is, the basaltic melts not only provide the heat but also contribute material to the Laoshan granite magmatism. This observation supports the hypothesis of lower continental crust melting for the intra-plate granitoids (Niu et al., 2015; also see Section 5.2.1 and 5.2.3 below).

The question then concerns the origin of the basaltic melts. Among the several ideas (see Section 5.3) about the mechanism of widespread lithosphere thinning throughout entire eastern China in the Mesozoic (Niu, 2005, 2014; Niu et al., 2015), the physically most likely process is the basal hydration weakening. That is, the lithosphere was being thinned by converting the basal portions of the lithosphere into the asthenosphere, accompanied by partial melting and basaltic magmatism (Niu, 2005, 2006, Niu and O'Hara, 2009, Niu, 2014; Niu et al., 2015). Niu (2014) suggested that basaltic melts are most likely to have been derived from being-hydrated and -thinned lithosphere with the water coming from the paleo-Pacific plate lying stagnantly in the mantle transition zone. The ascent, intruding and underplating of the basaltic magmas provide the heat for the widespread crustal melting for the intra-plate granitoid magmatism in eastern China (Niu et al., 2015).

Some studies (Yan and Shi, 2014; Zhao et al., 2017) suggested the upper continental crust as a candidate of the magma source, but this is not the case for the Laoshan granite. Because the basaltic melts required to provide the heat first encounter the deep crust to cause its melting, which prevents upper crustal melting. Upper crustal magma contamination is possible during magma ascent, but not the primary source.

5.2.3. The magma mixing model

As discussed above, we propose that the lithospheric mantlederived basalts provide both heat and material for the primary magmas parental to the Laoshan granite. To quantitatively estimate the relative contributions of the lithosphere mantle-derived melts and the lower continental crust, we used the average Nd isotope composition of the Mesozoic lithospheric mantle-derived melts in the Jiaodong Peninsula (basalts from Guo et al., 2013; dolerite from Liang et al., 2017) as the less enriched endmember, and the highest Nd isotope value of the lower continental crust of the Jiaodong Peninsula (Jahn et al., 2008) as the enriched endmember for binary isotope mixing calculation. The calculations show the significant contribution of the lower continental crust. This mixing calculation using Nd-Hf isotopes is conceptually illustrative on the significance of crustal melting induced by lithospherederived basaltic melts in the Mesozoic although the exact mass contributions cannot be constrained because of the two isotopic endmembers cannot be well constrained.

Our petrological modeling by lower continental crust anatexis (Fig. 10d) shows that ~7%–27% partial melting of the mafic granulite with 10% contribution of mantle-derived basaltic melts (Liang et al., 2017) can produce melts that match the least evolved (low SiO₂/MgO) composition of the Laoshan granite. Hence, with all the uncertainties considered, ~20%–25% melting of the mafic lower crust heated by and mixed with ~10% lithosphere-derived basaltic melts can explain the data. Varying extents of fractional crystallization from such least-evolved granitoid samples can explain the entire data range (e.g., SiO₂/MgO) of the Laoshan granite (see below). We emphasize the above modeling and analysis to be conceptually significant for the petrogenesis of the magmas parental to the Laoshan granite. We also

emphasize the estimated relative contributions of both crust and lithospheric mantle to be meaningful, although the exact mass contributions cannot be well constrained because of the many uncertainties discussed above.

5.3. Effect of crystallization on the petrogenesis of the Laoshan granite

The large compositional variation of the Laoshan granite in terms of SiO₂/MgO and the correlated variations with the abundances and ratios (i.e., A/NK and A/CNK) of other major elements result from varying extents of fractional crystallization from magmas parental to the Laoshan granite (Fig. 5). With cooling and crystallization, SiO₂/MgO decreases and the correlated trends with Al₂O₃, CaO, K₂O Na₂O, ^TFe₂O₃, TiO₂ and P₂O₅ result from varying extent of fractional crystallization of alkali feldspar, plagioclase, amphibolite, biotite, sphene, ilmenite, apatite and zircon, which is consistent with the petrography. The crystallization of plagioclase and alkali-feldspar results in Sr depletion and the resulting high Rb/Sr, hence the variably high 87Sr/86Sr (Fig. 7b; Shao et al., 2015) with ⁸⁷Sr largely resulting from radioactive decay of ⁸⁷Rb, hence, the significant ⁸⁷Sr/⁸⁶Sr-⁸⁷Rb/⁸⁶Sr bulk-rock isochron (Fig. 7b; Cavazzini, 1994; Mahood and Halliday, 1988; Sallet et al., 2000; Shao et al., 2105). Fig. 10a shows that plagioclase and potassium feldspar fractionation is critical in controlling Rb and Sr abundances. Fig. 6 shows that potassium feldspar and plagioclase fractionation is the primary cause of the Sr depletion as manifested by the data trend in Sr-Rb space (Fig. 10a) and Sr-Ba space (Fig. 10b). The effect of plagioclase fraction is also obvious as shown by the Eu/Eu*-Sr/Sr* correlation ($R^2 = 0.6801$; Fig. 7a; Niu and O'Hara, 2009; Shao et al., 2015).

