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1 **Long-term isolation of Hadean mantle domains revealed from coupled**

2 **$^{147-146}\text{Sm}$ - $^{143-142}\text{Nd}$ systematics in the eastern North China Craton**

3
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12
13 **Abstract**

14 The ^{146}Sm - ^{142}Nd systematics of Archean rocks have been extensively studied to decipher
15 chronological and compositional constraints on Hadean differentiation processes. However, the paucity
16 of ^{142}Nd data on Meso- and Neoproterozoic mantle-derived rocks relative to earlier periods contributes to
17 uncertainty about the ultimate fate of primordial silicate reservoirs in the convective system of the early
18 Earth. Here we present $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ and ^{176}Lu - ^{176}Hf zircon data for Mesoarchean (3.0-3.1 Ga) to
19 Paleoproterozoic (2.45 Ga) granitoids, amphibolites and sedimentary rocks representing the main
20 lithological units of the eastern North China Craton (NCC). The analyzed samples have well-resolved
21 positive ^{142}Nd anomalies, suggesting that the Eo- to Mesoarchean continental crust of the eastern NCC
22 is derived from a depleted Hadean mantle source. The model age of differentiation ($4.44^{+0.05}_{-0.07}$ Ga) and

23 the $^{147}\text{Sm}/^{144}\text{Nd}$ source ratio (0.211 ± 0.002) estimated from the 3.1 Ga Caozhuang amphibolites are
24 identical to those of the 3.8-3.6 Ga rocks from the North Atlantic Craton and the 2.7 Ga pyroxenites
25 from the Abitibi Greenstone Belt, suggesting that these mantle-derived rocks originated from a
26 common, moderately depleted reservoir that differentiated in the wake of the Moon-forming impact
27 and evolved in closed-system until at least 2.7 Ga. These observations contradict the commonly
28 accepted notion of progressive homogenization of ^{142}Nd anomalies in the Archean due to crustal
29 recycling and convective mixing, and instead suggest that primordial differentiation produced a
30 long-lived, depleted reservoir that remained largely isolated from convective mixing on a timescale of
31 several billion years.

32

33 Keywords: Hadean, Archean, North China Craton, extinct radioactivities, magma ocean

34

35 **1 Introduction**

36 During much of Earth's history, the geochemical evolution of the mantle-crust system was
37 governed by plate tectonics. Magmatic activity triggered by subduction of oceanic lithosphere led to
38 the formation of a long-lived continental crust enriched in incompatible elements and a complementary,
39 depleted reservoir that forms the convective upper mantle. Although similar processes may have
40 existed from the beginning of the Hadean ([Korenaga, 2021](#)), the composition and evolution of crustal
41 and mantle reservoirs during the first billion years of Earth's history are elusive. The first terrestrial
42 crust probably formed as a result of the crystallization of a magma ocean following the Moon-forming
43 impact ([Bennett et al., 2007](#); [Caro et al., 2005](#)). However, the role that this event played in the
44 formation of the chemical and isotopic heterogeneity of the Archean mantle relative to conventional

45 crust-forming processes remains unclear. Rapid continental growth in the Hadean may explain several
46 key features of the Archean isotopic record, assuming that a crustal volume similar to that of today
47 formed early (ca. 4.4 - 4.5 Gyr ago) and within a few tens of millions of years ([Armstrong et al., 1981](#);
48 [Korenaga, 2018](#)). In contrast, the outcome of magma ocean crystallization is poorly understood with
49 respect to the structure and composition of early Earth's mantle. Unresolved questions include the
50 propensity of a convective magma ocean to generate chemically differentiated reservoirs by
51 melt-crystal segregation (e.g., [Solomatov, 2015](#)), the role of a putative basal magma ocean in
52 generating long-lived differentiated reservoirs near the Core-Mantle boundary ([Labrosse et al, 2007](#);
53 [Caracas et al, 2019](#)), and the fate of these primordial reservoirs in the convective system of the early
54 Earth.

55 In the absence of a preserved Hadean rock record, indirect approaches based on radiogenic
56 isotopes can be used to determine the timing of early mantle differentiation and to trace the evolution
57 of differentiated silicate reservoirs through geological time. The short-lived ^{146}Sm - ^{142}Nd system
58 ($T_{1/2}=103$ Ma, [Marks et al., 2014](#); [Meissner et al., 1987](#)) is particularly well-suited for this approach.
59 Because ^{146}Sm became extinct about 4 Gyr ago, this chronometer selectively records differentiation
60 events that occurred within the first 500 Myr of Earth history. Extraction of voluminous crust (e.g.,
61 [Roth et al., 2014](#)) or internal differentiation at the magma ocean stage (e.g., [Caro et al., 2005](#)) would
62 result in large-scale Sm/Nd fractionation leading to the development of positive ^{142}Nd anomalies (i.e.,
63 higher $^{142}\text{Nd}/^{144}\text{Nd}$ values relative to the Bulk Silicate Earth) in chemically depleted (mantle) reservoirs
64 and negative anomalies in chemically enriched reservoirs. In combination with the long-lived
65 ^{147}Sm - ^{143}Nd system, the ^{146}Sm - ^{142}Nd chronometer provides precise clues to the age, composition, and
66 evolution of Hadean silicate reservoirs ([Caro et al., 2006](#)). This in turn provides important constraints

67 for geodynamic models of the early Earth, the nature of the Hadean crust, its longevity, and the lifetime
68 of primordial heterogeneities in the Earth's interior (e.g., [Rosas and Korenaga, 2018](#); [Debaille et al.,](#)
69 [2013](#); [Hyung and Jacobsen, 2020](#); [Roth et al; 2014](#)).

70 Attempts to detect ^{142}Nd variations in terrestrial rocks were initiated in the 1990s ([Harper and](#)
71 [Jacobsen, 1992](#)), and more precise measurements ([Caro et al, 2003](#)) later showed that both positive and
72 negative ^{142}Nd anomalies are common in Archean rocks. Obvious positive anomalies have been
73 detected in rocks from the Isua Supracrustal Belt and Itsaq gneiss complex in southwest Greenland
74 ([Boyet and Carlson, 2006](#); [Caro et al., 2006](#); [Bennett et al., 2007](#); [O'Neil et al., 2016](#); [Rizo et al., 2011](#);
75 [Rizo et al., 2013](#); [Saji et al., 2018](#)), the Archean Saglek block in northern Labrador ([Morino et al., 2017](#);
76 [Wasilewski et al., 2022](#)), the Abitibi greenstone belt ([Debaille et al., 2013](#)), the North China craton ([Li](#)
77 [et al., 2017](#)), and the Singhbhum Craton, India ([Maltese et al., 2022](#)). Negative ^{142}Nd anomalies have
78 also been reported in numerous locations, including the Acasta Gneiss Complex (3.4 - 4.0 Ga)
79 ([Reimink et al., 2018](#); [Roth et al., 2014](#)), the Nappier gneiss complex ([Guitreau et al., 2019](#)); the
80 Schapenburg and Barberton komatiites in the Kaapvaal Craton (3.55 Ga, [Puchtel et al., 2013, 2016](#);
81 [Boyet et al., 2021](#)), the Nuvvuagittuq/Ukaliq supracrustal belts and Innuksuaq Gneiss Complex (3.5-3.8
82 Ga) ([Caro et al., 2017](#); [O'Neil et al., 2008, 2012](#); [Roth et al., 2013](#)), the Dwalile Greenstone Remnant
83 from the Ancient Gneiss Complex, Swaziland (3.45 Ga, [Schneider et al., 2018](#)), and the Muzidian
84 gneiss complex in the Yangtze craton of central China ([Wang et al., 2023](#)). Overall, the terrestrial ^{142}Nd
85 record seems to indicate that the depletion of the Archean mantle is at least partly due to a major
86 differentiation event about 4.4 Gyr ago ([Morino et al., 2017](#)). The timing of this event is nearly
87 synchronous with the crystallization of the lunar mantle (e.g. [Brandon et al., 2009](#); [Boyet and Carlson,](#)
88 [2007](#); [McLeod et al., 2014](#)) and identical to the Pb-Pb "age of the Earth", interpreted to reflect Pb loss

89 during the giant impact ([Connelly et al., 2022](#)). These observations show that early differentiation
90 events, perhaps related to magma ocean processes, had a long-lasting influence on the structure and
91 compositional heterogeneity of the Hadean-Archean mantle.

