



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/80456/>

Version: Accepted Version

Article:

Chu, Z-Y, Harvey, J, Liu, C-Z et al. (2013) Source of highly potassic basalts in northeast China: Evidence from Re-Os, Sr-Nd-Hf isotopes and PGE geochemistry. *Chemical Geology*, 357. 52 - 66. ISSN: 0009-2541

<https://doi.org/10.1016/j.chemgeo.2013.08.007>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

1 Source of highly potassic basalts in northeast China: evidence
2 from Re-Os, Sr-Nd-Hf isotopes and PGE geochemistry

3
4 Zhu-Yin Chu^{a, *}, Jason Harvey^b, Chuan-Zhou Liu^a, Jing-Hui Guo^a, Fu-Yuan Wu^a, Wei
5 Tian^c, Yan-Long Zhang^d, Yue-Heng Yang^a

6
7 *a. State Key Laboratory of Lithospheric Evolution, Institute of Geology and*
8 *Geophysics, Chinese Academy of Sciences, Beijing 100029, China*

9 *b. School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*

10 *c. Key Laboratory of Orogenic Belts and Crustal Evolution, MOE, School of Earth*
11 *and Space Sciences, Peking University, Beijing 100871, China*

12 *d. College of Earth Sciences, Jilin University, Changchun 130026, China*

13
14
15 Corresponding author:

16 Dr. Zhuyin Chu

17 Tel: 0086-10-82998586

18 Fax: 0086-10-62010846

19 Email: zhychu@mail.igcas.ac.cn

20
21 Submitted to Chemical Geology

22

23 **Abstract**

24 The origin of the very young (0.5 Ma to 1721 AD) Wudalianchi-Erkeshan
25 (WDLC and EKS) highly potassic basalts in northeast (NE) China has been the
26 subject of considerable debate. In this study, we present new major-, trace- and
27 platinum group element (PGE) data together with Re-Os, Lu-Hf, and Sr-Nd isotopic
28 analyses for these potassic basalts in order to further constrain their source. It has been
29 shown that the WDLC and EKS basalts have unradiogenic to only moderately
30 radiogenic osmium isotope ratios with $^{187}\text{Os}/^{188}\text{Os}$ ranging from 0.1187 to \sim 0.17, and
31 only slight PPGE (Pt and Pd) enrichments relative to IPGE (Os, Ir and Ru). The
32 positive correlations between $^{187}\text{Os}/^{188}\text{Os}$ and $1/\text{Os}$ suggests that these basalts have
33 probably experienced about 2 ~ 8% of lower continental crust addition during magma
34 ascent. Moreover, the incorporation of sub-continental lithospheric mantle
35 (SCLM)-derived, primary sulphides and / or PGE micro-alloys during magma ascent
36 seems likely in some basalts, which preserve particularly unradiogenic Os
37 compositions. The complex interplay of signatures derived from crustal and SCLM
38 contamination means that the Os isotope systematics of the basalts do not
39 unequivocally fingerprint the source of the WDLC and EKS basalts.

40 The strong enrichments of light rare earth elements (LREE) and large ion
41 lithophile elements (LILE), high-K, EM1-like Sr-Nd-Hf isotopic characteristics, and
42 particularly strong fractionation of the heavy REE ($(\text{Sm}/\text{Yb})_{\text{N}} = 9.7 \pm 0.6$), suggest
43 that the WDLC and EKS basalts mainly originated from phlogopite-bearing
44 garnet-peridotite in the SCLM. Combined with low Ce/Pb ratios (\sim 9.4-13.5), the most

45 likely source of WDLC and EKS basalts is SCLM that has been metasomatized by
46 delaminated old, lower continental crust. This is different from previous hypotheses
47 that implicate a dominantly asthenospheric source with a contribution from
48 delaminated ancient SCLM or subducted oceanic crust with sediments, or a SCLM
49 source that has been metasomatized by melts derived from deep asthenosphere during
50 the Proterozoic.

51

52 *Keywords:* Re-Os isotopes; PGE; sulphide; Sr-Nd-Hf isotopes; potassic basalts; NE
53 China

54

55 **1. Introduction**

56 Cenozoic volcanic rocks, predominantly alkaline basalts, are widely distributed
57 in Northeastern China (NE China) (Fig. 1), and form an important part of the West
58 Pacific volcanic zone (e.g., Zhang et al., 1991, 1995, 1998, 2000; Zou et al., 2000,
59 2003; Liu et al., 2001; Choi et al., 2006; Chen et al., 2007; Yan and Zhao, 2008).
60 However, their petrogenesis remains equivocal, despite numerous detailed prior
61 investigations of the area. Interpreting the significance of the composition of
62 Cenozoic alkaline basalts from NE China is further complicated by the complex and
63 varying structure for the mantle beneath this region, as suggested by earlier studies
64 (e.g., Zhang et al., 2000; Zou et al., 2000, 2003; Choi et al., 2006; Chen et al., 2007;
65 Yan and Zhao, 2008; Zhang et al., 2011).

66 Among the Cenozoic basalts in NE China, the three potassic volcanic areas of

67 Wudalianchi (WDLC), Erkeshan (EKS) and Keluo (KL), together comprise the
68 Wudalianchi-Erkeshan-Keluo (WEK) volcanic field. This field is located in the
69 Xing'an Mongolian Orogenic Belt (XMOB) at the boundary between the
70 northwestern margin of the Songliao Basin and the Great Xing'an Ranges, in the
71 western Heilongjiang Province, NE China (Fig. 1). The geochemical features of the
72 WDLC, EKS and KL basalts (e.g., Zhang et al., 1991, 1995, 1998; Zou et al., 2003)
73 are similar to those of EM1-derived basalts (Zindler and Hart, 1986) and dramatically
74 different from those of Cenozoic basalts found elsewhere in eastern China (e.g., Zhou
75 and Armstrong, 1982; Peng et al., 1986; Song et al., 1990; Zhi et al., 1990; Basu et al.,
76 1991; Fan and Hooper, 1991; Liu et al., 1994; Chen et al., 2007).

77 Although the peculiar composition of the WEK potassic basalts in NE China has
78 been well documented, the origin of intraplate volcanism in this region is still the
79 subject of debate, resulting in several competing theories as to their origin: (i) Based
80 upon their Sr-Nd-Pb isotopic and trace elemental fingerprint, which resembles an
81 EM1 mantle component, it has been suggested that the WEK potassic basalts were
82 produced by small-degree (5 ~ 7 %) melting of ancient SCLM, which has
83 subsequently been overprinted by Proterozoic metasomatism after its formation
84 (Zhang et al., 1995, 1998, 2000). A phlogopite-bearing garnet peridotite source within
85 the 120 km thick lithosphere at this locality has been suggested as a probable source
86 (Zou et al., 2003); (ii) Based upon the similarities in incompatible trace element
87 concentrations with OIB, Choi et al. (2006) argued that the WEK basalts originated in
88 the shallow asthenosphere which contains fragments of delaminated SCLM from the

89 eastern North China Craton (NCC). The likely presence of “plum-pudding” mantle
90 (e.g., Phipps Morgan and Morgan, 1999) beneath NE China (Flower et al., 1998) and
91 basaltic Sr-Nd-Pb-Hf isotopic characteristics resembling a DMM-EM1 array have
92 been cited as strong evidence against a SCLM origin for the WEK basalts (Choi et al.,
93 2006); (iii) Mixing FOZO (Focal Zone; Hart et al., 1992) and LoMu (low U/Pb;
94 Douglass et al., 1999) mantle sources, instead of an EM1-like SCLM mantle source,
95 has been advocated by Chen et al. (2007); (iv) More recently, Kuritani et al. (2013)
96 argued that the WDLC and EKS basalts originated from a mantle transition zone
97 which has been metasomatized by K-rich sediment-derived fluids ~1.5 Ga ago,
98 through the stagnation of an ancient slab.

99 In addition, although wholesale contamination of the WDLC and EKS basalts
100 by the upper crust can largely be discounted, based on trace elemental and Sr-Nd-Pb
101 isotopic results (Zhang et al., 1995, 1998; Zou et al., 2003), previous studies have not
102 been able to unequivocally exclude the possible influence of less evolved lower crust
103 in the petrogenesis of the WDLC and EKS basalts (Zhang et al., 1995, 1998; Zou et
104 al., 2003). Unlike the lithophile-element based Sr-Nd-Pb isotope systems, Os isotopes
105 can be particularly sensitive to crustal contamination which generates isotope ratios
106 that are distinct from those of mantle sources (e.g., Chesley and Ruiz, 1998; McBride
107 et al., 2001; Chesley et al., 2004; Jung et al., 2011). Basaltic melt, contaminated
108 during its ascent through old continental crust, should develop a radiogenic Os
109 isotopic signature. In contrast, basalts originated from an enriched old lithospheric
110 mantle source would retain unradiogenic to only moderately radiogenic Os isotopic

111 compositions (e.g., McBride et al., 2001; Chesley et al., 2004; Rudnick and Walker,
112 2009). Therefore, Re-Os isotopes, together with PGE elemental abundances can
113 provide important constraints on the relative involvement of crustal materials in the
114 petrogenesis of the very young WDLC and EKS basalts.

115 Accordingly, this study presents new major-, trace- and platinum group element
116 (PGE) abundances together with Os, Hf and Sr-Nd isotopic data, for the WDLC and
117 EKS potassic basalts to further constrain their origin and the nature of the underlying
118 SCLM. Since the nearby Keluo basalts contain abundant mantle xenocrysts, they have
119 not been investigated for Re-Os isotopes and PGE geochemistry here. Based upon
120 new analyses, it seems likely that the WDLC and EKS basalts were mainly generated
121 in SCLM which has been metasomatized by recycled old lower continental crust
122 materials. Although crustal contamination during magma ascent has not materially
123 affected the elemental abundances of incompatible, lithophile elements and the
124 Sr-Nd-Hf isotope systems, evidence for low degrees of lower crustal contamination is
125 preserved in some basalts with particularly low Os abundances.

126

127 **2. Geological Background and sample descriptions**

128 The XMOB, part of the Central Asian Orogenic Belt (CAOB), is a composite
129 fold belt more than 1500 km wide, formed during a long period (Paleozoic to early
130 Mesozoic) of subduction and collision between the Siberian Craton in the north and
131 the NCC in the south (Sengör et al., 1993). The potassic basalts of the WEK field,
132 located in XMOB (Fig. 1), are distributed over an area of >1400 km². Among them,

133 the WDLC and EKS potassic basalts were erupted from about 0.5 Ma ago onwards
134 (Zhang et al., 1995; Liu et al., 2001). Two of the Wudalianchi cones, Laoheishan and
135 Huoshaoshan, erupted during 1719-1721 AD, according to the Qing Dynasty Records
136 (Zou et al., 2003). The potassic rocks consist mainly of olivine leucitite and leucite
137 basanite.

138 The samples studied here were collected from lava flows related to the
139 eruptions of Laoheishan (LHS) (1721 AD), Huoshaoshan (HSS) (1721 AD) and
140 Yaoquanshan (YQ) (0.25 Ma, Zhang et al., 1995) from the Wudalianchi volcanic area,
141 and lava flows related to the Erkeshan eruption (0.56Ma, Liu et al., 2001) from the
142 Kedong (KD) volcanic area (Fig.1). The sample locations (latitude and longitude) are
143 listed in Table 1. The detailed descriptions of the samples and petrography of some
144 representative samples are shown in the electronic supplement.

