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Huabiao Qiu, Wei Lin, Michel Faure, Yan Chen, Lingtong Meng, et al.. Late Triassic extensional tectonics in the northern North China Craton, insights from a multidisciplinary study of the Wangtufang pluton. *Journal of Asian Earth Sciences*, 2020, 200, pp.104462. 10.1016/j.jseaes.2020.104462 . insu-02877251

HAL Id: insu-02877251

<https://insu.hal.science/insu-02877251>

Submitted on 22 Jun 2020

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Journal Pre-proofs

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PII: S1367-9120(20)30255-8
DOI: <https://doi.org/10.1016/j.jseaes.2020.104462>
Reference: JAES 104462

To appear in: *Journal of Asian Earth Sciences*

Received Date: 20 March 2020
Revised Date: 7 June 2020
Accepted Date: 7 June 2020

Please cite this article as: Qiu, H., Lin, W., Faure, M., Chen, Y., Meng, L., Zeng, J., Ren, Z., Wang, Y., Li, Q., Late Triassic extensional tectonics in the northern North China Craton, insights from a multidisciplinary study of the Wangtufang pluton, *Journal of Asian Earth Sciences* (2020), doi: <https://doi.org/10.1016/j.jseaes.2020.104462>

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1 **Late Triassic extensional tectonics in the northern North**
2 **China Craton, insights from a multidisciplinary study of the**
3 **Wangtufang pluton**

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16 Abstract

17 To better understand Late Triassic tectonic setting in the northern North China Craton
18 (NCC), the emplacement mechanism of the Wangtufang pluton, which recorded the synmagmatic
19 regional tectonic signature, has been investigated. Zircon U-Pb ages, and Hf isotopic data, and
20 whole-rock geochemical analyses suggest that the Late Triassic Wangtufang pluton composed of
21 syenogranite and diorite is derived from partial melting of lower crust with some depleted mantle
22 components. Both the syenogranite and diorite appear isotropic. Anisotropy of magnetic
23 susceptibility and gravity studies have been carried out to characterize internal fabrics and shape
24 of the pluton. The diorite forms just thin remnants above the syenogranite. The syenogranite with
25 a series of NW-SE trending dykes intruded into the diorite and its country rocks. In the
26 syenogranite, the gently dipping magnetic foliations strike nearly parallel to the pluton border. The
27 shallow plunging magnetic lineations mainly strike NE-SW. Combining NE-SW trending
28 elongated subsurface shape with central root, unflat bottom, and moderate- to high- inward dipping
29 sidewalls, the syenogranite could be considered as a lopolith-like intrusion. The syenogranite was
30 likely emplaced by inflation of magma pulses from its central conduit and built up by floor
31 depression. Emplacement of the syenogranite was in an extensional setting, considering: (1) the
32 NE-SW striking magnetic lineation, (2) the NE-SW trending elongated subsurface pluton shape,
33 and (3) the orthogonal NW-SE striking syenogranitic dykes considered as tension gashes during
34 the NE-SW trending extension. The Wangtufang pluton provides reliable arguments to the Late
35 Triassic intracontinental extensional setting already suggested in the northern NCC.

36 **Key words:** North China Craton; early Mesozoic magmatism; Wangtufang pluton;
37 multidisciplinary study; Late Triassic extensional tectonics

38 1. Introduction

39 The early Mesozoic magmatism, represented by E–W trending Late Triassic alkaline
40 intrusive complexes, is conspicuous in the northern NCC. However, their tectonic and geodynamic
41 settings are still debated (Yang et al., 2012; Zhang et al., 2012; Zhao et al., 2015). Based on
42 structural observations and paleomagnetic studies, one group of researchers considers that these
43 Late Triassic granitic and syenitic plutons were due to large-scale Triassic thrusting and strike-slip
44 faulting in the northern margin of the NCC and produced in the local extensional areas by the pull-
45 apart of the strike-slip faults (e.g., Zhao et al., 2015). According to geochemical studies, another
46 group proposes that the Late Triassic alkaline complexes in the northern NCC, especially silica-
47 undersaturated syenites, occurred in an intracontinental extensional tectonic setting (e.g., Yang et
48 al., 2012; Zhang et al., 2012), implying the early timing of cratonic destruction during the Late
49 Triassic (Han et al., 2004). The Late Triassic tectonic regime is important to understand the
50 tectonic and geodynamic evolution of the NCC. However, only few small remnants of Late
51 Triassic sedimentary basins can be observed and offer little coeval structural information in the
52 northern NCC due to the intense post-Triassic tectonics (i.e., Xiabancheng basin and Niuyingzi-
53 Dengzhangzi basin in the Yanshan Fold-and-Thrust Belt (YFTB); Fig. 1; Davis et al., 2009; Meng
54 et al., 2014). Moreover, it is difficult to recognize the regional tectonic framework from these few
55 small remnant basins. Due to less impressive and controversial evidence, the nature of the Triassic
56 regime is in debate since long time with different hypotheses. Late Triassic contractional tectonics
57 was proposed according to the unconformity between Triassic and Lower Jurassic strata, and
58 Lower Jurassic syntectonic conglomerate (Zhao, 1990; Liu et al., 2012). Detrital zircon dating and
59 sedimentary studies suggest that the conformable Upper Triassic strata were deposited in an
60 extensional setting (Davis et al., 2009; Meng et al., 2014; Meng et al., 2019). Consequently, the
61 paucity of structural data makes difficult to assess the Late Triassic tectonic regime.