92 In this context, the Archean ^{142}Nd record represents a promising tool for tracking the evolution of
93 the mantle-crust system in the post-magma ocean Earth. However, despite a rapidly growing ^{142}Nd
94 database, there is no uniformly accepted interpretation of the Archean ^{142}Nd record. For instance,
95 [Debaille et al. \(2013\)](#) argue that the preservation of positive ^{142}Nd anomalies up to 2.7 Ga indicates
96 inefficient convective stirring favored by stagnant-lid convection, while [Hyung and Jacobsen \(2020\)](#)
97 argue that the ^{142}Nd record is consistent with a fast mantle stirring time of about 400 Myr since the
98 early Hadean. Alternatively, the ^{142}Nd evolution of the mantle has also been interpreted to reflect the
99 efficiency of crustal recycling in the early Earth ([Caro et al., 2006](#)). [Roth et al. \(2014\)](#) interpreted the
100 Archean ^{142}Nd record as reflecting massive crustal formation during the first few hundred Myr of Earth
101 history, followed by “slow” recycling of this early crust into the mantle with a crustal residence time of
102 ca. 750 Myr. Similar conclusions are reached by [Rosas and Korenaga \(2018\)](#), who suggest that the
103 gradually decreasing ^{142}Nd heterogeneity of Earth's mantle reflects that the net growth of continental
104 crust was complete by the end of the Hadean but that the rate of crustal recycling was much higher at
105 that time. Finally, based on the similarity of $^{146,147}\text{Sm}$ – $^{142,143}\text{Nd}$ model ages inferred for Theo's Flow,
106 Nulliak and Isua supracrustal rocks, [Morino et al. \(2017\)](#) proposed that their parent magmas originated
107 from depleted domains that evolved in closed-system over a period of several billion years. The
108 occurrence of positive ^{142}Nd anomalies in Archean rocks would then reflect episodic melting of a
109 depleted reservoir otherwise isolated from the convective system, rather than progressive
110 homogenization of the depleted upper mantle. This conclusion was reemphasized by [Saji et al. \(2018\)](#)

111 based on a similar treatment of the Archean ^{142,143}Nd database.

112 While models for the early evolution of the mantle-crust system have become increasingly
113 sophisticated, an important limiting factor is that the current ¹⁴²Nd record focuses on Eo- and
114 Paleoproterozoic terranes, and comparatively little is known about mantle evolution during the Meso- and
115 Neoproterozoic. This has significantly hampered our ability to constrain the isotopic evolution and
116 heterogeneity of the Archean mantle to determine geodynamic parameters such as the rates of crustal
117 growth and recycling. To gain a more comprehensive understanding of early mantle evolution, studies
118 that investigate the ^{142,143}Nd signature of mantle-derived rocks during this period are needed, focusing
119 on terranes with positive ¹⁴²Nd anomalies. Here, we report ^{146,147}Sm-^{142,143}Nd data and compile *in situ*
120 zircon ¹⁷⁶Lu-¹⁷⁶Hf data from Archean sedimentary rocks, granitoids, and mantle-derived rocks
121 (amphibolites) from the eastern North China Craton (NCC). The studied samples cover a wide age
122 range, from 3.5 Ga to 2.47 Ga, and represent the main lithological units of the eastern Hebei and
123 western Shandong regions in the NCC. The combined ¹⁴²Nd and *in situ* zircon Hf analysis provides
124 complementary information on the long-term evolution of Hadean mantle domains and the processes of
125 crustal additions and reworking in the NCC.

126

127 **2 Geological setting**

128 The NCC is the largest craton in China, covering an area of approximately 300,000 km² (Fig. 1).
129 Its tectonothermal evolution is marked by major crustal growth peaks during the late Neoproterozoic to
130 early Paleoproterozoic, in contrast to the typical ca. 2.7 Ga growth events and age peaks characteristics
131 of other Archean cratons (Liou et al., 2022b). Most of the samples used in this study, including
132 supracrustal rocks and associated granitoids of the Caozhuang group, were collected in the eastern

133 Hebei region (EH) of the NCC. The EH consists of high-grade Archean plutonic and supracrustal rocks
134 (Fig. 1). Among these, the oldest rocks are the ~3.78 Ga granodioritic gneisses reported by Wan et al.,
135 (2021). The Caozhuang group, also known as Caozhuang supracrustal sequence, consists of
136 decameter-sized enclaves of quartzite, amphibolite, hornblendite, garnet-biotite gneiss, calc-silicate
137 rock, marble, fine-grained biotite gneiss, and banded iron formation. Based on the deformation pattern
138 and other structural criteria, the amphibolites and related rocks in the Caozhuang area were first
139 proposed in 1980s to be the oldest rocks in eastern Hebei. This structural analysis was further
140 supported by Huang et al., (1986), Jahn et al., (1987), and Jahn et al., (1983) who determined an
141 emplacement age of ca. 3.5 Ga using whole-rock Sm-Nd isochrons on amphibolites from the
142 Caozhuang and Huangbaiyu areas. In contrast to this interpretation, Nutman et al. (2011) suggested that
143 this isochron represents a mixing relationship resulting from contamination of ca. 2.5 Ga magmas by
144 ancient felsic crust. Finally, Cui et al. (2018) reported ^{147}Sm - ^{143}Nd whole-rock isochron ages of
145 3580 ± 98 Ma and 3179 ± 90 Ma for two groups of mafic-ultramafic enclaves in the Caozhuang area.
146 These authors suggested that the emplacement ages of the Caozhuang amphibolites can be correlated to
147 two major crustal growth events in the NCC, at 3.5-3.7 Ga and 3.1-3.3 Ga.

148 Despite the limited availability of outcrops, Mesoarchean crustal material is present in the East
149 Hebei region and extensive new outcrops of Mesoarchean rocks have recently been identified (e.g.,
150 Liou et al., 2019; Nutman et al., 2011). These include ca. 2.9 Ga TTGs in the eastern EH and 3.3-2.8
151 Ga detrital or xenocrystic zircons found in the western EH. Finally, Neoproterozoic rocks are also
152 widespread in eastern Hebei, accounting for more than >95% of the total basement exposure. Plutonic
153 rocks dating from 2600 to 2500 Ma are the predominant rock type, accompanied by smaller amounts of
154 supracrustal rocks. These supracrustal rocks were intruded by a variety of coeval igneous rocks such as

155 pyroxenite, gabbro, diorite, tonalite-trondhjemite-granodiorite series (TTGs) to granites. [Zhao et al.](#)
156 [\(2001\)](#) proposed a mantle plume model given the exceptionally large exposure of granitoid intrusions
157 within a short period (2.55-2.50 Ga) in a ~800 km-wide area. Other studies suggest that the
158 diorite-TTG magmas ([Bai et al., 2016](#)), tholeiitic to calc-alkaline volcanic rocks ([Guo et al., 2017](#)), and
159 peridotites ([Polat et al., 2006](#); [Wu et al., 2022](#)) formed in subduction-related settings in the Neoproterozoic.

160 Samples analyzed in this study include amphibolites and hornblendites documented by [Cui et al.](#)
161 [\(2018\)](#) in the Caozhuang area, the 3.5 Ga fuchsite-bearing quartzites ([Liou et al., 2023](#)) and 3.1-2.9 Ga
162 granitoids reported by [Cui et al. \(2018\)](#), [Liou and Guo, \(2019\)](#) and [Liou et al., \(2019\)](#). In addition, two
163 2.5 Ga TTGs from the Caochang region and three ca. 2.7 Ga komatiite samples from the western
164 Shandong Province (WSP) were included for analysis. The WSP is an Archean granite–greenstone
165 terrane in the central part of the eastern NCC ([Wang et al., 2013](#)), with a total area of >10,000 km². The
166 main lithological assemblage consists of a ~2.5 Ga felsic volcano-sedimentary sequence, with
167 supracrustal rocks accounting for less than 10% of the exposed basement in the WSP ([Fig. 1a](#)). The
168 emplacement age of the komatiites is poorly constrained but has been estimated to be ~2.7 Ga based on
169 stratigraphic and structural evidence ([Zhang et al., 2001](#)). These rocks have undergone greenschist- to
170 amphibolite-facies metamorphism and intense deformation oriented in a northwest–southeast direction
171 along the central belt of the WSP.