145

146 **3. Analytical methods**

147 The rock samples were first sawn into chips, and surface contamination was
148 completely removed during this step. The samples were then further split into small
149 chips using a hammer wrapped in soft cloth. Small chips devoid of surface alteration
150 and mantle or/and crustal xenocrysts, were chosen and cleaned with 10% hydrochloric
151 acid in an ultrasonic bath for about half an hour. After ultrasonification, the chips were
152 cleaned three times with deionized water. Subsequently, selected rock chips were
153 crushed using an alumina ceramic jaw crusher, and then were ground into a fine
154 powder in agate shatter-boxes. This produced 20-30g of powder for each sample.

155

156 *3.1. Elemental analysis*

157 Major element data for whole-rock samples were obtained by X-ray
158 fluorescence spectrometry (XRF) on fused glass disks using an Axios-Minerals
159 instrument at the Institute of Geology and Geophysics, Chinese Academy of Sciences
160 (IGGCAS), following the procedures of [Chu et al. \(2009\)](#). Precision is 1-3% RSD for
161 elements present at >1 wt%, and about 10% RSD for elements present at <1 wt%. A
162 Chinese basalt reference material, GSR-3, was analyzed during the same period, and
163 the values determined are well within the range of consensus values ([GeoREM](#),
164 <http://georem.mpch-mainz.gwdg.de/>) ([Table 1](#)).

165 Trace element concentrations, including the rare earth elements (REE), were
166 determined by inductively coupled plasma mass spectrometry (ICP-MS) using an
167 Agilent 7500a system at IGGCAS, following the procedures described in [Chu et al.](#)
168 [\(2009\)](#). Basalt reference materials BHVO-2 and BCR-2 were measured to monitor the
169 accuracy of the analytical procedure, and the results are in good agreement with
170 reference values ([GeoREM](#), <http://georem.mpch-mainz.gwdg.de/>) ([Table 1](#)). Precision
171 is generally better than 3% for most elements based on replicate analyses of several
172 samples.

173 Sulfur concentrations were determined at the National Research Center for
174 Geoanalysis, Chinese Academy of Geological Sciences, using a high-frequency
175 infrared absorption spectrometer (HIR-944B, Wuxi High-speed Analyzer Co., Ltd.,
176 China), following the procedures described in [Chu et al. \(2009\)](#). The detection limit

177 for S was about 50 ppm.

178

179 *3.2. Sr-Nd-Hf isotope analyses*

180 Strontium, Nd, and Hf isotope compositions were determined at the State Key
181 Laboratory of Lithospheric Evolution, IGGCAS. A combined chemical procedure for
182 Lu-Hf, Rb-Sr, and Sm-Nd isotopic analyses from one sample digestion was used, as
183 described in detail by [Yang et al. \(2010\)](#). The Rb-Sr and Sm-Nd isotopic analyses
184 were conducted using an Isoprobe-T thermal ionization mass spectrometer made by
185 Isotopx Company (formerly GV instruments). Measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$
186 ratios were corrected for mass-fractionation using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}$
187 $= 0.7219$, respectively. During the period of data collection, the measured values for
188 the NBS-987 Sr standard and the JNdi-1 Nd standard were $^{87}\text{Sr}/^{86}\text{Sr} = 0.710245 \pm 16$
189 $(2 \text{ SD}, n = 8)$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512117 \pm 10 (2 \text{ SD}, n = 8)$, respectively. Lutetium
190 and Hf were measured using a Thermo-Fisher Neptune multicollector ICP-MS system
191 ([Yang et al., 2010](#)). Hafnium isotopic ratios were normalized to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$
192 and $^{176}\text{Lu}/^{175}\text{Lu}$ isotopic ratios were normalized using Yb isotopic ratios. During the
193 analytical session, an Alfa Hf standard was measured 9 times and the average value of
194 $^{176}\text{Hf}/^{177}\text{Hf}$ was $0.282181 \pm 5 (2 \text{ SD})$. The USGS basalt reference materials BCR-2
195 and BHVO-2 were measured for Rb-Sr, Sm-Nd and Lu-Hf isotopic composition to
196 monitor the accuracy of the analytical procedures; the results are in excellent
197 agreement with the reported reference values ([GeoREM](#),
198 <http://georem.mpch-mainz.gwdg.de/>) ([Table 2](#)). The procedural blanks were about 40

199 pg for Rb, 300 pg for Sr, 20 pg for Sm, 60 pg for Nd, 10 pg for Lu and 40 pg for Hf,
200 respectively.

201

202 3.3. *Re-Os and PGE analyses*

203 Re-Os isotopic compositions and PGE abundances were determined at the State
204 Key Laboratory of Lithospheric Evolution, IGGCAS, following procedures similar to
205 those described by [Pearson and Woodland \(2000\)](#).

206 In brief, about 2 g or 4 g of finely ground sample powder (200-400 mesh), and
207 appropriate amounts of a mixed ^{187}Re - ^{190}Os spike and a mixed ^{191}Ir - ^{99}Ru - ^{194}Pt - ^{105}Pd
208 spike were weighed into a clean, dry, chilled Pyrex[®] borosilicate glass Carius tube.
209 For 2 g samples, 3 mL of purified concentrated HCl and 6 mL of purified
210 concentrated HNO₃ were added to the tube, and then the tube was sealed ([Shirey and
211 Walker, 1995](#)); for 4 g samples, the amounts of these acids were scaled up accordingly.
212 The Carius tubes were put in a steel pressure vessel containing water to prevent the
213 explosion of the Carius tubes, as described in detail by [Qi et al. \(2007\)](#). The digestions
214 were performed at about 250 °C for 48-72 h in an oven. After opening the tubes, Os
215 was extracted from the aqua regia solution into CCl₄ ([Cohen and Waters, 1996](#)) and
216 then back-extracted into 4 mL of HBr; for 4 g samples, the amounts of CCl₄ and HBr
217 used were also scaled up. The Os samples were further purified via microdistillation
218 ([Birck et al., 1997](#)). The total procedural Os blank was 0.2-1 pg with a $^{187}\text{Os}/^{188}\text{Os}$ of
219 about 0.16. The blank Os contribution on total Os was less than 1% for all samples
220 and the blank correction was therefore negligible.

221 Rhenium, Ir, Ru, Pt and Pd remaining in aqua regia were separated from the
222 matrix and purified first by anion exchange chromatography using 2 mL of AG 1 × 8,
223 100 - 200 mesh resin. The Re and Ru fraction was further purified using a small anion
224 exchange column packed with 0.2 mL resin (AG 1 × 8, 100-200 mesh), whereas the
225 Ir-Pt and Pd fractions were further purified to remove Zr and Hf using Eichrom[®]-LN
226 columns. Total procedural blank was about 2 - 5 pg for Re, 2 pg for Ir, and 15 pg for
227 Ru, Pt and Pd. The maximum blank corrections were < 10% for low-Re samples.

228 Osmium isotopic compositions were measured at IGGCAS on an Isoprobe-T
229 mass spectrometer operated in negative ion mode (Creaser et al., 1991; Volkening et
230 al., 1991). Purified Os was loaded onto platinum filaments with Ba(OH)₂ as an ion
231 emitter and measured as OsO₃⁻. Most samples were measured using a single ETP
232 multiplier in peak-jumping mode, while some samples with relatively high Os
233 concentrations were run in static mode on Faraday cups. The measured Os isotopic
234 ratios were corrected for mass fractionation using $^{192}\text{Os}/^{188}\text{Os} = 3.08271$ (Shirey and
235 Walker, 1998). The in-run precisions for Os isotopic measurements were better than
236 0.2% (2 RSD) for all the samples. During the period of measurement of our samples,
237 the $^{187}\text{Os}/^{188}\text{Os}$ ratio of the Johnson-Matthey standard of University of Maryland
238 (UMD) was 0.11378 ± 4 (2 SD, n = 20) on nano-gram sized loads measured with
239 Faraday cups and 0.1138 ± 4 (2 SD, n = 13) on 3.5-175 pg sized loads measured with
240 the electron multiplier.

241 Measurements of $^{185}\text{Re}/^{187}\text{Re}$, $^{191}\text{Ir}/^{193}\text{Ir}$, $^{194}\text{Pt}/^{196}\text{Pt}$, $^{105}\text{Pd}/^{106}\text{Pd}$ and $^{99}\text{Ru}/^{101}\text{Ru}$
242 were conducted at IGGCAS using a Thermo-Fisher Neptune Multi-Collector ICP-MS

243 system with an electron multiplier in peak-jumping mode or using Faraday cups in
244 static mode, according to the measured signal intensity. The interferences of HfO (on
245 Ir and Pt), ZrO (on Pd) were confirmed to be negligible by scanning on ^{90}Zr and ^{180}Hf
246 peaks before sample measurement. Mass fractionation was corrected using Re, Ir, Ru,
247 Pt, and Pd standards that were interspersed with the samples. Some Ru samples were
248 run on the Isoprobe-T mass spectrometer in negative ion mode after a further
249 micro-distillation purification step, following the procedures described by [Becker and](#)
250 [Walker \(2003\)](#). In-run precisions for $^{185}\text{Re}/^{187}\text{Re}$, $^{191}\text{Ir}/^{193}\text{Ir}$, $^{194}\text{Pt}/^{196}\text{Pt}$, $^{105}\text{Pd}/^{106}\text{Pd}$, and
251 $^{99}\text{Ru}/^{101}\text{Ru}$ were typically 0.1 - 0.5% (2 RSD).

252 The USGS basalt standard BHVO-2 was measured to monitor the reliability of
253 the whole procedure. The Re, Os, Ir, Ru, Pt, and Pd concentrations and Os isotopic
254 ratio are in agreement with the reported values ([Meisel and Moser, 2004](#); [Shinotsuka](#)
255 [and Suzuki, 2007](#)) ([Table 3](#)).

256

257 **4. Results**

258 *4.1. Major and Trace elements*

259 Bulk-rock major and trace element compositions are presented in [Table 1](#).
260 Consistent with previously reported results ([Zhang et al., 1995](#)), the WDLC and EKS
261 basalts have high K_2O abundances ranging from 4.50 wt% to 6.09 wt% and $\text{K}_2\text{O}/\text{NaO}$
262 ranging from 1.09 to 1.67. The SiO_2 abundances range from 49.0 to 53.5 wt%. The
263 MgO , CaO and Al_2O_3 abundances range from 4.45 to 9.47 wt%, 5.09 wt% to 7.44
264 wt% and 12.2 wt% to 14.4 wt%, respectively. These basalts have relatively low $\text{Mg}^\#$

265 values ($100\text{Mg}^{2+}/(\text{Mg}^{2+}+\text{Fe}^{2+})$), falling between 61.9 and 70.6, except for sample YQ-4,
266 having $\text{Mg}^{\#}$ value of 55.3. The loss on ignition (LOI) values range from -0.2 to 0.1
267 wt%, consistent with the generally low degrees of alteration of these samples.
268 Negative LOI values of some samples are probably due to the oxidation of FeO to
269 Fe_2O_3 being more significant than loss of volatiles. Consistent with previous reports
270 (Zhang et al., 1995; Zou et al., 2003; Chen et al., 2007), the WDLC and EKS basalts
271 have relatively low CaO and particularly low Al_2O_3 at a given MgO content compared
272 to the basalts from elsewhere in NE China (Fig. 2).