62 During pluton emplacement, magma fabrics can potentially record information on both
63 magma dynamics and regional strain fields to which the magma was subjected (e.g., Bouchez, et
64 al., 1997; Paterson et al., 1998; Sant’Ovaia et al., 2000). The solid-state fabrics present structural
65 deformation after magma full crystallization (Paterson et al., 1989). Therefore, the fabric pattern
66 and shape of pluton are crucial to decipher the pluton emplacement process. The structural study
67 of plutons is an effective and practical way to unravel regional tectonic setting coeval with the
68 emplacement process (e.g., Bouchez, et al., 1997; De Saint Blanquat et al., 2011). Numerous
69 studies have proven that the fabrics of granitic plutons may provide signatures of the local and
70 regional constraints on the pluton emplacement (e.g., Paterson et al., 1998; De Saint Blanquat et
71 al., 2011; Lin et al., 2013b). Therefore, Late Triassic plutons from the NCC present good
72 opportunities to realize this purpose, and, accordingly, the Wangtufang pluton was chosen for this
73 study (Fig. 1). Indeed, such studies have been rarely performed on Late Triassic plutons of the
74 northern NCC. An integrated multidisciplinary investigation, including structural geology,
75 geochronology, geochemistry, Anisotropy of magnetic susceptibility (AMS), and gravity
76 modeling, has been conducted to decipher the Late Triassic tectono-magmatic setting in the
77 northern NCC. Given the correlation with other contemporaneous plutons or tectonics, the
78 proposed model may have regional implications for the Late Triassic tectonic setting in the
79 northern NCC.

80 **2. Geological setting**

81 After its assembly through the collision of the Eastern, Intermediate (or Fuping), and
82 Western blocks during the Paleoproterozoic (Zhao et al., 2001; Faure et al., 2007; Li and Zhao et
83 al., 2007; Li et al., 2012), the NCC formed a stable craton from Mesoproterozoic to Paleozoic.
84 Archaean and Paleoproterozoic gneiss, migmatites and granites were overlain by a

85 Mesoproterozoic to Permian sedimentary cover, separated by a widespread disconformity between
86 the Middle Ordovician and Upper Carboniferous sequences (Li et al., 2016). The closure time of
87 the Paleo-Asian Ocean to the north of the NCC is still controversial. Some authors argue for a Late
88 Permian to the Early Triassic age (e.g., Windley et al. 2007; Xiao et al., 2015), whereas others
89 propose the Paleo-Asian Ocean closed during the Late Devonian, followed by the Late
90 Carboniferous–Triassic intracontinental tectonics (Xu et al., 2013; Zhao et al., 2013). In the south,
91 the NCC collided with the South China Block before the Middle Devonian (e.g., Mattauer et al.,
92 1985; Xu et al., 1986) or in the Triassic (e.g., Meng and Zhang, 1999; Hacker et al., 2000; Li et
93 al., 2010, 2011, 2017, 2018). In the YFTB, the E-W trending ductile shear zone and thick- and
94 thin-skinned folds and faults occurred progressively from the northern margin toward the interior
95 (Wang et al., 2013). The ductile shear zone concerns the E-W trending Chicheng - Fengning,
96 Fengning - Longhua, and Damiao – Niangniangmiao ductile shear zones in the north (Wang et al.,
97 2013; Zhang et al., 2014; Figure 1), and the E-W trending folds and thrusts include the Unnamed
98 fault, Malanyu anticline, and Jixian thrust fault in the south (Davis et al., 2001; Ma et al., 2007).
99 Few Triassic remnant basins and a large number of contemporaneous plutons are exposed in the
100 northern NCC (Davis et al., 2009; Zhang et al., 2012; Meng et al., 2014).

101 During the Jurassic to earliest Cretaceous, the Mongol-Okhotsk Ocean closed
102 progressively from west to east in the north of the East Asian continent (Zorin, 1999; Daoudene et
103 al., 2013). Meanwhile, the subduction of the Paleo-Pacific Ocean plate occurred in the southeast
104 of the East Asian continent (Davis et al., 2001). A large scale intra-continental deformation and
105 magmatism, traditionally referred to as the Yanshanian movement, occurred in the NCC (Davis et
106 al., 2001; Faure et al., 2012; Zhang et al., 2014; Dong et al., 2015). The YFTB is a typical
107 intracontinental orogen, formed in the northern part of the NCC (Davis et al., 2001). The thrust

108 faults, which strike E–W in the west and NE–SW in the east, are distributed throughout the YFTB
109 (e.g., Davis et al., 2001; Faure et al., 2012; Fig. 1). As mentioned above, due to the intense
110 deformation during the Jurassic Yanshanian contractional events, only few pre-Jurassic structures
111 could be surely recognized in the YFTB (e.g., Davis et al., 2009; Zhang et al., 2012; Meng et al.,
112 2014; Zhang et al., 2014; Fig.1). In the Early Cretaceous, the NCC was dominated by extensional
113 tectonics (i.e., metamorphic core complexes (MCCs), A-type magmatism, graben or half-graben
114 basins; Li et al., 2012; Zhang et al., 2014, Lin et al., 2018).

115 **3. Structural observations**

116 **3.1 Field observations**

117 The Wangtufang pluton has a subcircular surface exposure with a radius of about 12 km.
118 It mainly consists of syenogranite in the southwest and diorite in the northeast (Fig. 2).
119 Macroscopically, these two types of rocks (i.e., pale red syenogranite and dark gray diorite) appear
120 totally isotropic, lacking of any planar and linear structures at outcrops (Figs. 3a and 3b). The main
121 rock-forming minerals, namely, quartz, K-feldspar, plagioclase, amphibole, and biotite, are
122 generally euhedral to subhedral without obvious preferred orientation. The Wangtufang pluton
123 intrudes into foliated, even mylonitic Archaean gneiss and undeformed migmatitic granite (Lin et
124 al., 2013a; Fig. 2). In the gneiss, in spite of the strike variation of foliation, the mineral and
125 stretching lineations are consistently oriented along a NW–SE direction (Figs. 2 and 3c–3d). A
126 top-to-the SE sense of shear is indicated by sigmoidal K-feldspar porphyroclasts (Fig. 3e). The
127 gneiss is pervasively folded by the top-to-the SE shearing, indicative of strong deformation before
128 pluton emplacement. In the northwest, steep and weak foliations are developed in the migmatitic
129 granite near the contact with the diorite (Figs. 2 and 3f). A remnant of the country rocks is

130 preserved in the southeast of the syenogranite (Fig. 2). The pluton is overlain by Cretaceous
131 pyroclastic rocks in its east (Fig. 2).