172

173 **3 Methods**

174 Please see the supplementary Information (Appendix A1-A2).

175 **4 Results**

176 **4.1. ^{146,147}Sm-^{142,143}Nd systematics of meta-igneous and meta-sedimentary rocks**

177 **Table 1** presents Sm–Nd results for samples collected from eastern Hebei and western Shandong
178 regions, including data from the long-lived ^{147}Sm – ^{143}Nd and short-lived ^{146}Sm – ^{142}Nd systems.
179 Complete datasets for ^{142}Nd measurements are provided in **Supplementary Tables 1 and 2**. Following
180 the usual convention, $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{142}\text{Nd}/^{144}\text{Nd}$ isotopic ratios are expressed as the deviation from,
181 respectively, the chondritic and terrestrial values, using the following notation:

$$\varepsilon^{143}\text{Nd} = \left[\frac{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}}}{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{BSE}}} - 1 \right] \times 10^4$$
$$\mu^{142}\text{Nd} = \left[\frac{(^{142}\text{Nd}/^{144}\text{Nd})_{\text{sample}}}{(^{142}\text{Nd}/^{144}\text{Nd})_{\text{BSE}}} - 1 \right] \times 10^6$$

182 where “BSE” refers to “Bulk Silicate Earth” (i.e., $^{147}\text{Sm}/^{144}\text{Nd} = 0.1960$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.51263$) (e.g.,
183 [Bouvier et al., 2008](#)). The $^{142}\text{Nd}/^{144}\text{Nd}$ signature of the BSE is identical to that of the modern silicate
184 Earth and is considered equivalent to the JNdi standard. ^{147}Sm – ^{143}Nd ages were estimated using the
185 IsoplotR program ([Vermeesch, 2018](#)) and the initial $\varepsilon^{143}\text{Nd}$ values were calculated using the method of
186 [Fletcher and Rosman \(1982\)](#). Errors on $\mu^{142}\text{Nd}$ and $\varepsilon^{143}\text{Nd}_i$ values are quoted as 2 standard deviations
187 (S.D.). The reproducibility of ^{142}Nd measurements was assessed through repeated analyses of the JNdi
188 standard during two analytical sessions performed in April 2021 (n=11) and June 2021 (n=11), which
189 yielded 2 S.D. = 2.3 ppm (Table S1). The dataset consists of 26 samples (14 amphibolites, 3 quartzites,
190 2 granites, 2 TTGs and 3 komatiites) and includes 8 duplicates and 1 triplicate analysis (Table S2).

191 A total of 14 mafic-ultramafic rocks (11 amphibolites and 3 hornblendites) from the Caozhuang
192 Group were selected for ^{146}Sm – ^{142}Nd analyses (**Fig. 2a**). Their ^{147}Sm – ^{143}Nd compositions, previously
193 reported by [Cui et al. \(2018\)](#), are summarized in **table 1**, along with ^{147}Sm – ^{143}Nd analyses for twelve
194 other samples obtained in this study. As shown in **Figure 2**, the ^{142}Nd composition of the Caozhuang
195 amphibolites is overall positive but shows significant variability, with $\mu^{142}\text{Nd}$ ranging from +0.7 to
196 +11.2. No correlation was observed between the isotopic composition and the major or trace element

197 characteristics of the samples (Fig. 2b and Supplementary Fig. 1h). However, the ^{142}Nd composition of
198 the Caozhuang amphibolites reflect the classification of Cui et al. (2018), who defined their Group 1
199 and Group 2 amphibolites based on field observations, particularly their association with banded iron
200 formation. As shown in Figure 2b, Cui et al.'s Group 1 amphibolites mainly cluster around a mean
201 $\mu^{142}\text{Nd}$ of + 2.2, but include one sample with $\mu^{142}\text{Nd} = +7.8$ (15CZ06-1). In contrast, Group 2
202 amphibolites are predominantly clustered around a mean $\mu^{142}\text{Nd}$ of +8.7, with one outlier at +3.3
203 (14CZ03-06). This overall agreement supports Cui et al.'s classification of the Caozhuang amphibolites
204 into two distinct groups, although the presence of two outliers suggests that some samples may have
205 been assigned to the incorrect group based on field observations. In the following, we use a modified
206 version of Cui et al's classification, reassigning these two outliers to their respective groups based on
207 their ^{142}Nd compositions. To avoid confusion with the original classification of Cui et al (2018), we
208 refer to these two groups of amphibolites as the Primitive Group (P-group) and the Depleted Group
209 (D-group) (Fig. 2b). The P-group consists of four samples with an average $\mu^{142}\text{Nd}$ of $+2.5 \pm 2.3$ ppm
210 and MgO ranging from 4.7 to 6.5 wt% and is broadly equivalent to Cui et al's Group 1. The D-Group
211 consists of seven samples with well resolved positive $\mu^{142}\text{Nd}$ anomalies averaging $+8.7 \pm 3.0$ ppm and
212 overall higher MgO contents (6.1-9.3 wt%) and is broadly equivalent to Cui et al.'s Group 2.

213 In addition, three hornblendites from the Caozhuang region exhibit moderate ^{142}Nd excesses
214 ranging from +3.5 to +6.6 (Table 1). These rocks were tentatively described by Cui et al. (2018) as part
215 of the same assemblage as the amphibolites. However, this characterization remains speculative, as the
216 petrogenesis of the hornblendites is not well understood. In the field, hornblendites typically occur as
217 deformed isolated enclaves and their relationship to the amphibolites is unclear. These samples cannot
218 be unambiguously assigned to either the D- or the P-group based on their isotopic compositions.

219 Instead, their intermediate $\mu^{142}\text{Nd}$ compositions suggest that mafic-ultramafic magmatism in the
220 Caozhuang region result from the melting of a heterogeneous mantle containing both primitive and
221 depleted components. Alternatively, this observation could reflect the hybridization of the parental
222 melts represented by the two amphibolite groups defined above.

223 Felsic rocks from the eastern Hebei region, ranging in age from 3.1 Ga to 2.5 Ga, also show
224 positive ^{142}Nd anomalies comparable in magnitude to those of the Caozhuang amphibolites. Two ca.
225 3.1 Ga TTGs from the Caozhuang region show homogeneous positive $\mu^{142}\text{Nd}$ (8.6 ± 2.9 and 9.5 ± 3.7)
226 similar to those of the D-group amphibolites, but have lower initial $\epsilon^{143}\text{Nd}$ (-2.6 to +0.7) than the
227 D-group amphibolites ($\epsilon^{143}\text{Nd}_i = 2.5 \pm 0.4$, Section 5.2) (Fig. 2a). In contrast, the two ca. 2.5 Ga TTGs
228 (LP288 and LP 131) are characterized by positive but less radiogenic $\mu^{142}\text{Nd}$ (6.0 ± 1.8 to 6.0 ± 2.9 , Fig.
229 2a) and negative initial $\epsilon^{143}\text{Nd}$ at 2.5 Ga (-1.6 and -5.8).

230 The three 3.5 Ga fuchsite-bearing quartzites show positive ^{142}Nd anomalies with values of $+6.8 \pm$
231 2.8 ppm, $+8.6 \pm 3.4$ ppm and $+10.4 \pm 2.5$ ppm (Fig. 2a). These quartzites exhibit unique geochemical
232 characteristics, notably containing significantly higher Cr contents (up to 320 ppm, Liou et al., 2023)
233 compared to continental crust (59 ppm, Rudnick and Gao, 2014) and similar to concentrations found in
234 the oceanic crust (317 ppm, White and Klein, 2014). The elevated Cr concentrations are primarily
235 attributed to the presence of fuchsite, a type of Cr muscovite. These fuchsite-bearing quartzites have
236 been proposed to have been derived from peridotites by multistage processes such as serpentinization,
237 carbonation, and weathering (Austrheim et al., 2021), or by sedimentary mixing of detrital grains of
238 various origins, including detrital chromites from ultramafic rocks and detrital quartz and zircons from
239 granitic rocks (Haugaard et al., 2021). Their positive ^{142}Nd anomalies are therefore likely inherited
240 from a contemporaneous (~3.5 Ga) crustal source in the eastern NCC. However, it is important to note

241 that this conclusion must be considered an educated guess due to uncertainties in the depositional age
242 and provenance of these sedimentary rocks.