273 The WDLC and EKS basalts have high rare earth element (REE) and large ion
274 lithophile element (LILE) concentrations. On a chondrite normalized REE diagram
275 (Fig. 3a), the WDLC and EKS basalts show uniform REE characteristics with strong
276 LREE enrichment ($(\text{La}/\text{Yb})_{\text{N}} = 51.0 \pm 2.5$). The heavy REEs are also strongly
277 fractionated with $(\text{Sm}/\text{Yb})_{\text{N}} = 9.7 \pm 0.6$. These samples also have uniform primitive
278 mantle-normalized trace element patterns (Fig. 3b), with strong LILE enrichment and
279 pronounced enrichment of Pb and K, slight enrichment of Zr and Hf, and significant
280 depletion of U, Th, Nb and Ta. Ce/Pb ratios of these basalts show slight variations
281 (10.6 ± 1.3), and are much lower than the values of ocean island basalt (OIB; 25 ± 5 ,
282 Hofmann et al, 1986). The La/Nb ratios of most basalts are greater than 1.2. Ba/Nb
283 ratios range from 23 to 29.

284 Most WDLC and EKS basalts have low S contents, ranging from lower than 50
285 ppm to 100 ppm, except for a single LHS sample, LHS-6, having a S content of 140
286 ppm. These concentrations are much lower than those of mid-ocean ridge basalts (>

287 1000 ppm, e.g., Gannoun et al., 2007).

288

289 4.2. Sr-Nd-Hf isotopes

290 The Sr and Nd isotopic compositions of the WDLC and EKS basalts are listed
291 in [Table 2](#). The basalt samples have relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios varying between
292 0.7051 and 0.7057. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios range from 0.5123 to 0.5125. The Sr-Nd
293 isotopes of the WDLC and EKS basalts are more evolved (i.e., Sr isotopic
294 compositions are more radiogenic and Nd isotopic compositions are less radiogenic)
295 than those of mantle xenoliths carried in nearby Keluo basalts ([Zhang et al., 2000](#);
296 [Zhang YL et al., 2011](#)) and Cenozoic basalts elsewhere in NE China (e.g., [Chen et al.,](#)
297 [2007](#); [Yan and Zhao, 2008](#)) ([Fig. 4a](#)). The $T_{\text{DM}}(\text{Nd})$ model ages of these basalts range
298 from 918 to 1057 Ma. Consistent with previously reported results ([Zhang et al., 1995](#);
299 [Zou et al., 2003](#)), $^{87}\text{Sr}/^{86}\text{Sr}$ correlates negatively with $^{143}\text{Nd}/^{144}\text{Nd}$, demonstrating
300 Sr-Nd isotope systematics similar to EM1 ([Zindler and Hart, 1986](#)) ([Fig. 4a](#)).

301 The Lu-Hf isotopic compositions of the WDLC and EKS basalts are also listed
302 in [Table 2](#). The Lu/Hf ratios range from 0.0018 to 0.0030, which are far lower than the
303 value for modern chondrite (0.0332, [Blichert-Toft and Albarède, 1997](#)). The
304 $^{176}\text{Hf}/^{177}\text{Hf}$ ratios vary from 0.2825 to 0.2827 ([Table 2](#); [Fig. 4b](#)). In term of Hf
305 isotopes, the WDLC and EKS basalts are also more evolved (i.e., have less radiogenic
306 Hf isotopic compositions) than the mantle xenoliths they host ([Zhang et al., 2011](#))
307 ([Fig. 4b](#)). Similar to Nd model ages, these basalts give uniform $T_{\text{DM}}(\text{Hf})$ model ages
308 ranging from 879 to 1076 Ma. On the Hf-Nd isotopic correlation diagram, no obvious

309 Hf-Nd decoupling is seen when compared to MORB or OIB (Fig. 4b).

310

311 4.3. Re-Os isotopes

312 Re-Os isotope data for the WDLC and EKS basalts are given in Table 3. In
313 general, compared with Cenozoic basalts from other intraplate localities such as
314 Columbia River, Hannuoba, South-Eastern (SE) Australia and Central Europe
315 (Chesley and Ruiz, 1998; McBride et al., 2001; Jiang and Zhi, 2010; Jung et al., 2011),
316 the WDLC and EKS basalts have higher Os and lower Re contents (Fig. 5a). Most
317 samples have Re concentrations less than 0.1 ppb. The only exception is one analysis
318 of sample LHS-6, giving Re concentrations of 0.895 ppb. The WDLC and EKS
319 samples have Os concentrations ranging from 0.029 ppb to greater than 0.2 ppb. One
320 analysis of sample LHS-6 gives extremely high Os concentration (1.55 ppb).

321 The $^{187}\text{Os}/^{188}\text{Os}$ values of most samples range from 0.13 to 0.17, which
322 overlaps with the $^{187}\text{Os}/^{188}\text{Os}$ ranges of OIB basalts summarized in Shirey and Walker
323 (1998) and Harvey et al. (2011), and MORB glass (e.g., Alard et al., 2005). The only
324 exception is the high Os concentration sample LHS-6. Two analyses of this sample
325 yield low $^{187}\text{Os}/^{188}\text{Os}$ values of 0.1187 and 0.1245, respectively. As shown in Fig. 5b,
326 compared with the Cenozoic continental basalts from Hannuoba, SE Australia and
327 Central Europe (Chesley and Ruiz, 1998; McBride et al., 2001; Jiang and Zhi, 2010;
328 Jung et al., 2011), the WDLC and EKS potassic basalts generally have much lower
329 age-corrected $^{187}\text{Os}/^{188}\text{Os}$ ratios.

330 Replicate analyses of some WDLC and EKS basalts (Table 3) not only rarely

331 gave reproducible Re and Os concentrations, but also failed to reproduce $^{187}\text{Os}/^{188}\text{Os}$
332 ratios. Especially, replicate analyses of sample LHS-6 gave highly heterogeneous Re
333 and Os concentrations, and Os isotopic ratio. The higher $^{187}\text{Os}/^{188}\text{Os}$ ratio of sample
334 LHS-6R relative to LHS-6 corresponds with a lower Os concentration.

335

336 *4.4. Platinum-group elements (PGE)*

337 PGE data for the WDLC and EKS basalts are presented in [Table 3](#). In general,
338 the WDLC and EKS basalts have low PGE abundances, ranging from 0.0244 to 0.282
339 ppb for Ir, 0.0525 to 0.364 ppb for Ru, 0.240 to 0.971 ppb for Pt, and 0.0571 to 0.295
340 ppb for Pd. Similar to the Re and Os concentration measurements, the PGE
341 abundances in replicate analyses of some samples also vary considerably, far beyond
342 analytical uncertainties ([Table 3](#)). Despite this, as shown in [Fig. 6](#), the
343 chondrite-normalized PGE patterns (and hence PGE element ratios) are generally
344 reproducible. The WDLC and EKS basalts show only slight PPGE enrichment relative
345 to IPGE ($(\text{Pd}/\text{Ir})_{\text{N}} = 1.9 \pm 1.1$) ([Table 3](#)). Exceptionally, consistent with its
346 un-radiogenic Os, sample LHS-6 has relatively high Ir and Os concentrations relative
347 to Pt and Pd ([Fig. 6](#)). Additionally, sample LHS-6 and LHS-6R (particularly LHS-6)
348 have elevated Os/Ru and Os/Ir ratios compared to those of the other samples.

349

350 **5. Discussion**

351 *5.1. PGE and Os isotope heterogeneity in the WDLC and EKS basalts*

352 Mantle sulphides and refractory PGE-rich alloys have parts-per-million (ppm)
353 to weight percentage (wt %) concentrations of PGE (e.g., [Lorand and Alard, 2001](#);

354 Walker et al., 2002; Pearson et al., 2004; Lorand et al., 2010, 2013), making them
355 prime candidates for a source of a possible “nugget effect”. For example, a 20 µg
356 mantle sulphide with an Os concentration of 20 ppm (e.g., Alard et al., 2000, 2002;
357 Pearson et al., 2002; Harvey et al., 2006, 2010, 2011; Lorand et al., 2013) contains
358 twice as much Os as 2 g of basalt with an Os concentration of 100 ppt. Therefore, the
359 heterogeneous distribution of a component that contains anomalously high Os (+ PGE)
360 abundances throughout the sampled rock powder could account for the observed
361 heterogeneities in replicate basalt analyses (Table 3). Although no discrete sulphide or
362 PGE alloy grains have been observed in the WDLC and EKS basalts, a “nugget
363 effect” due to incorporation of such mantle phases during the ascent of basalt through
364 the SCLM should be considered. Indeed, the inclusions enclosed in xenocrystic
365 material in basaltic lavas have been previously suggested as a mechanism to account
366 for unradiogenic $^{187}\text{Os}/^{188}\text{Os}$ and elevated Os concentrations (e.g., Widom et al., 1999;
367 Jackson and Shirey, 2011).

368 Although analysed samples of the WDLC and EKS basalts were hand-picked to
369 avoid obvious xenolith debris, microprobe analyses of olivine "phenocrysts" showed
370 that minor proportions of the olivines are mantle xenocrysts (i.e., a few olivine grains
371 from samples LHS-4 and KD-4 have Fo > 90, CaO < 0.10 wt % (Table S1), cf.,
372 Sobolev et al., 2007; Jackson and Shirey, 2011). Any sulphides hosted within
373 xenocrystic grains (e.g., Burton et al., 1999) would not have the opportunity to
374 become dispersed within a larger volume of melt. If its host was not recognized as
375 xenocrystic at the time of basalt preparation, this could readily account for the

376 elevated Os (+ IPGE) abundance and unradiogenic $^{187}\text{Os}/^{188}\text{Os}$ in some WDLC and
377 EKS samples, especially for LHS-6. Moreover, the WDLC and EKS basalts with
378 relatively high Ni and S content have the highest Os concentrations and least
379 radiogenic Os isotopic compositions (Fig. 7a-d), also consistent with the incorporation
380 of sulphide. Since it is possible that refractory alloys could be mechanically
381 transported in an ascending melt (e.g., Ballhaus et al., 2006), the heterogeneous
382 distribution of refractory alloys may also be possible to cause the “nugget effect” in
383 WDLC and EKS samples. This is supported by the relatively low Pt and Pd
384 concentrations relative to Ir and Ru in these samples compared to OIB and MORB
385 (especially LHS-6) (Fig. 6). In addition, Cr-spinel xenocrysts, of probable mantle
386 origin, are observed in sample LHS-4 (Fig. S1b). Although spinel itself is more
387 Os-rich than silicate mantle phases (Burton et al., 1999; Harvey et al., 2010, 2011), it
388 is unlikely to account for a significant proportion of mantle-derived PGE itself.
389 Consequently, it appears that sulphides or PGE alloys enclosed in xenocrysts are the
390 most likely candidates for the heterogeneity for PGE concentrations and Os isotopic
391 compositions in the WDLC and EKS basalt.

392 Although the incorporation of moderately radiogenic, interstitial metasomatic
393 sulphides from the SCLM also seems to be a plausible source of heterogeneity, in all
394 likelihood those sulphides would be dissolved by a S-undersaturated melt (Reisberg et
395 al., 2005; Sen et al., 2011) and its PGE budget homogenized within a relatively large
396 volume of melt compared to the volume of sulphide dissolved. It seems that this
397 process would not account for the PGE heterogeneity between different powder splits

398 of the same sample.