132 In the Wangtufang pluton, centimeter to ten-meter wide syenogranitic dykes extensively
133 intrude in the diorite (Fig. 2). Meter-scale dykes intruded into the diorite near the contact between
134 the syenogranite and diorite (Fig. 4a). Locally, diorite blocks are included in syenogranite dykes
135 (Fig. 4b). The contact between syenogranite and drop blocks of diorite is sharp. It can be observed
136 that numerous dykes of the syenogranite intruded into the diorite in its northeasternmost (Fig. 4c).
137 Furthermore, all dykes are steep and strike consistently NW–SE direction (Fig. 2). In the
138 syenogranite, several ten-meter xenoliths in diameter of the diorite are scattered in the syenogranite
139 (Fig. 4d). A remnant of diorite remains in the center of the syenogranite (Fig. 2). These phenomena
140 show that the diorite was dismembered by the intrusion of the syenogranite with a series of dykes
141 after the diorite had fully crystallized.

142 **3.2 Microscopic observations**

143 To determine the relationships between the minerals and magnetic fabrics, microstructures
144 are investigated in 36 sampling sites of the Wangtufang pluton (Fig. 5a). Under the microscope,
145 two textural types can be distinguished in the Wangtufang pluton. At most sites (67%), the
146 Wangtufang pluton presents magmatic fabrics without any evidence of deformation (Figs. 5a–5c).
147 Quartz crystals are anhedral, non-deformed, and do not show signs of undulose extinction or
148 dynamic recrystallization. K-feldspars present Carlsbad twinning and marginal replacement by
149 myrmekite (Fig. 5b). The euhedral biotite flakes have a sharp extinction and are neither kinked nor
150 bent (Fig. 5c). Plagioclase grains are euhedral and exhibit Carlsbad-albite compound twinning and
151 polysynthetic twinning (Fig. 5c). Besides, at some sites (33%), submagmatic fabrics can be also
152 observed (Fig. 5a). Millimeter-sized quartz grains show an undulose extinction, and small well-

153 individualized quartz grains occur at the border of the coarse grains (Figs. 5d and 5e). Generally,
154 significant solid-state deformation has not been observed. The fabrics are mostly acquired in
155 magmatic state but record some submagmatic deformation.

156 **4. Geochronology and geochemistry**

157 **4.1 Zircon U–Pb geochronology**

158 Considering the paucity of available dating in this pluton, new zircon U-Pb dating of two
159 samples WTF5 and WTF13 was performed by a Cameca IMS 1280 large-radius SIMS at the
160 Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), Beijing (Fig. 2;
161 Tab. 1). The zircon grains from these two samples are subhedral, transparent, and 50–150 μm in
162 length with aspect ratios between 1:1 and 3:1. CL images show clear oscillatory zoning (Fig. 6).
163 Th/U ratios of Sample WTF5 vary from 0.42 to 1.12. Twenty analyses of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$
164 results plotted on a Concordia diagram are relatively consistent, yielding a Concordia age of 209.0
165 ± 1.4 Ma, interpreted as the Late Triassic crystallization age of the syenogranite (Fig. 6, Tab. 1).
166 This age is in agreement with previous age at 207 ± 1 Ma (Liu et al., 2012; Fig. 2). Th/U ratios of
167 Sample WTF13 range from 0.38 to 1.50. Nineteen analyses of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ results
168 show a Concordia age of 208.8 ± 1.8 Ma (Fig. 6, Tab. 1). It corresponds to the Late Triassic
169 emplacement age of the diorite, older than a previous age at 191 ± 1 Ma (Liu et al., 2012; Fig. 2).
170 The ages of the syenogranite and diorite are the same within errors.

171 **4.2 Major and trace elements analyses**

172 Analyses of whole-rock major and trace elements were carried out at the IGGCAS. Major
173 elements were analysed by X-ray spectrometry. Analytical precision is estimated at 1–5% for
174 major elements. Trace elements were determined by inductively coupled plasma mass
175 spectrometry (ICP-MS). The major- and trace-element data are documented in Tab. 2. The

176 syenogranite samples have high SiO_2 contents ranging from 75.05 to 77.01 wt %. All samples are
177 relatively high in Al_2O_3 (12.44–13.34 wt %), Na_2O (3.51– 4.06 wt %) and total alkalis ($\text{K}_2\text{O}+$
178 Na_2O , 8.42–8.91 wt %), with $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of 0.71–0.84. They are low in P_2O_5 (0.02–0.04 wt
179 %) and TiO_2 (0.12–0.19 wt %) abundances, and have Mg number # of 6.76–17.73. In the total
180 alkali versus silica diagram (Fig. 7a), all samples plot in granite field. The diorite displays a SiO_2
181 abundance of 51.88–56.31 wt %. It is characterized by a high Al_2O_3 content (15.78–19.66 wt %),
182 a wide K_2O range of 1.46–3.50 wt % and total alkalis ($\text{K}_2\text{O}+ \text{Na}_2\text{O}$, 6.68–8.16 wt %), with
183 $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of 1.33–2.97. They have relatively high $\text{Fe}_2\text{O}_3^{\text{T}}$ (7.77–9.14 wt %) and low MgO
184 (2.52–3.63 wt %) contents, with Mg # of 30.67–51.97. The samples plot in the monzodiorite and
185 monzonite fields in the total alkali versus silica diagram (Fig. 7a). Both the syenogranite and the
186 diorite are peraluminous (Fig. 7b) and can be categorized as high-K calc-alkaline series rocks (Fig.
187 7c).