243 Lastly, the three komatiite samples from the ca. 2.7 Ga greenstone belt in the western Shandong
244 province yielded highly radiogenic $\epsilon^{143}\text{Nd}$ values of 6.9 ± 0.24 , 4.8 ± 0.28 and 8.1 ± 0.24 , but
245 non-radiogenic $\mu^{142}\text{Nd}$ values of 0.7 ± 4.8 , -0.2 ± 3.1 and $+1.6 \pm 3.3$, respectively (Fig. 2a, table 1).
246 These highly depleted ^{143}Nd signatures, combined with the lack of ^{142}Nd anomaly reflect that the
247 source of the komatiites formed after the extinction of ^{146}Sm .

248

249 4.2. U-Pb and ^{176}Lu - ^{177}Hf zircon systematics

250 Results of zircon U-Pb and Lu-Hf analyses of two Paleoproterozoic TTGs (LP288 and LP131) and
251 a Mesoarchean (3.1 Ga) granite (14CZ04-5) from the Caozhuang region are summarized in Figure 3.
252 Based on these and previous results, five stages of magmatic events can be identified in the eastern
253 Hebei region of the NCC (Fig. 3). Stage I (ca. 3.8-3.7 Ga) is witnessed by the presence of ~3.78 Ga
254 granodioritic gneisses in the eastern Hebei area (Wan et al., 2021). Stage II (3.5-3.4 Ga) has been
255 inferred from the ^{147}Sm - ^{143}Nd isochron ages of 3470 ± 59 Ma (Jahn et al., 1987) and 3509 ± 78 Ma
256 (Huang et al., 1986) for amphibolites (meta-basalts or dykes) that occur as layers or slabs in the
257 Caozhuang sedimentary sequences. Stage III (3.2-3.0 Ga) is represented by the 3.29-3.15 Ga tonalitic
258 gneisses of the Caozhuang region and the ca. 3.0-3.2 Ga xenocrysts and inherited zircon cores that
259 occur in the 2.9 Ga Caochang orthogneisses. The magmatic stage III is represented in our dataset by
260 zircons from TTG sample 15CZ04-5, which were first reported by Cui (2018) and reanalyzed here
261 (Supplementary Fig. 2), yielding a discordia line with an upper intercept of 3122 ± 11 Ma
262 (Supplementary Fig. 2). Some zircons in this sample have inherited cores crystallized between 3460

263 Ma and 3255 Ma. The $\epsilon\text{Hf}(t)$ values of the ca. 3.1 Ga zircons plot on the chondritic line, while inherited
264 cores define a trend towards negative $\epsilon\text{Hf}(t)$ indicative of an Eo/PaleoArchean precursor. All younger
265 concordant and discordant zircons plot along a line with $^{176}\text{Lu}/^{177}\text{Hf} = 0$, likely reflecting ancient
266 Pb-loss (Supplementary Fig. 1). Stage IV magmatism is mainly evident in the 2.9 Ga dioritic-tonalitic
267 rocks in the Caochang region of the eastern EH and 2.8-2.9 Ga inherited/xenocryst zircons of
268 Neoproterozoic TTG sample LP131. These inherited grains are characterized by near-chondritic to
269 subchondritic $\epsilon\text{Hf}(t)$ values (Fig. 3). Lastly, stage V magmatism is the most extensive and is
270 characterized by widespread ca. 2.5 Ga TTGs and granites as well as ultramafic-mafic volcanic rocks
271 in the region. Their zircon $\epsilon\text{Hf}(t)$ show a large scatter, and range from -13.0 to +4.6 (Fig. 3). Sample
272 LP288, which was used for ^{142}Nd analysis, shows significantly lower $\epsilon\text{Hf}(t)$ ranging from -13.0 to -6.3,
273 with one outlier at $\epsilon\text{Hf}(t) = 0$ (Fig. 3). Zircons from sample LP131 show a more complex core-rim
274 structure, with 2.9-2.8 Ga cores ranging from -3.4 to +1.2 and ca. 2.5 Ga rims ranging from +9.3 to -5.3
275 (Fig. 3).

276

277 5 Discussion

278 5.1. Preservation and crustal contamination

279 Before discussing the implications of the $^{146,147}\text{Sm}$ - $^{142,13}\text{Nd}$ systematics in the Caozhuang
280 amphibolites, it is important to assess whether these isotopic signatures may have been modified by
281 crustal contamination and post-emplacement processes such as alteration and metamorphism.
282 Following Polat and Hofmann (2003), several criteria were used to evaluate the robustness of trace
283 elements in the Caozhuang amphibolites. These include (1) the degree of correlation with the least
284 mobile element, Zr, on binary diagrams, (2) the presence of Ce anomalies on primitive

285 mantle-normalized diagrams, and (3) the presence of significant carbonate and silica enrichment (>2%).
286 Regarding the amphibolites analyzed in this study, most rare earth elements (REE) and High Field
287 Strength elements (HFSE) show strong linear correlations with Zr. The correlation coefficients are well
288 above 0.75 for Nd, Sm and the HREE, indicating the relatively low mobility of these elements
289 (Supplementary Fig. 1a-b). In contrast, the Large Ion Lithophile Elements (e.g., Sr, Rb, and Ba) show
290 considerable scatter (Supplementary Fig. 2c-e), which aligns with their susceptibility to alteration and
291 metasomatism. Finally, the CI-normalized REE profiles do not show significant Ce anomalies
292 (Supplementary Fig. 3), and the samples do not exhibit significant carbonate or silica enrichment.

293 Because evolved continental rocks possess high Zr, Nb and REE contents as well as high La/Yb
294 ratios relative to mafic/ultramafic rocks, these elements or element ratios may serve as indicators of
295 crustal contamination in mafic-ultramafic rocks. With the possible exception of sample 14CZ03-6, the
296 amphibolites in this study show no evidence of crustal contamination in the La/Yb and Nb/Yb - Zr
297 diagrams (Supplementary Fig. 1 f-g). Their overall low REE concentrations and flat REE patterns
298 (Supplementary Fig. 3), as well as the absence of xenocryst zircons, support this conclusion. In
299 addition, the $\mu^{142}\text{Nd}$ composition of the Caozhuang amphibolites shows no correlation with tracers of
300 crustal contamination (Supplementary Fig. 1h), indicating that the observed heterogeneities do not
301 result from assimilation of a preexisting crust with a positive $\mu^{142}\text{Nd}$.

302

303 5.2 Emplacement age of amphibolites of the Caozhuang region

304 The protoliths of the Caozhuang amphibolites were initially assigned an emplacement age of
305 3.5-3.6 Ga based on whole-rock ^{147}Sm - ^{143}Nd analyses (Huang et al., 1986; Jahn et al., 1987). However,
306 based on field observations, Cui et al. (2018) proposed that mafic-ultramafic enclaves of the

307 Caozhuang region can be divided into two groups; Group 1 amphibolites were found to occur as layers
308 in metasedimentary sequences, in association with banded iron formations, whereas Group 2
309 amphibolites occur as lenses or deformed dykes and sills and were never found associated with BIFs.
310 Regression of ^{147}Sm - ^{143}Nd whole-rock data based on this classification resulted in significantly
311 different ages for Group 1 and Group 2 amphibolites, with Group 1 emplaced at ca. 3.18 Ga and Group
312 2 at 3.6 Ga. Our results, however, show that both groups are heterogeneous in $^{142}\text{Nd}/^{144}\text{Nd}$ (Fig. 2b),
313 indicating differences in their initial $^{143}\text{Nd}/^{144}\text{Nd}$ composition. As a result, neither Group 1 nor Group 2
314 amphibolites can be regarded as strictly cogenetic and the age constraints derived from the
315 classification of Cui et al., (2018) may be unreliable.