399

400 5. 2. *Crustal contamination*

401 Since basaltic magmas have high concentrations of lithophile elements,
402 Sr-Nd-Pb-Hf isotopes and lithophile elements are not particularly sensitive to minor
403 crustal contamination. This will be especially true for the LILE- and LREE- rich
404 WDLC and EKS basalts. However, even minor amounts of crustal contamination
405 have the potential to significantly alter the Os isotopic composition of a basaltic
406 magma with low Os concentrations (cf., [Lassiter and Luhr, 2001](#); [McBride et al., 2001](#);
407 [Xu et al., 2007](#); [Qi et al., 2008](#); [Jung et al., 2011](#)). It is possible that some of the low
408 Os WDLC and EKS basalts have been affected by crustal contamination during
409 magma ascent, in particular, at degrees that are not easily detected using lithophile
410 elements. Therefore, the $^{187}\text{Os}/^{188}\text{Os}$ and PGE systematics of the WDLC and EKS
411 basalts potentially allow this small degree of crustal contamination to be quantified.

412 As argued above, it is possible that some WDLC and EKS basalts have
413 incorporated some primary sulphides (sulphides enclosed in silicate minerals, i.e.,
414 Os-rich, Re-poor, evolving in low-Re environment and preserving unradiogenic
415 osmium isotope ratios) or PGE alloys of SCLM origin during magma ascent.
416 Moreover, most of these basalts have relatively low MgO contents ([Table 1](#)) and are
417 thus unlikely to be primary melts, suggesting that Os concentrations in the WDLC and
418 EKS basalts were also likely to be strongly affected by differentiation. Consequently,
419 it is likely that the basaltic magmas arrived in the crust with a range of Os

420 concentrations. As a result, it is difficult to constrain the degree of crustal
421 contamination by assimilation–fractional crystallization (AFC) modeling (DePaolo,
422 1981). Nevertheless, as shown in Fig. 8, there is a significant covariation between
423 $^{187}\text{Os}/^{188}\text{Os}$ and $1/\text{Os}$ ($R^2 = 0.47$), demonstrating that it seems likely that the WDLC
424 and EKS basalts have been affected by minor crustal contamination during magma
425 ascent. An Os isotope ratio c. 0.128 is considered to be representative of the parental
426 basaltic magma as suggested by previous studies (e.g., McBride et al., 2001; Xu et al.,
427 2007; Jiang and Zhi, 2010; Jung et al., 2011). Therefore, we assume the parental
428 magma of the WDLC and EKS basalts to have roughly a $^{187}\text{Os}/^{188}\text{Os}$ of c. 0.128, but
429 with varying Os concentrations (about 0.03 ~ 1.6 ppb, based on samples analyzed in
430 this study, Table 3) when they arrive in the lower crust. Consequently, if an Os
431 isotope ratio of 0.8 and Os concentration of 49 ppt is taken as being representative of
432 the lower crust (Saal et al., 1998; Chesley et al., 2002), the degree of crustal
433 contamination observed in the WDLC and EKS basalts can be modeled by simple
434 binary mixing. It is found that the addition of about only 3.5% of lower crust can
435 replicate the observed covariation between $^{187}\text{Os}/^{188}\text{Os}$ and $1/\text{Os}$ ($R^2 = 0.47$; Fig. 8)
436 fairly well. Nonetheless, as shown in Fig. 8, it is possible that some samples,
437 especially from different volcanoes, have experienced different degrees of crustal
438 contamination ranging from 2% to 8%. The rough correlation between the Pd/Ir and
439 $^{187}\text{Os}/^{188}\text{Os}$ (Fig. 8) ($R^2 = 0.39$) is also consistent with minor crustal contamination in
440 some basaltic melts, since the samples with high Pd/Ir ratios are a result of low Ir
441 contents, not high Pd contents.

442 Nevertheless, there remains the possibility that some samples with radiogenic
443 Os isotopes, which plot above the line for 3.5% of crustal contamination, result from
444 preferential melting of interstitial sulphides (sulphides occurred along boundary of
445 mineral grains, Re-rich, Os-poor, evolving in high-Re environment and having
446 variable and radiogenic osmium isotope ratios) in a metasomatized mantle source
447 (Alard et al., 2005; Schulte et al., 2009; Harvey et al., 2011) and / or the addition of
448 minor SCLM-derived interstitial sulphides during magma ascent (e.g., Sen et al.,
449 2011). This is particularly true for the YQ samples, as reflected by their radiogenic Os
450 but relatively high Os concentrations. However, we still prefer that the YQ samples
451 have experienced a larger degree of crustal contamination since their Pd contents are
452 low. In contrast, the samples which plot below the line for 3.5% crustal contamination
453 are probably due to the incorporation of SCLM-primary sulphides.

454 Addition of minor amounts (2 ~ 8%) of lower crust would not have much effect
455 on incompatible elements and Sr-Nd-Pb-Hf isotopic ratios for the LILE- and
456 LREE-rich WDLC and EKS basalts. For example, if we assume the local lower crust
457 having Nd concentration of 20 ppm (Rudnick and Gao, 2003) and $^{143}\text{Nd}/^{144}\text{Nd}$ of
458 0.51265 (Wu et al., 2003), 8% contamination of lower crust only shift the $^{143}\text{Nd}/^{144}\text{Nd}$
459 of the WDLC and EKS basalts of about 0.000007. Similarly, incorporation of primary
460 mantle sulphides or the addition of metasomatized sulphides would also have
461 negligible effect on the lithophile element systems and Sr-Nd-Pb-Hf isotopes. As a
462 result, no correlation exists between Os isotopic compositions and incompatible trace
463 element ratios such as Ce/Pb and La/Nb, and Sr or Nd or Hf isotopic compositions

464 (not shown); indeed, there are very limited variations in Sr-Nd-Hf isotopes and Ce/Pb
465 and La/Nb ratios, especially for YQ samples (Tables 1 and 2).

466 5.3. Source of the WDLC and EKS basalts —SCLM vs. asthenosphere

467 It is highly debated that the EM1-like features of the Cenozoic basalts in NE
468 China originated from either the SCLM or the asthenospheric mantle (e.g., Basu et al.,
469 1991; Song et al., 1990; Zhang et al., 1995; Zou et al., 2003; Choi et al., 2006; Xu et
470 al., 2012; Kuritani et al., 2013). Based on the highly potassic, LREE and
471 LILE-enriched trace elemental characteristics, the strong fractionation of the heavy
472 REE (HREE), low Al₂O₃ content at a given MgO, significant excesses in ²³⁰Th, and
473 Sr-Nd-Pb isotopic characteristics, Zhang et al. (1995) and Zou et al. (2003) suggested
474 that the WDLC and EKS basalts were likely produced by small-degree melting of
475 phlogopite-bearing garnet peridotite in metasomatized SCLM. The presence of garnet
476 constrains the depth of the magma source to 80–120 km (Zou et al., 2003). However,
477 several studies have suggested that delaminated cratonic lithosphere from eastern
478 China may exist locally in the shallow asthenosphere beneath NE China (e.g., Xu et
479 al., 2005; Choi et al., 2006) and that basalts from this region may preserve evidence
480 for re-melting of this reservoir. They argued that the asthenospheric mantle beneath
481 eastern Asian is characterized by two distinct, large-scale domains — one a mixture of
482 DMM and EM1 components, and the other a mixture of DMM and EM2. More
483 recently, some authors (Xu et al., 2012; Kuritani et al., 2013) argued that the Cenozoic
484 basalts in NE China originated from an asthenospheric mantle source containing
485 recycled oceanic crust materials. They suggest that the subducted Pacific slab (Huang

486 [and Zhao, 2006](#)) and / or the stagnant ancient Pacific slab ([Kuritani et al., 2011](#)) in the
487 mantle transition zone have contributed to the Cenozoic magmatism in NE China.
488 This is reasonable as the re-melting of upwelling asthenospheric mantle containing
489 recycled oceanic or lower continental crust has widely been invoked to account for the
490 evolved Sr-Nd-Hf isotopic composition of intraplate basalts (e.g., [Sobolev et al., 2007](#);
491 [Chen et al., 2009](#); [Zhang et al., 2009](#); [Xu et al., 2012](#)).

492 As discussed above, crustal contamination has not played an important role in
493 the formation of the WDLC and EKS basalts. Therefore, consistent with previous
494 studies ([Zhang et al., 1995](#); [Zou et al., 2003](#)), data obtained in this study, including
495 low Al₂O₃ content at a given MgO ([Fig. 2a](#)), high K content, LREE and
496 LILE-enriched trace elemental characteristics ([Fig. 3a, b](#)), particularly strong
497 fractionation of the heavy REE ((Sm/Yb)_N = 9.7 ± 0.6), EM1-like Sr-Nd-Hf isotopic
498 characteristics ([Fig. 4a, b](#)), all suggest that the WDLC and EKS basalts mainly
499 originated from a phlogopite-bearing garnet peridotite in the SCLM. The presence of
500 phlogopite and rutile in some Keluo and WDLC xenoliths ([Zhang et al., 2000](#); [Zhang](#)
501 [YL et al., 2011](#)) also supports that the SCLM beneath WEK area has been
502 metasomatized by K-rich silicate melt.

503 In the model involving delaminated ancient SCLM from eastern China that
504 exists locally in the asthenosphere beneath NE China ([Choi et al., 2006](#)), amphibole
505 and phlogopite will breakdown at high pressure (> 3 GPa) and are thus not considered
506 to be stable in the asthenospheric mantle ([Class and Goldstein, 1997](#)). Moreover, a
507 delaminated ancient SCLM from eastern China is also unlikely to be the source

508 material for the EM1-like signature because the delaminated Archaean SCLM beneath
509 eastern China does not have an EM1-like composition (e.g., [Chu et al., 2009](#) and
510 [references therein](#)). Therefore, it seems plausible that phlogopite-bearing
511 metasomatized SCLM rather than an asthenospheric source containing fragments of
512 delaminated ancient cratonic mantle may provide a source for the WDLC and EKS
513 high-K basalts.

514 In the model that the potassic- and EM1-like natures of the basalts originated
515 from the mantle transition zone, which has been metasomatized by K-rich
516 sediment-derived fluids ~1.5 Ga ago through the stagnation of an ancient slab and
517 further recent hydration by the stagnation of the subducted Pacific slab ([Kuritani et al.,](#)
518 [2013](#)), it is difficult to envision such a process because of the great distance (>2000
519 km) between the WEK provinces and the active Pacific subduction zone (Japan Arc)
520 ([Zhang et al., 1998](#); [Zou et al., 2003](#)) in western NE China. Significant ²³⁰Th
521 enrichments in WDLC basalts also suggest that the source rocks were not
522 metasomatized by fluids released during recent (< 350 ka) subduction of Pacific
523 sediments ([Zou et al., 2003](#)). Furthermore, it has long been recognized that LILEs,
524 such as Ba, Rb, and Sr are fluid-mobile and have elevated concentrations in sub-arc
525 environments, while fluid-immobile elements such as Nb and Ta, are largely
526 unaffected by contributions of fluids from the subducting slab ([Arculus and Powell,](#)
527 [1986](#)). A mantle source which has been metasomatized by a subduction-related fluid
528 would be enriched in radiogenic Os ([Brandon et al., 1996](#); [Widom et al., 2003](#)). Due
529 to the effect of preferential melting of metasomatic components for Os isotopes (e.g.,

530 Sen et al., 2011; Harvey et al., 2011), melting of such a mantle source would produce
531 melts with slightly increasing $^{187}\text{Os}/^{188}\text{Os}$ along with increasing Ba/Nb (Chesley et al.,
532 2002). Such a trend is absent in the WDLC and EKS basalts (Fig. 10). In contrast,
533 some samples especially YQ samples with high $^{187}\text{Os}/^{188}\text{Os}$ have relatively low Ba/Nb
534 ratios. In fact, the WDLC and EKS basalts have very low Ba/Nb ratios with limited
535 variability (23-29).