188 The syenogranite and the diorite have total rare Earth element contents ($\sum\text{REE}$) varying
189 over 29.84–240.38 ppm, and 169.96–414.57 ppm, respectively, and both display right-dipping
190 chondrite-normalized REE patterns (Fig. 8a). Their $\sum\text{LREE}/\sum\text{HREE}$ ratios are 5.92–15.17 and
191 6.28–10.25, respectively. The syenogranite displays $(\text{La}/\text{Yb})_{\text{N}}$ and $(\text{Gd}/\text{Yb})_{\text{N}}$ ratios of 3.21–15.81
192 and 0.74–1.26 with high negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.16\text{--}0.54$), whereas the diorite shows
193 $(\text{La}/\text{Yb})_{\text{N}}$ and $(\text{Gd}/\text{Yb})_{\text{N}}$ ratios of 9.76–14.12 and 1.87–5.03 with low negative Eu anomalies
194 ($\text{Eu}/\text{Eu}^* = 0.64\text{--}0.94$) (Fig. 8a). In the primitive mantle-normalized variation diagrams (Fig. 8b),
195 the syenogranite and the diorite samples are both enriched in large-ion lithophile elements (LILE)
196 relative to high field strength elements (HFSE). Their REE and trace element patterns are similar
197 to the contemporaneous Dushan batholith to its south (Ye et al., 2014, Fig. 1).

198 **4.3 *In-situ* zircon Hf isotopes**

199 Previously analyzed zircon grains for U-Pb isotopes were chosen for *In-situ* zircon Hf
200 isotopic analyses. It was carried out in situ on a Neptune multi-collector ICP-MS equipped with a
201 Geolas-193 laser ablation system at IGGCAS. Results for in situ Hf isotope analyses of zircons
202 are shown in Fig. 9 and Tab. 3. Zircons from the syenogranite (WTF5) have variable Hf isotopic
203 compositions, $^{176}\text{Hf}/^{177}\text{Hf}$ ratios between 0.282377015 and 0.282469207, $\epsilon\text{Hf}(t)$ values between –
204 9.78 and –6.54, and two-stage depleted mantle Hf model ($t_{\text{DM}2}$) ages between 1840.9 and 1635.3
205 Ma. Zircons from the diorite (WTF13) have $^{176}\text{Hf}/^{177}\text{Hf}$ ratios between 0.282555378 and
206 0.282665470, a range of $\epsilon\text{Hf}(t)$ values varying from –3.42 to –0.01, and two-stage depleted mantle
207 Hf model ($t_{\text{DM}2}$) ages between 1439.9 and 1205.6 Ma. Magmatic zircons from the Wangtufang
208 pluton exhibit similar $\epsilon\text{Hf}(t)$ values from –13.69 to 3.94, and two-stage depleted mantle Hf model
209 ($t_{\text{DM}2}$) ages from 1582 to 950 Ma in the contemporaneous plutons (Yang et al., 2012; Zhang et al.,
210 2012; Ye et al., 2014; Xiong et al., 2017).

211 5. Anisotropy of magnetic susceptibility

212 Field and microscopic observations suggest that both planar and linear fabrics cannot be
213 directly observed in the Wangtufang pluton. Magnetic fabrics can often record the fabric elements
214 of anisotropic rocks where macro and microscopic features fail to do it (Archanjo et al., 1994;
215 Bouchez and Gleizes, 1995; Bouchez et al., 1997). In order to assess the fabric elements, an AMS
216 study has been carried out. Two hundred and four cores from 36 sites have been sampled for AMS
217 measurements in the Wangtufang pluton, 20 in the syenogranite and 16 in the diorite. The
218 measurements are realized in the Laboratory of Paleomagnetism and Chronology of IGGCAS. A
219 total of 204 cores from 36 sampling sites were cut into cylindrical specimens of 2.2 cm in length
220 and 2.5 cm in diameter. The anisotropy magnetic susceptibility and the bulk susceptibility were
221 measured with a KLY4 susceptometer. The mean orientation of three principal axes of the AMS

222 ellipsoid ($K_1 \geq K_2 \geq K_3$), the shape parameter (T), and the anisotropy degree (P_1) were calculated
223 by the ANISOFT package (Jelinek, 1981). The magnetic mineralogy was investigated to identify
224 the magnetic susceptibility carriers by several methods, including: (1) Isothermal Remanent
225 Magnetization (IRM); (2) thermomagnetic (K-T) curves, and (3) hysteresis loops.

226 **5.1 Magnetic mineralogy**

227 The histogram of mean magnetic susceptibility, $K_m = (K_1 + K_2 + K_3)/3$, displays a large
228 range of values in 36 sites, from 90 to $95,900 \times 10^{-6}$ SI (Fig. 10a and Tab. 4). In the diorite, all 16
229 sites exhibit K_m values higher than $7,000 \times 10^{-6}$ SI ($7,540$ to $95,900 \times 10^{-6}$ SI), demonstrating the
230 predominance of ferromagnetic minerals. In the syenogranite, K_m mainly varies from about 90 to
231 $15,400 \times 10^{-6}$ SI, and 7 out of 20 sites show K_m values lower than 500×10^{-6} SI, implying that the
232 paramagnetic minerals (biotite) may be the main carriers of the magnetic susceptibility (e.g.,
233 Tarling and Hrouda, 1993). In 13 out of 20 sites, K_m values are higher than 500×10^{-6} SI, suggesting
234 the presence of ferromagnetic minerals. It seems that both paramagnetic and ferromagnetic
235 minerals are the contributors to the magnetic fabrics in the syenogranite.