316 When samples with identical $^{142}\text{Nd}/^{144}\text{Nd}$ (and thus arguably identical initial $^{143}\text{Nd}/^{144}\text{Nd}$) are
317 pooled together, the ^{147}Sm - ^{143}Nd regressions for both the P- and the D-group yield consistent ages at
318 3.0-3.1 Ga, within errors of the age of the Caozhuang granitoids, but with distinct initial $\epsilon^{143}\text{Nd}$. For
319 instance, the ^{147}Sm - ^{143}Nd results on amphibolite samples from the D-group yield an isochron age of
320 3066 ± 40 Ma (95% CI; IsoplotR Model 3; one outlier excluded, Fig. 4), with an initial $\epsilon^{143}\text{Nd}$ of $2.5 \pm$
321 0.4 ; the ^{147}Sm - ^{143}Nd results on four samples from the P-group yield an isochron age of 3036 ± 55 Ma,
322 with an initial $\epsilon^{143}\text{Nd}$ of 1.1 ± 0.6 (Fig. 4). Rather than two distinct emplacement ages, these results
323 suggest that both groups of amphibolites reported by Cui et al. (2018) originate from a single magmatic
324 event 3.0-3.1 billion years ago (Stage III), but from a heterogeneous mantle source including primitive
325 and depleted components. The previous isochron age of 3.6 Ga may thus be an artifact induced by
326 combining samples with different initial isotopic compositions in the isochron calculations. Note,
327 however, that the whole-rock isochron for the P-group is strongly constrained by one sample with low
328 Sm/Nd and possibly affected by crustal assimilation (Supplementary Figure 1). As a result, the age and

329 initial isotopic composition of the P-group amphibolites remains uncertain. In contrast, the age and
330 initial $\epsilon^{143}\text{Nd}$ obtained for the D-group amphibolites are similar to those obtained by Cui et al (2018)
331 for group 2 amphibolites, thus confirming the occurrence of a ca. 3.05 Ga magmatic event in the
332 Caozhuang region. This emplacement age is also supported by the good agreement between $\mu^{142}\text{Nd}$ and
333 initial $\epsilon^{143}\text{Nd}$ compositions, back-calculated at 3.05 Ga, for the two groups of Caozhuang amphibolites
334 (Fig. 5a). In contrast, back-calculating the initial $\epsilon^{143}\text{Nd}$ values to 3.6 Ga results in significant scatter
335 and no significant relationship is observed between $\epsilon^{143}\text{Nd}$ and $\mu^{142}\text{Nd}$ (Fig. 5b).

336

337 **5.3 Contributions of Hadean mantle domains to Archean-Paleoproterozoic crust formation and** 338 **NCC evolution**

339 Understanding the formation of granitoids requires consideration of multi-stage reworking or
340 mixing processes. Coupled in situ analyses of individual zircon grains for both U-Pb and Lu-Hf
341 systematics have allowed detailed petrogenetic histories of silicic magmas to be unraveled. In contrast,
342 the ^{147}Sm - ^{143}Nd systematics of Archean granitoids may be subject to secondary alteration due to open
343 system behavior at the mineral scale (e.g., Fisher and Vervoort, 2018). Here, we therefore combine
344 zircon Hf-Pb analysis with the more robust ^{146}Sm - ^{142}Nd systematics to elucidate the nature of magma
345 sources and the process of crustal growth and reworking in the eastern Hebei region of the NCC.

346 The granitoids used for ^{142}Nd analyses consistently show positive ^{142}Nd anomalies, indicating that
347 the protocrust from which the NCC formed was ultimately derived from ancient (> 4 Ga) depleted
348 mantle domains. The presence in the Caozhuang area of ortho-amphibolites with a depleted $^{142,143}\text{Nd}$
349 composition confirms this observation and suggests that these Hadean mantle domains contributed to
350 the production of juvenile crust in the EH until at least 3.1 Ga. The Mesoarchean granitoids (15CZ04-5

351 and 15CZ06-8) exhibit positive $\mu^{142}\text{Nd}$ values of +8.6 and +9.5 (Fig. 2a), suggesting that their mafic
352 precursors originated from the same Hadean mantle source as the D-group amphibolites. However,
353 their Hf isotopic compositions range from subchondritic to chondritic and thus show no record of this
354 early depletion event (Fig. 3). Similar inconsistencies between the zircon Hf record and bulk-rock Nd
355 isotopic compositions were also observed in the Itsaq gneisses of southwest Greenland (Bennett et al.,
356 2007; Caro et al., 2003, 2006; Fisher and Vervoort, 2018) and have been interpreted as a secondary
357 perturbation of the ^{147}Sm - ^{143}Nd system, due to open-system behavior of REE-rich accessory phases,
358 compared to the more robust Hf zircon record. However, this proposed mechanism cannot artificially
359 generate ^{142}Nd heterogeneities because ^{146}Sm became extinct ca. 4 Gyr ago and the $\mu^{142}\text{Nd}$ signature of
360 Archean TTGs is therefore insensitive to open system behavior at the mineral scale. The decoupling of
361 the two isotope systems in the NCC thus more likely reflects the fact that the Hf isotopic composition
362 of Archean granitoids does not consistently reflect mantle evolution, but rather a complex history of
363 crustal addition and reworking that differentially affects extant and extinct radioactivities (Liou et al.,
364 2022a).

365 As shown in Figure 3, multiple stages of crustal reworking in the NCC can be identified between
366 stages III and V. Stage III magmatism, represented by sample 15CZ04-5, involves the reworking of
367 ancient felsic crust, as indicated by the presence of xenocrystic zircons showing a trend of decreasing
368 $\varepsilon\text{Hf}(t)$ with time. Extrapolation of this trend suggests that this precursor formed in the Eoarchean
369 (Stage I) and reached an $\varepsilon\text{Hf}(t)$ value of ca. -7 at 3.1 Ga. The near-chondritic composition of 3.1 Ga
370 zircons in sample 15CZ04-5 (Fig. 3) is therefore best explained by addition of mantle-derived melts
371 with positive $\varepsilon^{176}\text{Hf}$ to a pre-existing NCC crust with negative $\varepsilon^{176}\text{Hf}$. The addition of juvenile material
372 at this stage is also evidenced by the depleted $^{142,143}\text{Nd}$ compositions of the 3.1 Ga Caozhuang D-group

373 amphibolites. Note that if the Eoarchean NCC crust had a positive $\mu^{142}\text{Nd}$, as suggested by the 3.6 Ga
374 quartzite results, the addition of juvenile material with an isotopic composition similar to that of the
375 D-Group amphibolites would have no effect on the ^{142}Nd composition of the newly formed crust.

376 During stage IV, crustal reworking is suggested by the scattered ϵHf values observed in the 2.9 Ga
377 zircon cores of sample LP131, as well as in other 2.9 Ga granitoids, indicating the possibility of
378 incomplete mixing between a juvenile component and older crustal material (Fig. 3). Finally, the $\epsilon\text{Hf}(t)$
379 values of the zircon cores and rims of TTG sample LP131 suggest that Stage V magmatism (2.5 Ga)
380 resulted from the abundant production of juvenile melts associated with the reworking and/or
381 assimilation of pre-existing felsic crust.

382 The Paleoproterozoic (2481 Ma) granitoid LP288 exhibits sub-chondritic initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios,
383 with $\epsilon\text{Hf}(t)$ values ranging from 0 to -13.1 and averaging at -9.0 (Fig. 3, Stage V). Given that (1) the
384 Paleoproterozoic TTG sample is characterized by much higher Na_2O content (6.86 wt.%) and
385 $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio (6.24), (2) no xenocryst zircons or inherited cores are identified within, and (3) the
386 2.48 Ga granitoids plot near the inferred felsic $^{176}\text{Lu}/^{177}\text{Hf}$ trend of 0.004. For these reasons, together
387 with the positive $\mu^{142}\text{Nd}$ values of 6.3 ± 2.9 ppm (Fig. 2a), we suggest that the 2.48 Ga magmatism
388 represented by sample LP288 is derived from the reworking of an Eo-Paleoarchean LREE-enriched
389 mafic precursor extracted from Hadean depleted mantle domains, resulting in the evolution line with
390 $^{176}\text{Lu}/^{177}\text{Hf} = 0.022$ shown in Fig. 3. The $\mu^{142}\text{Nd}$ of samples LP288 and LP131 are also identical within
391 errors, at $\mu^{142}\text{Nd} \approx +6.0$ ppm (Fig. 2a), indicating a common crustal source.

392 Overall, the combined ^{142}Nd - ^{176}Hf results indicate that, despite the absence of depleted ϵHf
393 signatures in zircons, the Hadean mantle was massively involved in the Meso-Neoproterozoic and
394 Paleoproterozoic evolutionary process leading to the formation of the NCC. This occurred by i)

395 episodic addition of juvenile melts with a positive $^{142,143}\text{Nd}$ signature, which likely began in the
396 Eoarchean and continued until at least 3.1 Ga, and ii) multistage reworking of Eo-Mesoarchean
397 protocrust, during which this ^{142}Nd anomaly was progressively transferred to younger crustal domains.