536 Consequently, it seems most likely that the WDLC and EKS mainly originated
537 from low degree melting of a SCLM source metasomatized by an EM1-like signature,
538 rather than an EM1 signature asthenospheric mantle source.

539 In terms of Os isotopes, the WDLC and EKS basalts generally have
540 unradiogenic to moderately radiogenic Os isotopic compositions ($^{187}\text{Os}/^{188}\text{Os} =$
541 $0.1187 \sim 0.17$). In principle these relatively OIB-like Os isotopic values are not
542 inconsistent with an asthenospheric origin (Liu et al., 2008; Harvey et al. 2011).
543 However, as discussed before, the measured Os isotope ratios cannot be attributed
544 solely to the mantle reservoir from which the basalts were produced. Most of the
545 $^{187}\text{Os}/^{188}\text{Os}$ values have been elevated by up to 2 ~ 8% crustal contamination and / or
546 the effects of incorporating metasomatic sulphide en route to the surface, while the
547 most unradiogenic values may be deceptively low because of the incorporation of
548 xenocryst-hosted primary sulphide. Similarly, the relative flat PGE patterns ($(\text{Pd}/\text{Ir})_{\text{N}}$
549 $= 1.9 \pm 1.1$) compared to MORB and OIB (Fig. 6) could indicate the contribution of a
550 SCLM source for the WDLC and EKS basalts and, like Os isotope ratios, can also be
551 interpreted in a number of ways. Therefore, notwithstanding the clear utility of Os

552 isotopes and PGE in fingerprinting the sources of basalts that have not experienced
553 complex histories (cf., Shirey and Walker, 1998; Day, 2013), these tools do not
554 unequivocally distinguish between an asthenospheric and a lithospheric source for the
555 WDLC and EKS basalts.

556

557 *5.4. Nature of the SCLM underlying the WEK area*

558 As discussed above, the WDLC and EKS basalts mainly originated from the
559 underlying SCLM. Despite this, as the WDLC and EKS basalts have more evolved
560 Sr-Nd-Hf isotopic signatures than those of mantle xenoliths carried in nearby Keluo
561 highly potassic basalts (Zhang et al., 2011) (Fig. 5a, b), the role of peridotite with the
562 composition similar to that of Keluo xenoliths can be largely discounted in the
563 petrogenesis of the WDLC and EKS basalts. Moreover, since the Keluo xenoliths
564 mainly comprise spinel lherzolites and harzburgites with minor dunites and wehrlites,
565 they should have been located in the SCLM above the source of the WDLC and EKS
566 basalts (garnet peridotites). Therefore, it is possible that the lithospheric mantle
567 underlying the WEK area is layered, at least in terms of Sr-Nd-Hf isotopes, i.e., the
568 lower part of lithospheric mantle (the potential source of the WDLC and EKS basalts)
569 has more radiogenic Sr and less radiogenic Nd and Hf than the upper part of
570 lithospheric mantle (represented by the Keluo mantle xenoliths), despite their similar
571 Nd and Hf model ages (Zhang et al., 2000) (Table 2).

572 The crustal growth in XMOB during the Phanerozoic is significant, as reflected
573 by the radiogenic Nd-Hf isotopic compositions of granites in the area (e.g., Wu et al.,

574 [2003; Zhang et al., 2010](#)), while the potassic rocks originating from the underlying
575 SCLM have EM1-like Sr-Nd-Hf isotopic signatures as demonstrated above. This
576 suggests that the SCLM beneath the WEK area is decoupled from the overlying crust.
577 Previous studies argued that the SCLM beneath the Phanerozoic XMOB is ancient
578 and have been metasomatised extensively by SiO₂-undersaturated potassic magma
579 that was likely generated from low-degree partial melting of deep asthenosphere
580 during the Proterozoic ([Zhang et al., 1995, 2000; Zou et al., 2003; Zhang YL et al.,](#)
581 [2011](#)).

582 EM1-like signatures of the WDLC and EKS basalts cannot be owed to
583 metasomatism by melts derived from subducted oceanic crust related to the closure of
584 the Paleo-Asian Ocean in the Paleozoic and Paleo-Pacific Ocean during the Mesozoic.
585 Their isotopic compositions fall outside the range for those of oceanic basalts and
586 MORB that are believed to be derived primarily from the asthenospheric mantle.
587 Especially, the very unradiogenic Pb isotopic signatures of the potassic rocks
588 ($^{206}\text{Pb}/^{204}\text{Pb}=16.3-17.3$), which require a long-term residence (>2 Ga) of low U/Pb in
589 the mantle source, indicate that the Pb isotopic signatures of the WEK basalts cannot
590 be attributed to modifications by Phanerozoic subduction events in the region ([Zhang](#)
591 [et al., 1998](#)). Moreover, the partial melting of peridotite cannot cause a large U/Pb
592 fractionation and, therefore, the melt generated from low-degree partial melting of
593 asthenosphere cannot have a significantly different U/Pb ratio from that of the
594 depleted mantle ([Kuritani et al., 2013](#)). Therefore, it is also difficult to derive the very
595 unradiogenic Pb isotopic signatures of the potassic rocks ($^{206}\text{Pb}/^{204}\text{Pb}=16.3-17.3$) with

596 the model presented by [Zhang et al. \(1995\)](#) and [Zou et al. \(2003\)](#).

597 As lower continental crust is known to be depleted in U relative to Pb (e.g.,
598 [Rudnick and Gao, 2003](#)), given enough time it will develop unradiogenic Pb isotopic
599 compositions. Consequently, based on low Ce/Pb (~9.4-13.5) and EM1-like Sr-Nd-Hf
600 isotopic signatures, in conjunction with low Pb isotope ratios ($^{206}\text{Pb}/^{204}\text{Pb} = 16.61$ to
601 17.06) as reported by [Zhang et al. \(1995\)](#) and [Zou et al. \(2003\)](#), different from the
602 previous studies ([Zhang et al., 1995, 1998](#); [Zou et al., 2003](#); [Kuritani et al., 2013](#)), we
603 suggest that the mantle source of WDLC and EKS basalts have been metasomatised
604 by recycled old lower continental crust materials (i.e., an EM1-like signature). It is
605 likely that some pyroxenite would be formed in the SCLM if mantle peridotite was
606 metasomatised by melt containing a contribution from lower crustal materials (e.g.,
607 [Xu, 2002](#)). Some pyroxenite xenoliths were found in WEK basalts ([Zhang et al.,](#)
608 [2000](#)), consistent with such an explanation. This is also supported by the relatively
609 low CaO abundance at a given MgO ([Fig. 2b](#)) for the WDLC and EKS basalts, as
610 melts of pyroxenite are generally low in CaO owing to the dominant effect of residual
611 clinopyroxene (e.g., [Herzberg, 2011](#)).

612 It is likely that the present lower crust in XMOB is significantly different from
613 earlier crust at this locality. As there are probably some Precambrian fragments
614 present in NE China ([Wu et al., 2003](#); [Meng et al., 2010](#)), it is likely that the original
615 crust in WEK area was old. It is possible that the original lower crust together with
616 SCLM foundered probably during lithospheric thinning in eastern China that started
617 in the Mesozoic. The delamination of the old lower crust is probably related to the

618 multiple subduction events in this region. Subsequently, the newly-formed SCLM
619 beneath the WEK area was metasomatised by melt contributed from the delaminated
620 lower crust. The whole SCLM beneath the WEK area was extensively and
621 contemporaneously metasomatised as reflected by the similar Nd (Hf) model age
622 between the mantle xenoliths (Zhang et al., 2000; Zhang YL et al., 2011) and the
623 potassic basalts (Table 2) in this area. It is possible that the lower part of the SCLM
624 have been affected more strongly than the upper part of the SCLM. This
625 metasomatism leads to the SCLM underlying the WEK area having more radiogenic
626 Sr and less radiogenic Nd and Hf isotopic compositions than the overlying
627 Phanerozoic crust.

628 Conclusively, consistent with previous studies (Zhang et al., 1995, 1998; Zou et
629 al., 2003), we suggest that the WDLC and EKS basalts originated from
630 phlogopite-bearing garnet peridotite within the SCLM. During low degree of the
631 partial melting of the SCLM, metasomatic components such as phlogopites are easily
632 melted and their high-K characteristics exported into the WDLC and EKS basalts
633 (Zou et al., 2003). In contrast, garnet is mainly retained in the mantle source. This
634 leads to significant ^{230}Th excess in the WDLC and EKS basalts (Zou et al., 2003).
635 Similarly, hafnium isotopes could uniquely trace contributions from the SCLM if
636 melts are derived from garnet-bearing SCLM (Jung et al., 2011). Given sufficient time,
637 the strong increase of Lu/Hf relative to Sm/Nd in mantle with significant garnet would
638 result in trends that deviate from the crust-mantle Hf-Nd isotope array, towards
639 radiogenic $^{176}\text{Hf}/^{177}\text{Hf}$ at a given $^{143}\text{Nd}/^{144}\text{Nd}$ (e.g., Salters and Zindler, 1995; Bizimis

640 et al., 2007; Chen et al., 2009). However, the WDLC and EKS potassic lavas have
641 very low Lu/Hf ratios (Table 2) and do not show Hf-Nd isotope decoupling on Hf-Nd
642 correlation diagrams (Fig. 4b). This also indicates a low degree melting of the
643 phlogopite-bearing garnet peridotites, and consequently the Lu-Hf isotopic signature
644 of garnet in the SCLM has not been exported into the resulting basaltic magma.

645

646 **6. Concluding remarks**

647 (1) The WDLC and EKS highly potassic basalts show uniform REE and trace
648 elemental characteristics and relatively homogeneous Sr-Nd-Hf isotopic compositions,
649 but heterogeneous Os isotopic compositions ranging from 0.1187 to ~0.17. It is
650 possible that some samples with radiogenic Os isotopic compositions may have been
651 contaminated by minor amounts of lower crustal materials, while other samples, with
652 un-radiogenic Os isotopic compositions, may have incorporated small amounts of
653 mantle materials such as xenocryst-hosted primary sulphides and / or PGE
654 micro-alloys during magma ascent through the overlying SCLM. Both the correlation
655 between the $^{187}\text{Os}/^{188}\text{Os}$ and $1/\text{Os}$, and the positive correlation between $^{187}\text{Os}/^{188}\text{Os}$
656 and Pd/Ir are consistent with these scenarios. In contrast, the minor crustal
657 contamination and incorporation of sulphides in the SCLM have an insignificant
658 influence on the lithophile elements and Sr-Nd-Hf isotopic compositions.