236 All hysteresis curves of six representative samples display nonlinear variations (Figs. 11a–
237 11c). Sudden saturation of the isothermal magnetic remanence below 300 mT occurs in all samples
238 (Figs. 11d–11f). Thermomagnetic measurements show a rapid drop of magnetic susceptibility at
239 $\sim 580^\circ\text{C}$ (Figs. 11g–11i). All these results suggest that magnetite is likely an overwhelming
240 contributor to the magnetic carriers in the Wangtufang pluton despite the presence of biotite. The
241 ratios of hysteresis parameters M_r/M_s and H_{cr}/H_c display the mean grain size of the magnetite of
242 the analyzed samples is within the pseudo-single domain (PSD) zone (Dunlop, 2002; Fig. 12),
243 indicating that the principal axes of the magnetic susceptibility ellipsoid (K_1 and K_3 measured in

244 this study) correspond to the major morphological axes of minerals, representing magnetic
245 lineation and the pole of magnetic foliation, respectively.

246 More than 92% of the sampled sites display an anisotropy degree (P_J) lower than 1.2 (Figs.
247 10b and 10c), concordant with the magmatic fabrics recognized by microscopic observations, and
248 the remaining sites come from the diorite, implying that their higher P_J value may be due to the
249 high concentration of magnetite (Cruden, et al., 1999). The shape parameter (T) mainly ranges
250 between -0.551 and 0.829, showing a dominant oblate shape (~86%) for magnetic fabrics (Figs.
251 10c and 10d). Obvious correlations between P_J , T, and K_m is lacking, implying that AMS varies
252 independently from the magnetic minerals (Borradaile and Henry, 1997; Figs. 10b–10d).

253 5.2 AMS results

254 The site-average orientation with corresponding 95% confidence level ($\alpha_{95\max}$ and $\alpha_{95\min}$)
255 was calculated for K_1 and K_3 axes of each site (Jelinek, 1978; Fig. 13). For a confidence level
256 larger than 25° , the direction of the corresponding magnetic axis is considered as poorly defined,
257 whereas it is considered as well-defined or reliable when lower than 25° . More than 78 % of the
258 AMS sites are well defined for both K_1 and K_3 . The magnetic fabrics were mapped throughout the
259 Wangtufang pluton (Fig. 14).

260 At the map scale, the magnetic foliations in the diorite strike subparallel to the pluton
261 boundary and dip inward at variable angles (Fig. 14a). The magnetic lineations are highly scattered
262 with variable dips (Fig. 14b). This may be due to an overprint by the late-stage tectonomagmatism.
263 Instead, in the syenogranite, both the magnetic foliations and lineations are highly grouped (Fig.
264 14a). Magnetic foliations, also parallel to the pluton boundary, display a concentric arrangement.
265 The majority of specimen (14 out of 20 sites) show subhorizontal foliations with dip angles ranging
266 from 3° to 40° . Specimens from six sites have moderately steep magnetic foliations (dip angles

267 ranging from 45° to 70°). These sites are almost near the contacts with the country rock and the
268 diorite. The magnetic lineations are all horizontal to subhorizontal (mainly $\sim 9^{\circ}$ to 29°) and have
269 nearly constant NE–SW plunges (Fig. 14b).

270 **6. Gravity modeling**

271 Gravity modeling has been long proved its efficiency to constrain the geometry and
272 possible feeder zones of pluton (e.g., Vigneresse et al., 1990; Améglio and Vigneresse, 1999; Lin
273 et al., 2013b). We carried out a gravity study to characterize the shape of the Wangtufang pluton
274 at depth.

275 **6.1 Residual Bouguer anomaly and 2D modeling**

276 The short wavelengths of the gravity anomaly originate from upper crust (down to a few
277 kilometers). The long wavelengths of the gravity anomaly, which reflect the deep structures, must
278 be removed from the complete Bouguer anomaly to highlight the Wangtufang pluton related
279 anomalies. Available Bouguer anomaly map (1: 200,000) in the Wangtufang pluton and its
280 surrounding area was derived from the Chinese regional gravity survey. A regional lower-
281 resolution ($2' \times 2'$) Bouguer grid acquired from the International Gravimetric Bureau database
282 (Bonvalot et al., 2012). The long wavelengths of the gravity anomaly were extracted using a 200
283 km low-pass Butterworth filter from a lower-resolution ($2' \times 2'$) Bouguer grid after several attempts.
284 The residual Bouguer anomaly map was obtained from the complete Bouguer anomaly by
285 subtracting the filtered regional Bouguer anomaly related to the long wavelengths (Fig. 15a).

286 2D gravity modeling was also performed to characterize the geometry of the Wangtufang
287 pluton. To build these models, several constraints have been taken into account, including (1)
288 geological contacts, lithological units, and structural data from geological maps and our field
289 observations; (2) geometrical constraints, derived from indirect analysis of gravity anomaly, and

290 (3) densities of geological units, determined by the laboratory measurements. The residual gravity
291 anomaly has been modelled along three profiles across the center of the pluton (Fig. 15b).