398

399 **5.4 Coupled $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ chronometry**

400 Due to the short lifetime of ^{146}Sm ($t_{1/2} = 103$ Ma), the presence of positive ^{142}Nd anomalies in the
401 D-group Caozhuang amphibolites indicates that their mantle source differentiated prior to 4.0 Gyr ago
402 (Fig.). The differentiation time and time-integrated $^{147}\text{Sm}/^{144}\text{Nd}$ of their source can be further
403 constrained by coupled $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ chronometry, assuming a two-stage model as a first-order
404 approximation of its evolution (see the Appendix 2). The first stage corresponds to the evolution of a
405 primitive reservoir between the origin of the solar system at ca. 4.57 Ga (t_0) and a differentiation event
406 at t_d , which for simplicity is considered to be instantaneous. This event produces an early depleted
407 mantle (EDM) characterized by low LREE content and high Sm/Nd. The second stage represents the
408 period separating this event from the time when the EDM melted to produce mafic rocks of the
409 Caozhuang region 3.1 Gyr ago.

410 Results from the two-stage model show that the depleted mantle source of the D-group
411 amphibolites differentiated $4.44_{-0.07}^{+0.05}$ Gyr ago, with a corresponding $^{147}\text{Sm}/^{144}\text{Nd}$ source ratio of 0.211
412 ± 0.002 (Fig. 6c). Assuming a slightly superchondritic $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.2008 for the Bulk Silicate
413 Earth (Caro et al., 2008; Caro and Bourdon, 2010; Johnston et al., 2022; Frossard et al., 2022) would
414 translate into an older $^{142,143}\text{Nd}$ model age of $4.51_{-0.07}^{+0.05}$ Ga. These age constraints are consistent with
415 those inferred from other Archean terranes characterized by positive ^{142}Nd anomalies (with the
416 exception of the Singhbhum granitoids; Maltese et al., 2022). In particular, similar model ages and

417 time-integrated Sm/Nd were obtained from metasediments (Caro et al., 2006) and amphibolites of the
418 Isua supracrustal belt (O'Neil et al., 2016; Rizo et al., 2011; Saji et al., 2018), the Nulliak ultramafic
419 rocks of the Saglek block (Morino et al., 2017), and the 2.7 Ga Theo's Flow in the Abitibi Greenstone
420 belt (Debaille et al., 2013) (Fig. 6 a-c). These concordant results suggest that these mantle-derived
421 rocks, with ages ranging from 3.8 to 2.7 Ga, originated from a common reservoir that differentiated
422 shortly after the Moon-forming impact and was preserved from rehomogenization on a timescale of
423 several billion years.

424

425 **5.5 Significance of the ^{142}Nd record for Hadean-Archean geodynamics**

426 A classic interpretation of the ^{142}Nd record is that primordial heterogeneities were gradually
427 homogenized during the Archean as a result of crustal recycling and/or convective stirring (e.g., Hyung
428 and Jacobsen, 2020; Rosas and Korenaga, 2018). A critical aspect of these models, however, is that
429 they rely on global compilations of ^{142}Nd data (Fig. 7a) that are strongly biased in favor of the
430 Eoarchean, due in particular to the large number of data published on the Isua Supracrustal Belt (ISB).
431 As a result, the assumption that ^{142}Nd anomalies decrease with time relies for the most part on highly
432 radiogenic values (up to +18 ppm) reported for some Isua amphibolites and on the less scattered but
433 sparse ^{142}Nd data for Neoproterozoic and Mesoproterozoic rocks (Fig. 7a).

434 The majority of ^{142}Nd data on ISB mantle-derived rocks (amphibolites) comes from 5 datasets,
435 whose results are summarized in Fig. 8a (Saji et al. 2018; Rizo et al. 2011, 2013; Caro et al 2006;
436 O'Neil et al. 2016). It must be kept in mind that these data are from amphibolite groups that differ in
437 age, location, and composition within the ISB and thus are unlikely to originate from a compositionally
438 homogeneous mantle reservoir. Nevertheless, all datasets are in excellent agreement, averaging $+10.6 \pm$

439 2.0 ppm (2 S.D.), which is similar to the composition of the D-group Caozhuang amphibolites, Nulliak
440 and Theo's flow (Fig. 8a). In contrast, these datasets differ in terms of sample dispersion (Fig. 8b),
441 ranging from ± 1.4 ppm (2 S.D.; N=7; Saji et al., 2018) to ± 9 ppm (2 S.D.; N=16; Rizo et al., 2011).
442 Most importantly, these datasets also differ in terms of the reproducibility of the ^{142}Nd measurements.
443 As shown in Fig. 8b, the analytical error estimated from repeated standard measurements for the five
444 ISB datasets varies between ± 2 and ± 6 ppm (2 S.D.) and correlates positively with sample dispersion.
445 This observation holds for the majority of Archean ^{142}Nd studies, where sample dispersion is typically
446 within $\pm 30\%$ of analytical reproducibility (Fig. 8b). Thus, the heterogeneity of the Archean ^{142}Nd
447 record, including the ISB, appears to be primarily analytical in nature, and caution should be exercised
448 when evaluating geodynamic parameters based on the apparent dispersion in global compilations of
449 ^{142}Nd data (Fig. 7). When limited to studies with an external precision of < 4 ppm (2 S.D.), the database
450 for Archean mantle-derived rocks shows no conclusive evidence for a more heterogeneous mantle in
451 the Eoarchean or a progressive homogenization of positive ^{142}Nd anomalies (Fig. 7b). Models that use
452 an unfiltered ^{142}Nd database (e.g., Fig. 7a) to quantify mixing and/or recycling rates for the Archean
453 mantle are therefore likely to overestimate the isotopic heterogeneity of the Eoarchean mantle and the
454 rate at which primordial heterogeneities were destroyed.

455 Assuming that the EDM composition is representative of the Archean convective mantle, its
456 apparent evolution in closed-system (Fig. 6a-c) would imply limited crustal recycling and/or inefficient
457 homogenization of recycled crustal material. Such long-term isolation may imply that, if there are any
458 links between the efficiency of crustal recycling and the tectonic regimes of early Earth, the eventual
459 emergence of plate tectonics should be postponed to 2.7 Ga or later. However, the current Archean
460 ^{142}Nd record provides little support for this hypothesis. For instance, mantle-derived rocks of tholeiitic

461 affinity from the Nuvvuagittuq and Ukaliq supracrustal belts (3.5-3.8 Ga; NE Superior Province,
462 O'Neil et al., 2008, 2016; Caro et al., 2017) typically cluster around $\mu^{142}\text{Nd} \approx 0$ and show no evidence
463 for an EDM contribution. Mafic rocks in the Nuvvuagittuq and Ukaliq belts show striking similarities
464 to modern arc lavas, suggesting their protoliths formed in a subduction-like context (Caro et al., 2017;
465 Grocolas et al., 2022). The absence of a depleted mantle component in such context contrasts with
466 modern plate-tectonic settings where arc lavas are characterized by predominantly positive $\varepsilon^{143}\text{Nd}$ and
467 ε^{Hf} , reflecting a ubiquitous depleted mantle contribution mixed with slab-derived Hf-Nd to arc
468 magmatism (e.g., Collins et al., 2011). On a larger scale (Fig.), Archean terranes and cratons
469 worldwide also show no evidence of mixing between isotopically enriched ($\mu^{142}\text{Nd} < 0$) and depleted
470 ($\mu^{142}\text{Nd} > 0$) material but appear to be characterized by $\mu^{142}\text{Nd}$ compositions that range from either 0 to
471 positive values (North China craton, North Atlantic craton, Singbhum craton) or from 0 to negative
472 values (Acasta gneiss complex, Innuksuaq gneiss complex, Kaapvaal craton). Collectively, these
473 observations suggest that the $\mu^{142}\text{Nd}$ composition of the prevailing Archean mantle may have been
474 distinct from that of the EDM, perhaps close to $\mu^{142}\text{Nd} = 0$ as early as 3.8 - 4.0 Ga.