659 (2) The strong enrichments of LREE and LILE, and EM1 like Sr-Nd-Hf
660 isotopic characteristics suggest that the WDLC and EKS highly potassic basalts
661 mainly originated from metasomatized SCLM. Combined with the WDLC and EKS

662 basalts having Ce/Pb ratios (~9.4-13.5) much lower than typical OIB and MORB, and
663 low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, it seems likely that the source of WDLC and EKS basalts is
664 SCLM that has been metasomatized by delaminated old lower continental crust
665 materials. Furthermore, since the WDLC and EKS basalts have more radiogenic Sr
666 and less radiogenic Nd-Hf isotopic compositions than the SCLM xenoliths carried in
667 nearby Keluo highly potassic basalts, the lithospheric mantle underlying the
668 Wudalianchi-Erkeshan-Keluo (WEK) area is likely layered, at least in terms of
669 Sr-Nd-Hf isotopes.

670

671 **Acknowledgements**

672 Roberta Rudnick, Richard Walker, Hong Zhong, Lihui Chen, Yanjie Tang and
673 Jifeng Ying are sincerely thanked for helpful discussions and constructive suggestions.
674 Yan-Bin Zhang, He Li, Jie Cao, Hongyue Wang, Dingshuai Xue, Qian Mao and
675 Yuguang Ma are thanked for their help on ICP-MS, XRF and EPMA analysis. This
676 work was financially supported by National Natural Science Foundation of China
677 (NSFC Grants 40873008, 41273018 and 41273021) and the Institute of Geology and
678 Geophysics, Chinese Academy of Sciences (IGGCAS Grant ZC1002). Yigang Xu
679 (reviewer), an anonymous reviewer and Laurie Reisberg (editor) are sincerely thanked
680 for their constructive comments which greatly improve the quality of this manuscript.

681

682 **Figure captions**

683

684 **Fig. 1** Sketch map of Northeast (NE) China (modified after [Chen et al., 2007](#)), in
685 which the Cenozoic basalts, Great Xing'an Ranges, Songliao Basin and the locations
686 of the Wudalianchi, Erkeshan and Keluo volcanic rocks are shown. Dashed line is the
687 approximate boundary between the North China Craton (NCC) and Xing'an
688 Mongolian Orogenic Belt (XMOB); Abbreviations of volcanic fields are as follows:
689 WDLC (Wudalianchi), KD (Kedong), KL (Keluo) and HNB (Hannuoba).

690

691 **Fig. 2** CaO vs MgO (a) and Al₂O₃ vs MgO (b) for WDLC and EKS basalts. Solid
692 circles: this study; Open circles: WDLC and EKS data from [Zou et al. \(2003\)](#) and
693 [Chen et al. \(2007\)](#); Crosses: data for basalts from NE China elsewhere ([Chen et al.,](#)
694 [2007](#); [Yan and Zhao, 2008](#)).

695

696 **Fig. 3** Chondrite-normalized rare earth element patterns (a) and primitive
697 mantle-normalized trace element patterns (b) for the WDLC and EKS basalts.
698 Chondrite normalizing values are from [Masuda et al. \(1973\)](#) divided by 1.2; Data for
699 OIB, N-MORB and primitive mantle are from [McDonough and Sun \(1995\)](#).

700

701 **Fig. 4** Sr-Nd (a) and Hf-Nd (b) isotope diagrams for WDLC and EKS basalts. In (a):
702 literature data for WLDC and EKS basalts are from [Peng et al. \(1986\)](#), [Basu et al.](#)
703 [\(1991\)](#), [Zhang et al. \(1995, 1998\)](#) and [Zou et al. \(2003\)](#); Field for lower continental
704 crust (LCC) in WDLC and EKS area is based on [Wu et al. \(2003\)](#). Field for Cenozoic
705 basalts in eastern China is based on [Chen et al. \(2007\)](#) and [Yan and Zhao \(2008\)](#);

706 MORB, OIB, BSE, EM1 and EM2 end members are from [Zindler and Hart \(1986\)](#). In
707 (b): MORB and OIB fields are based on [Salters and White \(1998\)](#); the bulk Earth
708 $^{176}\text{Hf}/^{177}\text{Hf}$ value (BSE) and the Mantle-Crust array are based on [Blichert-Toft and](#)
709 [Albarède \(1997\)](#).

710

711 **Fig. 5** Re vs. Os (a) and Os concentration vs. $^{187}\text{Os}/^{188}\text{Os}$ (b) variation diagrams. Data
712 sources: Central European ([Jung et al., 2011](#)); HNB, Hannuoba ([Jiang and Zhi, 2010](#));
713 SE Australia ([McBride et al., 2001](#)); Columbia River ([Chesley and Ruiz, 1998](#)); Keluo
714 mantle xenoliths ([Zhang et al., 2011](#)); MORB and OIB fields are from [Shirey and](#)
715 [Walker \(1998\)](#): OIB TH, ocean island basalt tholeiites; OIB AB, ocean island alkali
716 basalts. In (b): Samples with Os > 0.8 ppb are not plotted for clarity; $^{187}\text{Os}/^{188}\text{Os}$ ratios
717 are all age-corrected values.

718

719 **Fig. 6** Chondrite-normalized PGE patterns for WDLC and EKS basalts. Chondrite
720 values are from [McDonough and Sun \(1995\)](#). Primitive mantle (PM) values are based
721 on [Becker et al. \(2006\)](#). Data for OIB-Canary Island alkali basalts with calculated
722 parental melt of 12 wt% MgO, and MORB are based on [Day \(2013\)](#) and references
723 [therein](#). LCC (lower continental crust) values are based on [Rudnick and Gao \(2003\)](#).

724

725 **Fig. 7** Diagrams of Os concentration vs. Ni content (a), Os concentration vs. S content
726 (b), $^{187}\text{Os}/^{188}\text{Os}$ vs. Ni content (c) and $^{187}\text{Os}/^{188}\text{Os}$ vs. S content (d) for WDLC and
727 EKS basalts.

728

729 **Fig. 8** $^{187}\text{Os}/^{188}\text{Os}$ vs. $1/\text{Os}$. The solid lines represent binary mixing lines modeled as
730 follows: (1) basaltic magma arrived in the crust with variable Os concentrations
731 (about 0.03 ~ 1.6 ppb, based on samples analyzed in this study) but similar Os
732 isotopic compositions (we assume $^{187}\text{Os}/^{188}\text{Os} = 0.128$); (2) addition of 2%, 3.5% and
733 8% of lower crust ($^{187}\text{Os}/^{188}\text{Os} = 0.8$ and Os concentration = 49 ppt, [Saal et al., 1998](#))
734 to the basaltic magma. The line for addition of 3.5% of lower crust is consistent with
735 the regression line (the dashed line, $R^2 = 0.47$) for data points from all the volcanoes.
736 The arrows show the trends for addition of lower continental crust (LCC), secondary
737 sulphides and primary sulphides.

738

739 **Fig. 9** $^{187}\text{Os}/^{188}\text{Os}$ vs. $(\text{Pd}/\text{Ir})_N$ for WDLC and EKS basalts. The solid line denotes the
740 regression line for all the data points except for LHS-6R. Symbols and arrows as in
741 **Fig. 8**. The Os isotopic composition and $(\text{Pd}/\text{Ir})_N$ of LCC are about 0.8 ([Saal et al.,](#)
742 [1998](#)) and 46 ([Rudnick and Gao, 2003](#)), respectively.

743

744 **Fig. 10** $^{187}\text{Os}/^{188}\text{Os}$ vs. Ba/Nb for WDLC and EKS basalts. Symbols as in **Fig. 8**.
745 Trends for contamination of mantle source of basalts by subduction-related fluids,
746 fields of Ba/Nb and $^{187}\text{Os}/^{188}\text{Os}$ for the subduction fluids and the lower crust based are
747 based on [Chesley et al. \(2002\)](#). Numbers along trend lines represent percentage of
748 fluid required to influence the mantle source. Large numbers along trend lines
749 represent the Os in ppt for subduction-related fluids used in the two-component

750 mixing model (the mantle source of WDLC and EKS basalts is assumed to be 1000
751 ppt). The real trend should possibly toward more radiogenic Os along with increasing
752 Bb/Nb ratios due to the effect of preferential melting of metasomatic components in
753 mantle source for Os isotopes (e.g., Harvey et al., 2011).

754

755 **Supplementary materials:**

756 Detailed descriptions for WDLC and EKS samples;

757 Petrography of representative samples for WDLC and EKS basalts (Figure S1);

758 EPMA data for olivines in WDLC and EKS basalts (Table S1).

759

760 **References**

761 Arculus R.J., Powell R., 1986. Source component mixing in the regions of arc magma
762 generation. *J. Geophys. Res.* 91, 5913-5926.

763 Alard, O., Griffin, W.L., Lorand, J.-P., Jackson, S.E., O'Reilly, S.Y., 2000.
764 Nonchondritic distribution of the highly siderophile elements in mantle sulphides.
765 *Nature* 407, 891-894.

766 Alard, O., Griffin, W.L., Pearson, N.J., Lorand, J.-P., O'Reilly, S.Y., 2002. New
767 insights into the Re–Os systematics of subcontinental lithospheric mantle from
768 in-situ analysis of sulphides. *Earth Planet. Sci. Lett.* 203, 651-663.

769 Alard, O., Luguet, A., Pearson, N.J., Griffin, W.L., Lorand, J.-P., Gannoun, A., Burton,
770 K.W., O'Reilly, S. Y., 2005. In-situ Os isotopes in abyssal peridotites bridge the
771 isotopic gap between MORBs and their source mantle. *Nature* 436, 1005-1008.

772 Ballhaus, C., Bockrath, C., Wohlgemuth-Ueberwasser, C., Vera Laurenz, V., Berndt, J.,
773 2006. Fractionation of the noble metals by physical processes. *Contrib. Mineral.*
774 *Petrol.* 152, 667–684.

775 Basu, A.R., Wang, J.W., Huang, W.K., Xie, G.H., Tatsumoto, M., 1991. Major element,
776 REE, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of
777 eastern China: implications for their origin from suboceanic-type mantle
778 reservoirs. *Earth Planet. Sci. Lett.* 105, 149-169.

779 Becker, H., Walker, R.J., 2003. In search of extant Tc in the early solar system: ^{98}Ru
780 and ^{99}Ru abundances in iron meteorites and chondrites. *Chem. Geol.* 196, 43-56.

781 Becker, H., Horan, M.F., Walker, R.J., Gao, S., Lorand, J.-P., Rudnick, R.L., 2006.
782 Highly siderophile element composition of the Earth's primitive upper mantle:
783 constraints from new data on peridotite massifs and xenoliths. *Geochim.*
784 *Cosmochim. Acta* 70, 4528-4550.

785 Birck, J.L., Roy-Barman, M., Capmas, F., 1997. Re-Os isotopic measurements at the
786 femtomole level in natural samples. *Geostand. Newslett.* 20, 19-27.

787 Bizimis, M., Griselein, M., Lassiter, J.C., Salters, V.J.M., Sen, G., 2007. Ancient
788 recycled mantle lithosphere in the Hawaiian plume: osmium-hafnium isotopic
789 evidence from peridotite mantle xenoliths. *Earth Planet. Sci. Lett.* 257, 259-273.

790 Blichert-Toft, J., Albarède, F., 1997. The Lu-Hf geochemistry of chondrites and the
791 evolution of the mantle-crust system. *Earth Planet. Sci. Lett.* 148, 243-258.

792 Brandon, A.D., Creaser, R.A., Shirey, S.B., Carlson, R.W., 1996, Os recycling in
793 subduction zones. *Science* 272, 861-864.