To explain four samples with lower middle REEs from Sm to Tm (Fig. 6), we tried different mineral assemblages based on the petrography in fractional crystallization modeling (Fig. 10c). The parental magma composition is assumed to be the value of QD15–01, which is not that highly evolved. Calculations indicate that the REE pattern is mainly controlled by fractionation of amphibole, apatite and plagioclase. By assuming co-precipitation modes of 42% amphibole, 0.03% apatite and 57.97% plagioclase, about 50% to 60% fractional crystallization of these minerals can form REE patterns similar to those of the four samples (Fig. 10c).

In summary, the primary magma parental to the Laoshan granite was derived by partial melting of the lower crust induced by and mixed with basaltic melts derived from the lithospheric mantle. Varying extents of fractional crystallization of such parental magmas led to the variably evolved compositions of the Laoshan granite samples.

5.4. Tectonic significance

As discussed above, the magma parental to the Laoshan granite was derived from lower continental crustal melting induced by lithospheric



Fig. 10. (a), (b) Rb-Sr and Ba-Sr covariation diagram, indicating that the evolution of the Laoshan granite was controlled largely by alkali-feldspar fractionation. Mineral fractionation vectors (Kf = K-feldspar; Pl = plagioclase; Am = amphibole; Bi = biotite) calculated using partition coefficients from Ewart and Griffin (1994), Nash and Crecraft (1985) and Bacon and Druitt (1988). Tick marks indicate the percentage of mineral phase removed, in 10% intervals. See Appendix 4 for relevant partition coefficients used to calculate. (c) Shows 20%, 30%, 50%, 60% fractional crystallization of the mineral assemblages of Model from assumed magma (QD15–01) along with the Laoshan granite on chondrite normalized rare earth element diagram. (d) Fe₂O₃ vs. SiO₂/MgO. The MELTS (Ghiorso and Sack, 1995) used for the modeling is set at 10 kbars with the temperature range of 1200–700 °C at 20 K intervals. The composition of 90DA1-Granulite (Zhou et al., 2002) and YC-LCC (Gao et al., 1998) represent source materials of the presidues are compiled in Appendix 5. The composition of mixing magma is calculated by using data of the melts of granulite (90%) with the partial melting range of 7% - 28% and the data of dolerite (LYYJ2–1) from Liang et al. (2017) represented the mantle-derived basaltic contribution (10%).

Moving continental China Continental crust China Continental crust China Convective asthenosphere Stagnant paleo-Pacific slab

Fig. 11. The conceptual model of the Cretaceous magmatism in the NW-SE cross section (modified after Niu et al., 2015) shows the intra-plate tectonic setting and origin of magmas parental to the Laoshan granite. The stagnant paleo-Pacific slab in the Mesozoic released water in the form of hydrous melts that ascended and weakened and converted the basal portions of the mantle lithosphere into asthenosphere while producing basaltic magma from the being-converted mantle lithosphere. Such magma rose and intruded the continental crust, providing both heat and material for the parental magmas of the Laoshan granite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mantle-derived basaltic melts in an intraplate setting. The origin of the basaltic melts has been interpreted as relating to the Mesozoic subcontinental lithosphere thinning in eastern continental China (Fan et al., 2001; Gao et al., 2002; Guo et al., 2014; Liang et al., 2017; Liu et al., 2008; Niu, 2005; Niu et al., 2015). What is the mechanism of the lithospheric thinning and the cause of extensive granitoid magmatism in the Jurassic-Cretaceous Mesozoic? (1) Mantle plumes have been proposed as a mechanism causing the Mesozoic lithosphere thinning and the intra-plate magmatism in eastern China (Deng et al., 2004), but contemporary continental flood basalts with domal uplift expected to be associated with mantle plumes (He et al., 2003) are missing in eastern China. Besides, the observation that the "cold" subducted Paleo- Pacific slab lies in the mantle transition-zone (between 410 and 660 km seismic discontinuities) beneath eastern China (Zhao, 2009) argues against the presence and working of hot mantle plumes beneath eastern China (Niu, 2005). (2) Lithosphere delamination (e.g., Gao et al., 2009; Xu et al., 2006) is unlikely to happen because the compositionally buoyant subcontinental lithosphere cannot sink into the compositionally dense asthenosphere (Niu, 2005). (3) Lithosphere stretching induced asthenosphere upwelling can be ruled out because there is no stretching-related linear magmatism in eastern continental China (Niu. 2005).