475 The formation of depleted mantle domains throughout geological times is classically considered
476 to be the result of melt extraction at uppermost mantle pressures, leading to the formation of a
477 chemically depleted convective upper mantle and a more primitive lower mantle. However, the
478 formation of deep, depleted reservoirs isolated from a more primitive convective mantle is a plausible
479 outcome of magma ocean crystallization (e.g., Caro et al., 2005; Boyet et al., 2021). Such reservoirs
480 could result from the gravitational overturn of an unstable stratification causing shallow, Fe-rich
481 cumulates to be returned to the deep mantle, where they may survive for billions of years (Ballmer et
482 al., 2017). Alternatively, the formation of a basal magma ocean (BMO) was predicted based on the

483 presence of a density crossover between crystals and melts at pressures above ~50 GPa (Labrosse et al.,
484 2007; Caracas et al., 2019). As the BMO cooled, Fe and incompatible elements would have partitioned
485 into the remaining melt, producing a depleted cumulate near the core-mantle boundary. If the
486 cumulates crystallizing from the BMO are positively buoyant, their entrainment in mantle upwellings
487 could explain the formation of crustal terranes with positive ^{142}Nd anomalies as well as the apparent
488 closed-system evolution of the EDM.

489 Beyond these speculative scenarios, the ubiquity of ^{142}Nd anomalies in conjunction with the
490 apparent isotopic dichotomy of Archean cratons indicates that destabilization and reworking of
491 primordial Hadean silicate reservoirs played a crucial role in crust formation at least until ~ 3 Gyr ago.
492 The absence of positive ^{142}Nd anomalies post-Archean mantle-derived rocks may indicate the eventual
493 exhaustion of deep depleted reservoirs, their homogenization in the convective system, or a transition
494 from plume-dominated crust-forming processes to modern plate tectonics. Given the limited $^{142,143}\text{Nd}$
495 database for Neoproterozoic and Proterozoic mantle-derived rocks, none of these scenarios can be
496 completely ruled out. However, our results show that the commonly held assumption that positive
497 ^{142}Nd anomalies were gradually homogenized by convection and recycling during the Archean is
498 currently not supported by observations. The possibility that the EDM separated early from the
499 convective system should therefore be considered.

500

501 **6 Conclusion**

502 The $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ and zircon ^{176}Lu - ^{176}Hf systematics of Archean sedimentary rocks,
503 granitoids and mantle-derived rocks, representing the main lithologic units of the eastern NCC, were
504 investigated. The main conclusions of this study can be summarized as follows:

505 (1) Despite the absence of depleted $\epsilon\text{Hf}(t)$ compositions in granitoid zircons, rocks from the EH
506 region show a ubiquitous positive ^{142}Nd anomaly, suggesting that Hadean mantle domains were
507 involved in the formation of the NCC from 3.7-3.8 Ga until at least 3.1 Ga. The apparent decoupling of
508 the ^{142}Nd and ^{176}Hf signals reflects the multi-stage reworking of Eo-Mesoarchean crust, during which
509 this ^{142}Nd anomaly was gradually diluted by the addition of juvenile material and transferred to
510 younger crustal rocks.

511 (2) Application of coupled $^{142,143}\text{Nd}$ chronometry to the 3.1 Ga Caozhuang amphibolites originally
512 described by Cui et al. (2018) yielded a two-stage model age of $4.44^{+0.05}_{-0.07}$ Ga, with a $^{147}\text{Sm}/^{144}\text{Nd}$
513 source ratio of 0.211 ± 0.002 . These estimates are identical to those obtained from other Archean
514 mantle-derived rocks with ages between 2.7 and 3.8 Ga, suggesting that their parental melts originated
515 from a common mantle reservoir that differentiated shortly after the Moon-forming impact and
516 subsequently evolved in closed system until at least 2.7 Ga.

517 (3) The high degree of isotopic heterogeneity observed in Eoarchean rocks appears to be largely
518 analytical in nature and thus does not provide conclusive evidence that the Eoarchean mantle was more
519 depleted and/or heterogeneous compared to the late Archean period. Accordingly, the generally
520 accepted notion that positive ^{142}Nd anomalies were homogenized by convection and recycling during
521 the Archean should be reconsidered.

522 (4) The apparent closed-system evolution of the EDM, combined with the isotopic dichotomy of
523 Archean cratons, suggests that Hadean depleted domains remained convectively isolated after magma
524 ocean crystallization and that their eventual destabilization was an important process of crust formation
525 in the Archean.

526

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535

536 **Figure captions**

537 **Fig. 1** Geological map of the Eastern Hebei (EH) region of the North China Craton (NCC). The inset
538 shows the location of the (EH) and Western Shandong region (WS) in the NCC, and the distribution
539 map of three ancient terranes (>2.6 Ga) from [Wan et al., \(2015\)](#). The areas circled by thick dashed lines
540 counterclockwise are the Eastern Ancient Terrane (EAT), the Central Ancient Terrane (CAT), and the
541 Southern Ancient Terrane (SAT), respectively. The blue stars represent the sampling locations.
542 Amphibolites from the Primitive, Depleted Group and Cumulate Group, as well as the Caozhuang
543 Quartzites and the Caozhuang Granites were sampled in the Caozhuang region. The 2.5 Ga granitoids
544 were sampled in the Caochang region of west EH. The komatiites were sampled in the Mengyin region
545 in the WS.

546

547 **Fig. 2** (a) $\mu^{142}\text{Nd}$ values of whole-rocks for the NCC samples and JNdi standard analyzed in study. The
548 horizontal grey band represents the reproducibility (2 S.D.) of the standard analyses (shown as light

549 grey circles). Error bars for individual data points are expressed as 2 S.E., while the mean values of two
550 or more replicates are assigned an error of ± 2.2 ppm (2 S.D.), which corresponds to the external
551 precision estimated from the standard analyses. (b) Diagram of MgO versus $\mu^{142}\text{Nd}$ for mafic and
552 ultramafic rocks analyzed in this study. The classification of Cui et al. (2018) based on field
553 observations is shown for comparison. With the exception of samples 15CZ06-1 and 14CZ03-6,
554 amphibolites from the D-Group correspond to amphibolites of Group 2 of Cui et al (2018), while
555 amphibolites from the P-Group correspond to Cui et al's Group 1. Note that 14CZ03-6 may be affected
556 by crustal contamination.

557

558 **Fig. 3** Compilation of in situ zircon Lu-Hf isotope analyses in the study area in the EH, NCC. The gray
559 bands labeled Stage I to V represent the magmatic events identified so far in the NCC. These occurred
560 at 3.8-3.7 Ga (Stage I; [Wan et al., 2021](#)), 3.5-3.4 Ga (Stage II; e.g., [Jahn et al., 1987](#); [Wang et al., 2019](#)),
561 3.0- 3.1 Ga (Stage III; this study, [Nutman et al., 2011](#)), 2.9-2.8 Ga (Stage IV; [Liou and Guo, 2019](#); [Liou](#)
562 [et al., 2019](#)), and 2.6-2.5 Ga (Stage V; e.g., [Bai et al., 2016](#); [Guo et al., 2017](#)).

563

564 **Fig. 4** ^{147}Sm - ^{143}Nd isochron diagrams for amphibolites of the Depleted Group (a) and Primitive Group
565 (b) in the eastern Hebei province, NCC.

566

567 **Fig 5.** $\mu^{142}\text{Nd}$ versus initial $\epsilon^{143}\text{Nd}$ compositions for amphibolites from the Caozhuang region. Initial
568 $\epsilon^{143}\text{Nd}$ values are calculated for each individual sample assuming a crystallization age of (a) 3.05 Ga
569 and (b) 3.6 Ga. Model ages (solid lines) and time-integrated $^{147}\text{Sm}/^{144}\text{Nd}$ source ratios (dashed curves)
570 were calculated using a two-stage evolution model (Section 5.4.) assuming a chondritic $^{147}\text{Sm}/^{144}\text{Nd}$

571 ratio of 0.1960 for the Bulk Silicate Earth. Assuming a slightly non-chondritic composition for the BSE
572 (Johnston et al., 2022) would shift the reference isochrons to the right of the diagram, thus yielding
573 older model ages. Note that one outlier has been excluded from the average value of the D-group
574 amphibolites in panel (a).