794 Burton, K.W., Schiano, P., Birck, J.-L., Allègre, C.J., 1999. Osmium isotope
795 disequilibrium between mantle minerals in a spinel-lherzolite. *Earth Planet. Sci.*
796 *Lett.* 172, 311-322.

797 Chen, L.H., Zeng, G., Jiang, S.Y., Hofmann, A.W., Xu, X.S., 2009. Sources of
798 Anfengshan basalts: Subducted lower crust in the Sulu UHP belt, China. *Earth*
799 *Planet. Sci. Lett.* 286, 426-435.

800 Chen, Y., Zhang, Y.X., Graham, D., Su, S.G., Deng, J.F., 2007. Geochemistry of
801 Cenozoic basalts and mantle xenoliths in Northeast China. *Lithos* 96, 108-126.

802 Chesley, J.T., Ruiz, J., 1998. Crust-mantle interaction in large igneous provinces:
803 implications from the Re-Os isotope systematics of the Columbia River flood
804 basalts. *Earth Planet. Sci. Lett.* 154, 1-11.

805 Chesley, J.T., Ruiz, J., Righter, K., Ferrari, L., Gomez-Tuena, A., 2002. Source
806 contamination versus assimilation: an example from the Trans-Mexican Volcanic
807 Arc. *Earth Planet. Sci. Lett.* 195, 211-221.

808 Chesley, J.T., Righter, K., Ruiz, J., 2004. Large-scale mantle metasomatism: a Re-Os
809 perspective. *Earth Planet. Sci. Lett.* 219, 49-60.

810 Choi, S.H., Mukasa, S.B., Kwon, S.-T., Andronikov, A.V., 2006. Sr, Nd, Pb and Hf
811 isotopic compositions of late Cenozoic alkali basalts in South Korea: evidence for
812 mixing between the two dominant asthenospheric mantle domains beneath East
813 Asia. *Chem. Geol.* 232, 134-151.

814 Chu, Z.Y., Wu, F.Y., Walker, R.J., Rudnick, R.L., Pitcher, L., Puchtel, I.S., Yang, Y.H.,
815 Wilde, S.A., 2009. Temporal evolution of the lithospheric mantle beneath the

816 eastern North China Craton. *J. Petrol.* 50, 1857-1898.

817 Class, C., Goldstein, S.L., 1997. Plume– lithosphere interactions in the ocean basins:
818 constraints from the source mineralogy. *Earth Planet. Sci. Lett.* 150, 245– 260.

819 Cohen, A.S., Waters, F.G., 1996. Separation of osmium from geological materials by
820 solvent extraction for analysis by TIMS. *Anal. Chim. Acta* 332, 269-275.

821 Creaser R. A., Papanastassiou D. A. and Wasserburg G. J., 1991. Negative thermal ion
822 mass spectrometry of osmium, rhenium, and iridium. *Geochim. Cosmochim. Acta*
823 55, 397–401.

824 Day, J.M.D, 2013. Hotspot volcanism and highly siderophile elements. *Chem. Geol.*
825 341, 50–74.

826 DePaolo, D., 1981. Trace element and isotopic effects of combined wallrock
827 assimilation and fractional crystallization. *Earth Planet. Sci. Lett.* 53, 189–202.

828 Douglass, J., Schilling, J.-G., Fontignie, D., 1999. Plume-ridge interactions of the
829 Discovery and Shona mantle plumes with the southern Mid-Atlantic Ridge
830 (40°-55°S). *J. Geophys. Res.* 107, 2941-2962.

831 Fan, Q., Hooper, P.R., 1991. The Cenozoic basaltic rocks of eastern China: petrology
832 and chemical composition. *J. Petrol.* 32, 765-810.

833 Flower, M., Tamaki, K., Hoang, N., 1998. Mantle extrusion: a model for dispersed
834 volcanism and DUPAL-like asthenosphere in East Asia and the Western Pacific.
835 In: Flower, M., Chung, S.-L., Lo, C.-H., Lee, T.Y. (Eds.), *Mantle dynamics and*
836 *plate interactions in East Asia*, Am. Geophys. Union, *Geophys. Monogr.*, vol. 27,
837 pp. 67-88.

838 Gannoun, A., Burton, K.W., Parkinson, I.J., Alard, O., Schiano P., Thomas, L.E., 2007.
839 The scale and origin of the osmium isotope variations in mid-ocean ridge basalts.
840 Earth Planet. Sci. Lett. 259, 541-556.

841 Hart, S.R., Hauri, E.H., Oschmann, L.A., Whitehead, J.A., 1992. Mantle plumes and
842 entrainment—Isotopic evidence. Science 256, 517–520.

843 Harvey, J., Gannoun, A., Burton, K.W., Rogers, N.W., Alard, O., Parkinson, I.J., 2006.
844 Ancient melt extraction from the oceanic upper mantle revealed by Re–Os
845 isotopes in abyssal peridotites from the Mid-Atlantic ridge. Earth Planet. Sci. Lett.
846 244, 606-621.

847 Harvey, J., Gannoun, A., Burton, K.W., Schiano, P., Rogers, N.W., Alard, O., 2010.
848 Unravelling the effects of melt depletion and secondary infiltration on mantle
849 Re–Os isotopes beneath the French Massif Central. Geochim. Cosmochim. Acta
850 74, 293-320.

851 Harvey, J., Dale, C.W., Gannoun, A., Burton, K.W., 2011. Osmium mass balance in
852 peridotite and the effects of mantle-derived sulphides on basalt petrogenesis.
853 Geochim. Cosmochim. Acta 75, 5574-5596.

854 Herzberg, C., 2011, Identification of source lithology in the Hawaiian and Canary
855 Islands: implications for origins. J. Petrol. 52, 113-146.

856 Hofmann, A.W., Jochum, K.P., Seuffer, M., White, W.M., 1986. Nb and Pb in oceanic
857 basalts: new constraints on mantle evolution. Earth Planet. Sci. Lett. 79, 33-45.

858 Huang, J.L., Zhao, D.P., 2006. High-resolution mantle tomography of China and
859 surrounding regions. J. Geophys. Res. 111, B09305.

860 Jackson, M.G., Shirey, S.B., 2011. Re–Os isotope systematics in Samoan shield lavas
861 and the use of Os-isotopes in olivine phenocrysts to determine primary magmatic
862 compositions. *Earth Planet. Sci. Lett.* 312, 91–101.

863 Jiang, L., Zhi, X.C., 2010. Re-Os isotope geochemistry of basalts from Hannuoba,
864 North China: Evidence for Re volatile loss and crust-mantle interaction (in
865 Chinese with English abstract). *Acta Petrol. Sin.* 26: 1265-1276.

866 Jung S., Pfänder J.A., Brauns M., Maas R., 2011. Crustal contamination and mantle
867 source characteristics in continental intra-plate volcanic rocks: Pb, Hf and Os
868 isotopes from central European volcanic province basalts. *Geochim. Cosmochim.*
869 *Acta* 75, 2664-2683.

870 Kuritani, T., Ohtani, E., Kimura, J.-I., 2011. Intensive hydration of the mantle
871 transition zone beneath China caused by ancient slab stagnation. *Nat. Geosci.* 4,
872 713–716.

873 Kuritani T., Kimura J-I., Ohtani E., Miyamoto H., Furuyama K., 2013. Transition
874 zone origin of potassic basalts from Wudalianchi volcano, northeast China. *Lithos*
875 156–159, 1–12.

876 Lassiter, J.C., Luhr, J.F., 2001, Osmium abundance and isotope variations in mafic
877 Mexican volcanic rocks: Evidence for crustal contamination and constraints on
878 the geochemical behavior of osmium during partial melting and fractional
879 crystallization. *Geochem. Geophys. Geosyst.* 2, 2000GC000116.

880 Liu, C.Q., Masuda, A., Xie, G.H., 1994. Major- and trace-element compositions of
881 Cenozoic basalts in east China: petrogenesis and mantle source. *Chem. Geol.* 114,

882 19– 42.

883 Liu, C.Z., Snow, J.E., Hellebrand, E., Brugmann, G., von der Handt, A., Buchl, A.,
884 Hofmann, A.W., 2008. Ancient, highly heterogeneous mantle beneath Gakkel
885 ridge, Arctic Ocean. *Nature* 452, 311-316.

886 Liu, J.Q., Han, J.T., Fyfe, W.S., 2001. Cenozoic episodic volcanism and continental
887 rifting in northeast China and possible link to Japan Sea development as revealed
888 from K-Ar geochronology. *Tectonophysics* 339, 385–401.

889 Lorand, J.-P., Alard, O., 2001. Platinum-group element abundances in the upper
890 mantle: New constraints from in situ and whole-rock analyses of Massif Central
891 xenoliths (France). *Geochim. Cosmochim. Acta* 65, 2789-2806.

892 Lorand, J.-P., Alard, O., Luguët, A., 2010. Platinum-group element micronuggets and
893 refertilization process in the Lherz peridotite. *Earth Planet. Sci. Lett.* 289,
894 298–310.

895 Lorand, J.-P., Luguët, A., Alard, O., 2013. Platinum-group element systematics and
896 petrogenetic processing of the continental upper mantle: A review. *Lithos*,
897 164-167, 2-21.

898 Masuda, A., Nakamura, N., Tanaka, T., 1973. Fine structures of mutually normalised
899 rare-earth patterns of chondrites. *Geochim. Cosmochim. Acta* 37, 239-244.

900 McBride, J.S., Lambert, D.D., Nicholls, I.A., Price, R.C., 2001. Osmium isotopic
901 evidence for crust-mantle interaction in the genesis of continental intraplate
902 basalts from the Newer Volcanics Province, Southeastern Australia. *J. Petrol.* 42,
903 1197-1218.

904 McDonough, W.F., Sun, S.S., 1995. The composition of the Earth. *Chem. Geol.* 120,
905 223–253.

906 Meisel, T, Moser, J., 2004. Platinum-Group element and rhenium concentrations in
907 low abundance reference materials. *Geostand. Geoanal. Res.* 28, 233-250.

908 Meng, E., Xu, W.L., Pei, F.P., Yu, Y., Zhang, X.Z., 2010. Detrital-zircon
909 geochronology of Late Paleozoic sedimentary rocks in eastern Heilongjiang
910 Province, NE China: Implications for the tectonic evolution of the eastern
911 segment of the Central Asian Orogenic Belt. *Tectonophysics*, 485, 42-51.

912 Pearson, D.G., Woodland, S.J., 2000. Solvent extraction/anion exchange separation
913 and determination of PGEs (Os, Ir, Pt, Pd, Ru) and Re-Os isotopes in geological
914 samples by isotope dilution ICP-MS. *Chem. Geol.* 165, 87-107.

915 Pearson, D.G., Irvine, G.J., Ionov, D.A., Boyd, F.R., Dreibus, G.E., 2004. Re-Os
916 isotope systematics and platinum group element fractionation during mantle melt
917 extraction: a study of massif and xenolith peridotite suites. *Chem. Geol.* 208,
918 29-59.

919 Pearson, N.J., Alard, O., Griffin, W.L., Jackson S.E., O'Reilly S.Y., 2002. In situ
920 measurement of Re–Os isotopes in mantle sulphides by laser-ablation
921 multi-collector inductively coupled plasma mass spectrometry: analytical
922 methods and preliminary results. *Geochim. Cosmochim. Acta* 66, 1037-1050.