292 **6.2 Results**

293 In the residual Bouguer gravity anomaly map, the Wangtufang pluton displays a NE–SW
294 trending elongated negative anomaly with a highest value in its center (Fig. 15a). The negative
295 anomalies decrease, even change into positive anomalies outwards. Particularly, the diorite shows
296 a less negative anomaly in its northwest and a higher positive anomaly in its southeast, suggesting
297 its thin thickness. The Wangtufang pluton becomes thinner outwards, presenting an overall funnel-
298 shaped geometry. The country rocks display high positive anomalies in its east. To the southwest,
299 the country rocks show a high negative anomaly, indicating the possible continuity of the pluton
300 underlain the country rocks. The highest negative anomaly is located in its northwest due to a large
301 area of Archaean migmatitic granite. Three 2D modeling profiles image the detailed geometry of
302 the two major intrusions (Fig. 15b), revealing (1) a thin thickness of the diorite that overlies the
303 syenogranite; (2) a maximal thickness of about 4 km in the center of the syenogranite which
304 progressively decreases outwards; (3) a slightly NE–SW trending elongated subsurface shape of
305 the syenogranite with inward dipping sidewalls.

306 **7. Discussion**

307 **7.1 Magma sources of the Wangtufang pluton**

308 Both high SiO₂ syenogranite and relatively low SiO₂ diorite are characterized by low MgO,
309 enrichment in LREE and LILE, and depletion in HREE and HFSE, with negative Eu anomalies
310 (Figs. 7 and 8), suggesting that they mainly derived from partial melting of ancient lower crust.
311 However, their in-situ zircon two-stage depleted mantle Hf model ages (t_{DM2}) are both Proterozoic,
312 ranging from ~1.840 to 1.635 Ga and ~1.439 to 1.205 Ga, respectively (Fig. 9). Considering that

313 the Wangtufang pluton intrudes into Archean gneiss and migmatitic granite (> 2.5 Ga), the
314 sources should be derived from the partial melting of Archean TTG in the lower crust with a
315 contribution from a depleted mantle source. The $\epsilon_{\text{Hf}}(t)$ values for the syenogranite range from –
316 9.78 to –6.54 and those of the diorite from –3.42 to –0.01 (Fig. 9). Although the diorite was mainly
317 derived from melting of ancient lower crust, $\epsilon_{\text{Hf}}(t)$ values of the diorite are much higher than
318 normal crustal melting (Fig. 9), requiring some input of depleted asthenospheric mantle
319 components. The $\epsilon_{\text{Hf}}(t)$ values of the syenogranite are higher than those of the Archean lower crust
320 (–28 ~ –13; Jiang et al., 2013). It suggests that the syenogranite has a contribution from an enriched
321 subcontinental lithospheric mantle. Therefore, the Wangtufang pluton was mainly derived from
322 partial melting of the ancient lower crust of the NCC with some involvements of enriched
323 subcontinental lithospheric mantle and depleted asthenospheric mantle components. **Coeval with**
324 **the Wangtufang pluton, Late Triassic silica-undersaturated syenites in the alkaline complexes in**
325 **the northern NCC were derived from partial melting of an enriched lithospheric mantle, coupled**
326 **with crustal assimilation and crystal fractionation in an intracontinental extensional setting (i.e.,**
327 **rift; Yang et al., 2012). Its similarity with the contemporaneous alkaline complexes may indicate**
328 **an asthenosphere–lithospheric mantle interaction in the northern NCC during the Late Triassic**
329 **(Yang et al., 2012; Zhang et al., 2012). Briefly, the Wangtufang pluton was derived from the**
330 **mixing of magmas from asthenospheric upwelling-induced melting of subcontinental lithospheric**
331 **mantle and ancient lower crust during an intracontinental extensional setting.**

332 **7.2 Emplacement model**

333 Geochronology data suggest that both the syenogranite and the diorite were emplaced in
334 the Late Triassic (both at ~ 209 Ma; Fig. 6). Concerning the fabric pattern of the diorite, magnetic
335 foliations show variable dip angles and scattered magnetic lineations, and this may be due to the

336 later intrusion of the syenogranite (Fig. 14). The border-parallel magnetic foliations are usually
337 considered as a consequence of magma inflation during the intrusion. Gravity modeling reveals
338 thin remnants of diorite, which are close to the roof of the syenogranite (Fig. 15). Furthermore,
339 field observations indicate that numerous syenogranite dykes intruded into the diorite with sharp
340 contact and dismembered the diorite after its fully crystallization (Fig. 4). As the fabric pattern
341 seems to be modified, it is difficult to retrace the emplacement process of the diorite, therefore, we
342 shall focus on the emplacement of the syenogranite.

343 In the syenogranite, the current exposure is close to the roof of the pluton due to the
344 covering of the diorite remnants (Fig. 15). The mostly subhorizontal magnetic foliations, roughly
345 parallel to the contact, develop near the roof (Fig. 14a). Bouguer gravity anomaly reveals a NE-
346 SW trending elongated subsurface shape with an overall funnel-shaped geometry, an unflat
347 bottom, and moderate- to high- inward dipping sidewalls (Fig. 15). The root of the syenogranite
348 as a feeder zone is located in its center. Thus, it might be estimated as a lopolith-like intrusion (Fig.
349 16). Considering the lack of significant emplacement-related ductile deformation in the country
350 rocks, the syenogranite with a concentric fabric pattern could emplace by the inflation of the
351 magma from its central feeder zone and the pluton is built up by floor depression (Fig. 16). The
352 subhorizontal magnetic fabrics could have developed by magmatic flow subparallel to a roof,
353 represented by the floor of the diorite (e.g., McNulty et al., 2000). A dominant gentle magnetic
354 fabric could be formed by flattening of magma mush against its roof, driven by later magma pulses
355 (McNulty et al., 2000). The arrivals of later magma batches resulted in downward inflation of
356 magma chamber against the roof. Floor depression occurred and created space for the pluton
357 building (Fig. 16). Close to the pluton, the country rocks were pushed aside and it resulted in the
358 border-parallel foliations in the surrounding gneiss (Fig. 2). We suggest that the diorite made a

359 first intrusion, probably with a thin thickness, and then the syenogranite intruded and possibly
360 dismembered the former with a series of dykes after the diorite had fully crystallized (Fig. 16).