575

576 **Fig. 6** (a-b) Compiled $\mu^{142}\text{Nd}$ and $\epsilon^{143}\text{Nd}$ data for Isua, Nulliak, Caozhuang, and Theo's flow. The green
577 curves represent the evolution of a depleted mantle reservoir with $^{147}\text{Sm}/^{144}\text{Nd}=0.211$, assuming
578 instantaneous differentiation at $T_d=4.4$ Ga. The purple curves represent the evolution of the depleted
579 mantle in the two-box model of [Rosas and Korenaga \(2018\)](#). The model assumes rapid extraction of a
580 continental mass similar to the present one about 4.4 to 4.5 Gyr ago, followed by a steady state
581 evolution in which the production of new crust is balanced by recycling, eventually leading to
582 homogenization of the Archean mantle. Despite the possibility of more complex evolution scenarios,
583 the $^{142,143}\text{Nd}$ data are consistent with a simple two-stage evolution model. This observation confirms the
584 accuracy of model ages inferred from coupled $^{146,147}\text{Sm}-^{142,143}\text{Nd}$ systematics. (c) Coupled $^{146,147}\text{Sm}-$
585 $^{142,143}\text{Nd}$ systematics of the Caozhuang amphibolites. The model age obtained from the D-group
586 amphibolites is in agreement with those obtained from metasediments ([Caro et al., 2006](#)) and
587 amphibolites ([O'Neil et al., 2016](#); [Rizo et al., 2011](#); [Saji et al., 2018](#)) of the Isua supracrustal belt, the
588 Nulliak ultramafic rocks of the Saglek block ([Morino et al., 2017](#)), and the 2.7 Ga Theo's flow (Abitibi)
589 ([Debaille et al., 2013](#), [Morino et al., 2017](#)).

590

591 **Fig. 7** (a) A global compilation of the Archean ^{142}Nd dataset. Mafic/ultramafic rocks showing resolved
592 positive ^{142}Nd anomalies are shown as colored symbols. The dark and light gray horizontal bands

593 represent the minimum and maximum analytical error reported in the literature. Data are from Bennett
594 et al., (2007), Boyet et al., (2021), Caro et al., (2006, 2017), Debaille et al., (2013), Li et al., (2017),
595 Hasenstab-Dübeler et al., (2022), Maltese et al., (2022), Maya et al., (2016), Murphy et al., 2021;
596 Morino et al., (2017), O'Neil et al., (2012, 2016), O'Neil and Carlson (2017), Puchtel et al., (2013, 2016,
597 2018), Reimink et al., (2018), Reimink et al., (2020), Rizo et al., (2011, 2013), Roth et al., (2014), Saji
598 et al., (2019), Schneider et al., (2018), Wang et al., (2023), Wasilewski et al., (2022) and this study. (b)
599 Compilation of ^{142}Nd data for Archean mantle-derived rocks showing only studies with an external
600 error of < 4 ppm (2 S.D.) (Bennett et al., 2007, Caro et al., 2006, 2017, Debaille et al., 2013, Morino et
601 al., 2017, Murphy et al., 2021, Puchtel et al., 2013, 2016, 2018; Saji et al., 2019, and this study).

602

603 **Fig. 8** (a) Compiled ^{142}Nd data for Isua metabasalts (from left to right: Saji et al., 2018, Rizo et al. 2011,
604 Rizo et al. 2013, O'Neil et al. 2016, Caro et al. 2006). Crosses represent individual samples. The blue
605 circles represent the average for each dataset and the error bars represent the sample dispersion
606 expressed as 2 S.D. The results obtained for Theo's Flow (Debaille et al., 2013), the Caozhuang (this
607 study) and Nulliak (Morino et al., 2017) mafic-ultramafic rocks are shown for comparison; (b) Sample
608 dispersion vs analytical reproducibility for this and previous studies of Archean mafic/ultramafic rocks.
609 The straight line corresponds to $2 \text{ S.D.}_{\text{samples}} = 2 \text{ S.D.}_{\text{standards}}$. The dashed lines represent a $\pm 30\%$
610 deviation from the 1:1 line. Note that mafic/ultramafic rocks from the Nuvvuagittuq and Ukaliq
611 supracrustal belts show significant excess scatter ($2 \text{ S.D.}_{\text{sample}} = 13 \text{ ppm}$) reflecting either in situ decay
612 of ^{146}Sm (O'Neil et al., 2008) or a heterogeneous mantle source (Caro et al., 2017). The heterogeneous
613 nature of the Caozhuang mantle is also reflected in significant excess scatter relative to standard
614 analyses. Other datasets show no or limited excess scatter, with $2 \text{ S.D.}_{\text{samples}}$ typically within $\pm 30\%$ of 2

615 S.D_{standards}. The grey circles show the analytical and sample dispersion reported in other studies of
616 Archean mafic/ultramafic rocks (Boyet et al., 2021; Maltese et al., 2022; Maya et al., 2016; Morino et
617 al, 2017; Murphy et al 2021; Puchtel et al., 2013, 2016, 2018).

618

619 **Fig. 9** histograms of ¹⁴²Nd data for the main Archean cratons, including all rock types except
620 sedimentary rocks. Data sources: North China craton: Li et al. (2017) and this study. Singhbhum craton:
621 Maltese et al. (2022). North Atlantic craton: Bennett et al (2007); Caro et al. (2006); Morino et al.
622 (2017); O'Neil et al. (2016); Rizo et al. (2011, 2013). Kaapvaal craton: Boyet et al. (2021); Puchtel et al.
623 (2013, 2016); Schneider et al. (2018). NE Superior craton: Caro et al. (2017); O'Neil and Carlson
624 (2017); O'Neil et al. (2012). Acasta gneiss complex: Reimink et al. (2018), Roth et al. (2014).

625

626 **Supplementary Material**

627 **Supplementary Fig. 1** Diagrams of Zr versus selected elements or element ratios to evaluate the effects
628 of post-magmatic alteration (a–e) and crustal contamination (f-g) for the amphibolites analyzed in this
629 study. The blue squares represent compositions of the BSE (Palme and O'Neill, 2014). Most REEs (e.g.,
630 Sm and Nd) exhibit strong linear correlations with correlation coefficients well above 0.75 (a-b),
631 indicating relatively low mobility of these elements. In contrast, the LILEs (e.g., Sr, Ba, and Rb) show
632 considerable scatter (c-e), which aligns with their susceptibility to fluid circulation; (f-g) Plots of La/Yb
633 and Nb/Yb versus Zr to assess the contamination of the amphibolites by evolved crustal components.
634 The geochemical composition of the contaminant is represented by the crustal endmember of the ca.
635 3.8 Ga granitoids in the study region reported by Wan et al., (2021); (h) plot of La/Yb versus $\mu^{142}\text{Nd}$.
636 No obvious correlation can be seen, indicating that the range in $\mu^{142}\text{Nd}$ of the amphibolites cannot be

637 explained by crustal contamination of ancient felsic crust with positive $\mu^{142}\text{Nd}$.

638

639 **Supplementary Fig. 2** (a-b) Diagrams of zircon U-Pb ages and zircon Lu-Hf isotope data v.s. apparent

640 $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the Mesoarchean granitoid (15CZ04-5). (c) Diagrams of zircon U-Pb ages of the

641 Mesoarchean granitoid (15CZ06-8). In situ zircon U-Pb ages were analyzed using a Cameca

642 SIMS-1280 at IGGCAS. Zircon Lu-Hf isotopes were measured using a Geolas-193 laser-ablation

643 system attached to a Thermo Neptune Plus multicollector ICP-MS equipped in the same institute. The

644 zircon U-Pb and Lu-Hf isotopic data have been reported by [Cui \(2018\)](#). These samples were reanalyzed

645 for the purpose of this study, and a revised interpretation based on this new dataset is presented in

646 section 5.3.

647

648 **Supplementary Fig. 3** Chondrite-normalized Rare Earth Element (REE) profiles of (a) D-group

649 amphibolites, (b) P-group amphibolites and (c) hornblendites from the Caozhuang region. CI

650 normalization values are from [McDonough and Sun \(1995\)](#).

651

652 **Supplementary Table 1:** ^{142}Nd analyses (standards).

653 **Supplementary Table 2:** ^{142}Nd analyses (samples).

654 **Supplementary Table 3:** ^{143}Nd analyses (samples and standards)

655 **Supplementary Table 4:** Compilation of zircon U-Pb-Hf data in Fig. 3.

656

657 **Appendix 1:** Analytical techniques.

658 **Appendix 2:** Coupled $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ systematics.

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