923 Peng, Z.C., Zartman, R.E., Futa, K., Chen, D.G., 1986. Pb-, Sr- and Nd-isotopic
924 systematics and chemical characteristics of Cenozoic basalts, Eastern China.
925 *Chem. Geol.* 59, 3-33.

926 Phipps Morgan, J., Morgan, W.J., 1999. Two-stage melting and the geochemical
927 evolution of the mantle: a recipe for mantle plum-pudding. *Earth Planet. Sci. Lett.*
928 170, 215-239.

929 Qi, L., Zhou, M.F., Wang, C.Y., Sun, M., 2007. Evaluation of the determination of Re
930 and PGEs abundances of geological samples by ICP-MS coupled with a modified
931 Carius tube digestion at different temperatures. *Geochem. J.* 41, 407-414.

932 Qi, L., Zhou, M.-F., 2008. Platinum-group element and Sr-Nd-Os isotope
933 geochemistry of Permian Emeishan flood basalts, in Guizhou Province, SW
934 China. *Chem. Geol.* 248, 83-103.

935 Reisberg, L., Zhi, X., Lorand, J.P., Wagner, C., Peng, Z., Zimmermann, C., 2005.
936 Re-Os and S systematics of spinel peridotite xenoliths from east central China:
937 Evidence for contrasting effects of melt percolation. *Earth Planet. Sci. Lett.* 239,
938 286–308.

939 Rudnick, R.L., Gao, S., 2003. Composition of the continental crust. In: Rudnick, R.L.
940 (Ed.), *Treatise on Geochemistry*. Elsevier, pp. 1-64.

941 Rudnick, R.L., Walker, R.J., 2009. Interpreting ages from Re-Os isotopes in
942 peridotites. *Lithos* 112, 1083-1095.

943 Saal, A.E., Rudnick, R.L., Ravizza, G.E., Hart, S.R., 1998. Re-Os isotope evidence for
944 the composition, formation and age of the lower continental crust. *Nature*, 393,
945 58–61.

946 Salters, V.J.M., Zindler, A., 1995. Extreme $^{176}\text{Hf}/^{177}\text{Hf}$ in the sub-oceanic mantle.
947 *Earth Planet. Sci. Lett.* 129, 13-30.

948 Salters, V.J.M., White, W.M., 1998. Hf isotope constraint on mantle evolution. *Chem.*
949 *Geol.* 145, 447–460.

950 Schulte, R.F., Schilling, M., Anma, R., Farquhar, J., Horan, M.F., Komiya, T., Piccoli,
951 P.M., Pitcher, L., Walker, R.J., 2009. Chemical and chronologic complexity in the
952 convecting upper mantle: evidence from the Taitao ophiolite, southern Chile.
953 *Geochim. Cosmochim. Acta* 73, 5793-5819.

954 Sen, I.S., Bizimis, M., Sen, G., Huang, S., 2011, A radiogenic Os component in the
955 oceanic lithosphere? Constraints from Hawaiian pyroxenite xenoliths. *Geochim.*
956 *Cosmochim. Acta* 75, 4899-4916.

957 Sengör, A., Natal'lin, B.A., Burtaman, V.S., 1993. Evolution of the Altaid tectonic
958 collage and Palaeozoic crustal growth in Eurasia. *Nature* 364, 299-307.

959 Shinotsuka, K., Suzuki, K., 2007. Simultaneous determination of platinum group
960 elements and rhenium in rock samples using isotope dilution inductively coupled
961 plasma mass spectrometry after cation exchange separation followed by solvent
962 extraction. *Anal. Chim. Acta*, 603:129-139.

963 Shirey, S.B., Walker, R.J., 1995. Carius tube digestions for low blank
964 rhenium-osmium analysis. *Anal. Chem.* 67, 2136-2141.

965 Shirey, S.B., Walker, R.J., 1998. The Re-Os isotope system in cosmochemistry and
966 high temperature geochemistry. *Annu. Rev. Earth Planet. Sci.* 26, 423-500.

967 Sobolev A.V., Hofmann A.W., Kuzmin D.V., Yaxley G.M., Arndt, N.T., Chung S.-L.,
968 Danyushevsky L.V., Elliott T., Frey, F.A., Garcia M.O., Gurenko A.A.,
969 Kamenetsky V.S., Kerr, A.C., Krivolutsкая N.A., Matvienkov V.V., Nikogosian I.

970 K., Rocholl A., Sigurdsson I.A., Sushchevskaya N.M., Teklay, M., 2007. The
971 amount of recycled crust in mantle-derived melts. *Science* 316, 412–417.

972 Song, Y., Frey, F.A., Zhi, X., 1990. Isotopic characteristics of Hannuoba basalts,
973 eastern China: implications for their petrogenesis and the composition of
974 subcontinental mantle. *Chem. Geol.* 85, 35-62.

975 Volkening J., Walczyk T., Heumann K., 1991. Os isotope ratio determinations by
976 negative thermal ionisation mass spectrometry. *Int. J. Mass Spectrom. Ion*
977 *Process.* 105, 147–159.

978 Walker, R.J., Pitchard, H.M., Ishiwatari, A., Pimentel, M., 2002. The osmium isotopic
979 composition of convecting upper mantle deduced from ophiolite chromites.
980 *Geochim. Cosmochim. Acta* 66, 329-345.

981 Widom, E., Hoernle, K.A., Shirey, S.B., Schmincke, H.-U., 1999. Os isotope
982 systematic in the Canary Islands and Madeira: lithospheric contamination and
983 mantle plume signatures. *J. Petrol.* 40, 297-314.

984 Widom, E., Kepezhinskas, P., Defant, M., 2003. The nature of metasomatism in the
985 sub-arc mantle wedge: evidence from Re-Os isotopes in Kamchatka peridotite
986 xenoliths. *Chem. Geol.* 196, 283-306.

987 Wu, F.Y., Jahn, B.M., Wilde, S.A., Lo, C.H., Yui, T.F., Lin, Q., Ge, W.C., Sun, D.Y.,
988 2003. Highly fractionated I-type granites in NE China (II): isotopic geochemistry
989 and implications for crustal growth in the Phanerozoic. *Lithos* 67, 191-204.

990 Xu, J.F., Suzuki, K., Xu, Y.G., Mei, H.J., Li, J. 2007. Os, Pb, and Nd isotope
991 geochemistry of the Permian Emeishan continental flood basalts: insights into the

992 source of a large igneous province. *Geochim. Cosmochim. Acta* 71, 2104-2119.

993 Xu, Y.G., 2002. Evidence for crustal components in mantle source and constraints on
994 recycling mechanism: pyroxenite xenoliths from Hannuoba, North China. *Chem.*
995 *Geol.* 182, 301–322.

996 Xu, Y.G., Ma, J.L., Frey, F.A., Feigenson, M.D., Liu, J.F., 2005. Role of
997 lithosphere-asthenosphere interaction in the genesis of Quaternary alkali and
998 tholeiitic basalts from Datong, western North China Craton. *Chem. Geol.* 224,
999 247-271.

1000 Xu, Y.G., Zhang, H.H., Qiu, H.N., Ge, W.C., Wu, F.Y., 2012. Oceanic crust
1001 components in continental basalts from Shuangliao, Northeast China: Derived
1002 from the mantle transition zone? *Chem. Geol.* 328, 168-184.

1003 Yan, J., Zhao, J.X., 2008. Cenozoic alkali basalts from Jingpohu, NE China: The role
1004 of lithosphere-asthenosphere interaction. *J. Asian Earth Sci.* 33, 106-121.

1005 Yang, Y.H., Zhang, H.F., Chu, Z.Y., Xie, L.W., Wu, F.Y., 2010. Combined chemical
1006 separation of Lu, Hf, Rb, Sr, Sm and Nd from a single rock digest and precise and
1007 accurate isotope determinations of Lu-Hf, Rb-Sr and Sm-Nd isotope systems
1008 using Multi-Collector ICP-MS and TIMS. *Int. J. Mass Spectrom.* 290, 120-126.

1009 Zhang, J.J., Zheng, Y.F., Zhao, Z.F., 2009. Geochemical evidence for interaction
1010 between oceanic crust and lithospheric mantle in the origin of Cenozoic
1011 continental basalts in east-central China. *Lithos* 110, 305-326.

1012 Zhang, M., Menzies, M.A., Suddaby, P., Thirlwall, M.F., 1991. EM1 signature from
1013 the post-Archaean subcontinental lithospheric mantle: isotopic evidence from the

1014 potassic volcanic rocks in NE China. *Geochem. J.* 25, 387-398.

1015 Zhang, M., Suddaby, P., Thompson, R.N., Thirlwall, M.F., Menzies, M.A., 1995.

1016 Potassic volcanic rocks in NE China: geochemical constraints on mantle source

1017 and magma genesis. *J. Petrol.* 36, 1275-1303.

1018 Zhang, M., Zhou, X.H., Zhang, J.B., 1998. Nature of the lithospheric mantle beneath

1019 NE China: evidence from potassic volcanic rocks and mantle xenoliths. In:

1020 Flower, M., Chung, S.-L., Lo, C.-H., Lee, T.Y. (Eds.), *Mantle Dynamics and Plate*

1021 *Interactions in East Asia*, Am. Geophys. Union, *Geophys. Monogr.*, Vol. 27, pp.

1022 197-219.

1023 Zhang, M., Suddaby, P., O'Reilly, S.Y., Norman, M., Qiu, J., 2000. Nature of the

1024 lithospheric mantle beneath the eastern part of the Central Asian fold belt: mantle

1025 xenolith evidence. *Tectonophysics* 328, 131-156.

1026 Zhang, Y.L., Ge, W.C., Gao, Y., Chen, J.S., Zhao, L., 2010. Zircon U–Pb ages and Hf

1027 isotopes of granites in Longzhen area and their geological implications. *Acta*

1028 *Petrol. Sin.* 26, 1059–1073 (in Chinese with English abstract).

1029 Zhang, Y.L., Liu, C.Z., Ge, W.C., Wu, F.Y., Chu, Z.Y., 2011. Ancient sub-continental

1030 lithospheric mantle (SCLM) beneath the eastern part of the Central Asian

1031 Orogenic Belt (CAOB): Implications for crust-mantle decoupling. *Lithos* 126,

1032 233-247.

1033 Zhi, X.C., Song, Y., Frey, F.A., Feng, J.L., Zhai, M.Z., 1990. Geochemistry of

1034 Hannuoba basalts, eastern China: constraints on the origin of continental alkalic

1035 and tholeiitic basalt. *Chem. Geol.* 88, 1 - 33.

1036 Zhou, X.H., Armstrong, R.L., 1982. Cenozoic volcanic rocks of eastern China-secular
1037 and geographic trends in chemistry and strontium isotopic composition. *Earth*
1038 *Planet. Sci. Lett.* 58, 301-329.

1039 Zindler, A., Hart, S.R., 1986. Chemical geodynamics. *Annu. Rev. Earth Planet. Sci.* 14,
1040 493-571.

1041 Zou, H., Zindler, A., Xu, X., Qi, Q., 2000. Major, trace element, and Nd, Sr and Pb
1042 isotope studies of Cenozoic basalts in SE China: mantle sources, regional
1043 variations, and tectonic significance. *Chem. Geol.* 171, 33-47.

1044 Zou, H., Reid, M.R., Liu, Y., Yao, Y., Xu, X., Fan, Q., 2003. Constraints on the origin
1045 of historic potassic basalts from northeast China by U-Th disequilibrium data.
1046 *Chem. Geol.* 200, 189-201.

1047