361 **7.3 Relationships between the pluton emplacement and regional tectonics**

362 The microstructures observed in the Wangtufang pluton are typical of magmatic or sub
363 magmatic fabrics that developed during, or just after, the full crystallization of the magma.
364 However, the lack of significant emplacement-related ductile deformation in both the pluton and
365 its country rocks does not preclude that a regional tectonic event, dominated by brittle deformation
366 occurred during the Wangtufang pluton emplacement. The syenogranite intruded the diorite after
367 its full crystallization as shown by the dyke swarm containing diorite xenoliths (Fig. 4b). All the
368 syenogranitic dykes are steeply dipping and striking NW–SE. We interpret these syenogranite
369 dykes as tension gashes developed in the brittle upper crust, and controlled by a NE–SW stretching.
370 This view implies a possible NE–SW trending regional extension (Fig. 16).

371 Moreover, the plutons shape and internal fabric can record some increments of the regional
372 strain to which the magma was subjected (e.g., Paterson et al., 1998; Sant’Ovaia et al., 2000).
373 Because mineral fabrics are easily reset, they reflect only the last strain increment developed in
374 soft material such as magmatic rocks before their full crystallization. Furthermore, without any
375 regional strain or pre-existing structural control, the magmatic lineation that reflects the magma
376 flow within the pluton would have variable orientations and plunges (e.g., Paterson, 1989; Liu et
377 al., 2018). Thus, we argue that the syenogranite, presenting a general NE–SW magnetic lineation,
378 may have recorded a NE–SW trending regional extension (Fig. 16). Meanwhile, the pluton growth
379 could have been guided by the NE–SW trending regional tectonic regime, suggested by a NE–SW
380 trending elongated subsurface shape of the pluton (Fig. 15a).

381 Geochemical data suggest that the Wangtufang pluton was derived from the partial melting
382 of Archaean TTG in the lower crust with a contribution from a depleted mantle source. This feature
383 is consistent with the geochemical characteristics of the E–W trending alkaline intrusive
384 complexes along the northern NCC (Zhang et al., 2012; Fig. 17). Especially, the silica-
385 undersaturated syenites comply with a Late Triassic intracontinental extensional setting after the
386 final formation of the Central Asian Orogenic Belt (Yang et al., 2012; Fig. 17). Besides, a NE–
387 SW trending regional extension in the northern NCC has been documented in the Sonid Zuoqi
388 MCC in the vicinity of the Solonker zone (Davis et al., 2004; Fig. 17). The $^{40}\text{Ar}/^{39}\text{Ar}$ ages of
389 muscovite in the detachment fault were 224~208 Ma. Detrital zircon dating and sedimentological
390 studies of these basin remnants showed a fining and deepening upward depositional system as well
391 as abundant volcanoclastic rocks from the conformable Upper Triassic to Lower Jurassic strata,
392 suggesting a Late Triassic extensional tectonic setting (Davis et al., 2009; Meng et al., 2014; Fig.
393 1). The emplacement of the Wangtufang pluton provides new structural constraints on the Late
394 Triassic NE–SW trending extensional setting in the northern NCC.

395 **8. Conclusions**

396 A multidisciplinary study, including geochronology and geochemistry, field and
397 microscopic observations, anisotropy of magnetic susceptibility (AMS), and gravity investigation,
398 has been carried out to characterize the emplacement mode and tectonic setting of the Late Triassic
399 Wangtufang pluton. These results reveal that: (1) both the syenogranite and the diorite in the
400 Wangtufang pluton are derived from the partial melting of the lower crust with a contribution from
401 a depleted mantle source; (2) the diorite, represented just by thin remnants, was intruded and
402 dismembered by the later syenogranite intrusion coeval with a NW–SE trending dyke swarm after
403 the diorite full crystallization; (3) the syenogranite, a lopolith-like intrusion, emplaced by the

404 inflation of magma batches from a conduit in its center, and the emplacement space was mainly
405 created by floor depression for the pluton building; (4) if the consistently NW–SE striking dykes
406 may be considered as tension gashes, the Wangtufang pluton emplaced in a NE–SW trending
407 regionally extensional tectonic setting, providing more reliable arguments to the Late Triassic
408 intracontinental extensional setting already suggested in the northern NCC.

409 **Acknowledgements**

410 This work has been financially supported by the National Key R&D Program of China
411 (2016YFC0600102 and 2016YFC0600401) and the NSFC (91855212, 91755205, and 41472193).
412 Prof. Sanzhong Li and two anonymous reviewers together with the editors are very much thanked
413 for their constructive comments and suggestions, which lead to a great improvement of our
414 manuscript.

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625 **Figure Captions**

626 **Fig. 1.** Simplified geological map of the Yanshan fold and thrust belt and location of the
627 Wangtufang pluton. CFSZ: Chicheng-Fengning ductile shear zone, FLSZ: Fengning-Longhua,
628 ductile shear zone, DNSZ: Damiao-Niangniangmiao ductile shear zone, UF: Unnamed fault,
629 JXT: Jixian thrust, MLYA: Malanyu anticline, XBCB: Xiabancheng basin, NDB: Niuying-
630 Dengzhangzi basin, WTF: Wangtufang pluton.

631 **Fig. 2.** Geological map and cross-sections in the Wangtufang pluton and its adjacent area.
632 Numbers in circles and stereonet show the locations and attitudes of the measured dykes,
633 respectively. U–Pb zircon data from Liu et al. (2012). See Fig. 1 for location.