Physically, the most likely mechanism is the basal hydration weakening by converting the basal portions of the lithosphere (i.e., subcontinental lithospheric mantle or SCLM into the asthenosphere accompanied by partial melting and basaltic magmatism (Niu, 2005, 2006, Niu and O'Hara, 2009, Niu, 2014; Niu et al., 2015). That is, the paleo-Pacific plate lying stagnant in the mantle transition zone release water by dehydration (Niu,2005). The water ascent in the form of hydrous melt can effectively hydrate the basal portion of the lithosphere and convert it to rigidity, strength and viscosity highly reduced asthenosphere (Niu, 2005, 2014), hence the lithosphere being thinned. Niu et al. (2015) demonstrate that the random distribution of the Jurassic-Cretaceous (~190 to ~90 Ma) granitoids in eastern continental China in space and time is best explained as a special consequence of plate tectonics. They were genetically associated with the paleo-Pacific plate lying stagnant in the mantle transition zone beneath eastern continental China (Niu, 2005, 2014; Niu et al., 2015). Underplating and intrusion of the basaltic magmas as the result of lithospheric mantle melting caused by basal hydration weakening indirectly caused the crustal melting and the widespread granitoid magmatism in the interiors of eastern continental China (Niu et al., 2015). In summary, the origin of the Laoshan granite is consistent with the origin of the Cretaceous granitoids in the continental interiors of eastern China as discussed in Niu et al. (2015). It is genetically associated with the lithosphere thinning by means of basal hydration weakening (Niu, 2005, 2014) with the water ultimately, in the form of hydrous melt, coming from dehydration of the paleo-Pacific plate lying stagnant in the mantle transition zone (see Fig. 11; Niu et al., 2015).

Xue et al. (2018) proposed that the petrogenesis of the Cretaceous granitoids along the southeast coast of continental China is more directly related to the active subduction of the paleo-Pacific plate with the mantle wedge derived basaltic melts (the more depleted endmember) intruding/underplating the overlying crust. Figs. 8 and 9 show that the Laoshan granite differs distinctly from those of the coastal granitoids (Hong et al., 2018; Xue et al., 2018). The result of the comparison is mutually corroborating with our understanding that the Laoshan granite was formed in the intraplate setting, rather than an active subduction setting. This observation supports the hypothesis of Niu et al. (2015) that the Cretaceous granitoids in the continental interiors of eastern China is a consequence of the lithosphere thinning by means of basal hydration weakening. The magmatism of the granitoids is ultimately controlled by the dehydration of the paleo-Pacific plate lying stagnant in the mantle transition zone (Niu, 2005, 2014).

6. Conclusions

- The primary magmas parental to the Laoshan granite were derived by anatexis of the lower continental crust heated by and mixed with lithosphere-derived basaltic melts.
- The large compositional variation of the Laoshan granite results from varying extent of fractional crystallization as expressed in the SiO₂/ MgO variation diagrams.
- 3. The Laoshan granite, like other widespread Cretaceous granitoids in the continental interiors of eastern China, is genetically associated with the lithosphere thinning by means of basal hydration weakening (Niu et al., 2005). The magmatism is ultimately controlled by dehydration of the paleo-Pacific plate lying stagnant in the mantle transition zone, which releases water in the form of hydrous melt. The melts ascend and convert the basal portions of the mantle lithosphere into the viscosity-reduced asthenosphere.

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Appendix A. Supplementary data

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