634 **Fig. 3.** Field photographs of the Wangtufang pluton and its country rocks. (a) Syenogranite in the
635 south of the Wangtufang pluton. (b) Diorite in the north of the Wangtufang pluton. (c) Archaean
636 gneiss in the south of the Wangtufang pluton. (d) NW–SE trending lineation in Archaean gneiss.
637 (e) Sigmoidal K-feldspar porphyroclast in Archaean gneiss, indicating a top-to-the-SE sense of
638 shearing. (f) Migmatitic granite in the north of the Wangtufang pluton.

639 **Fig. 4.** Field photographs of the dykes and xenoliths in the Wangtufang pluton. (a) Syenogranitic
640 dykes near the contact between the syenogranite and the diorite. (b) Dioritic xenoliths in the
641 syenogranitic dykes. (c) Syenogranitic dykes near the northeastern border of the Wangtufang
642 pluton. (d) Dioritic xenolith in the syenogranite.

643 **Fig. 5.** Microstructures of typical investigated samples in the Wangtufang pluton. (a)
644 Distribution map of the different types of microstructures. (b) and (c) Magmatic microstructures
645 in the syenogranite and the diorite, respectively. (d) and (e) Submagmatic microstructures in the
646 syenogranite and the diorite, respectively.

647 **Fig. 6.** Cathodoluminescence (CL) images and U-Pb diagrams of Concordia age of
648 representative zircons from collected samples. White solid ellipses are Secondary Ion Mass
649 Spectrometer (SIMS) U-Pb analysis locations. White dashed circles are locations of LA-MC-
650 ICPMS Hf analyses. Age and $\epsilon\text{Hf}(t)$ data are listed under individual zircons with ages ahead.
651 MSWD: mean square of weighted deviates.

652 **Fig. 7.** Chemical analyses diagrams of major elements for the Wangtufang pluton. (a) SiO_2 vs.
653 $\text{Na}_2\text{O}+\text{K}_2\text{O}$ diagram. (b) SiO_2 vs. K_2O diagram. (c) Plot of A/CNK vs. ANK.

654 **Fig. 8.** Trace elements diagrams for the Wangtufang pluton. (a) Chondrite-normalized REE
655 patterns. (b) Primitive mantle normalized element spider patterns.

656 **Fig. 9.** Diagram of $\varepsilon_{\text{Hf}}(t)$ vs. U-Pb ages Plot of all previously analyzed zircons for U-Pb isotopes
657 in the Wangtufang pluton. Hf isotopic compositions of zircons from the contemporaneous
658 plutons are from: Yang et al. (2012); Ye et al. (2014) and Xiong et al. (2017).

659 **Fig. 10.** AMS scalar parameters of the Wangtufang pluton. (a) Histogram of site mean magnetic
660 susceptibility (K_m). (b) Anisotropy degree P_J value vs. Bulk magnetic susceptibility K_m . (c)
661 Shape parameter T vs. Bulk magnetic susceptibility K_m . (d) Shape parameter T vs. anisotropy
662 degree P_J value.

663 **Fig. 11.** Magnetic mineralogy investigations of representative specimens from the Wangtufang
664 pluton. (a–c) hysteresis loops, (d–e) acquisition of isothermal remanent magnetization (IRM),
665 and (g–i) thermomagnetic curves ($K(T)$ curves).

666 **Fig. 12.** Day plot of hysteresis parameters. M_s : saturation of magnetic remanence, M_s :
667 saturation of induced magnetization, H_{cr} : coercivity of magnetic remanence, H_r : coercivity of
668 the measured sample. SD: single domain, PSD: pseudo-singledomain, MD: multidomain.

669 **Fig. 13.** Equal-area projections (lower hemisphere) of AMS results for each sampling site.
670 Confidence ellipses at 95% level are drawn around each average orientation direction.

671 **Fig. 14.** Mesoscopic and magnetic fabric patterns and orientation diagrams of K_3 and K_1 . (a)
672 Foliations. (b) Lineations.

673 **Fig. 15.** Gravity modeling. (a) Residual Bouguer gravity anomaly of the Wangtufang pluton and
674 adjacent areas after subtraction of a 200 km wavelength regional trend from the complete
675 Bouguer anomaly. Symbols and captions are the same as in Fig. 2. (b) 2D gravity modeling
676 across the Wangtufang pluton. Note that the arrows show the possible feeder zones for the
677 pluton.

678 **Fig. 16.** Block diagrams of emplacement mode of the Wangtufang pluton.

679 **Fig. 17.** Triassic tectonic framework of the NCC showing Late Triassic tectonic setting of the
680 northern NCC. XBCB: Xiabancheng basin, NDB: Niuying-Dengzhangzi basin, WTF:
681 Wangtufang pluton.

682 **Table 1.** SIMS zircon U-Pb data of the collected samples in the Wangtufang pluton.

683 **Table 2.** Major- and trace-element concentrations of the Wangtufang pluton.

684 **Table 3.** LA-ICP-MS in-situ Hf isotopic analyses of zircons for the Wangtufang pluton.

685 **Table 4.** The results of AMS measurements for the Wangtufang pluton. Lat: latitude, Long:
686 longitude, N: the number of cylinders measured in each site, K_m : mean magnetic susceptibility,
687 P_J and T: anisotropy degree and shape parameter, respectively, K_1 and K_3 : magnetic lineation
688 and pole of magnetic foliation, respectively, Inc: inclination, and Dec: declination, $\alpha_{95\max}$ and
689 $\alpha_{95\min}$: Jelinek's statistic confidence at 95% level (Jelinek, 1981) in degrees, respectively.