1 **Paleomagnetism of Mesoproterozoic margins of the Anabar Shield: A**
2 **hypothesized billion-year partnership of Siberia and northern**
3 **Laurentia**

4

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19

20 **ABSTRACT**

21 Siberia and Laurentia have been suggested as near neighbors in
22 Proterozoic supercontinents Nuna and Rodinia, but paleomagnetic
23 evidence has been sparse and ambiguous. Here we present four new
24 paleomagnetic poles from undeformed Paleo-Mesoproterozoic (lower
25 Riphean) sedimentary rocks and mafic intrusions of the northwestern
26 Anabar uplift in northern Siberia. Combining these results with other
27 Proterozoic data from Siberia and Laurentia, we propose a tight
28 juxtaposition of those two blocks (Euler parameters 77°, 098°, 137° for
29 Anabar to North America) spanning the interval 1.7–0.7 Ga, constituting a

30 long-lived connection that outlasted both the Nuna and Rodinia
31 supercontinental assemblages.

32

33 **INTRODUCTION**

34 Proterozoic continental reconstructions are crucial for understanding
35 long-term Earth history, but their development has occurred over decades
36 with some major components yet unresolved, including precise
37 configurations of the supercontinents Nuna and Rodinia (reviewed by
38 Evans, 2013). Paleomagnetic data are an integral component of such
39 reconstructions, but the Proterozoic database has been dominated by
40 results from Laurentia and Baltica (Buchan, 2013). The present study
41 addresses reconstruction of Siberia, one of the major Proterozoic cratons.
42 Siberia's paleogeographic relationship to Laurentia has been contentious,
43 with juxtapositions ranging from Laurentia's western margin (Sears and
44 Price, 1978, 2000, 2003) to its northern margin in a variety of orientations
45 (Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Rainbird et al.,
46 1998).

47 In the past 15 years, paleomagnetic data have strongly supported a mid-
48 Proterozoic location of Siberia near Laurentia's northern margin, such that
49 southern Siberia faced northern Laurentia (Gallet et al., 2000; Ernst et al.,
50 2000; Pavlov et al., 2002; Metelkin et al., 2007; Wingate et al., 2009;
51 Didenko et al., 2009). An unresolved issue is whether such a fit is loose, in
52 which the two cratons were separated by several thousand km (Pisarevsky
53 and Natapov, 2003; Pisarevsky et al., 2008) or tight (Pavlov et al., 2002;
54 Metelkin et al., 2007; Evans and Mitchell, 2011). The loose-fit hypothesis
55 is inspired primarily due to a perceived incongruity between 1.1-1.0 Ga
56 poles from the two cratons, but as will be described further, such a
57 conclusion rests on ages of Siberian sedimentary strata with rather poor
58 constraints. Evans and Mitchell (2011) proposed the two cratons to be
59 tightly joined in Nuna but separating through the interval 1.38-1.27 Ga—
60 the era of numerous mafic intrusive events throughout Laurentia, Siberia,
61 and neighboring Baltica—to achieve the more distant relative position
62 apparently required by the 1.1-1.0 Ga poles. Nonetheless, the matching
63 LIP “barcode” record spanning 1.7-0.7 Ga from Laurentia and Siberia

64 (Gladkochub et al., 2010a; Ernst et al., 2016a) may alternatively suggest a
65 tight fit between the two blocks enduring as late as 0.7 Ga. A relative lull in
66 tectonic activity or sedimentary record (e.g. passive margins) in southern
67 Siberia throughout that interval could also suggest that margin's location
68 within a continental interior (Gladkochub et al., 2010b). It is more difficult
69 to apply the same test to northern Laurentia, because that margin is
70 largely covered by Phanerozoic strata (e.g., Kerr, 1982).

71

72 The purpose of this paper is to report new paleomagnetic data from nearly
73 pristine igneous and sedimentary rocks of the Anabar uplift in northern
74 Siberia, to assess the aggregate paleomagnetic record of Siberia and
75 Laurentia in Proterozoic time, and to propose a new, static configuration
76 between the two blocks that honors both the geologic and paleomagnetic
77 datasets. Preliminary data from some of the sites described herein were
78 reported by Veselovskiy et al. (2009), but our present contribution
79 supersedes the western and northern Anabar datasets reported in that
80 earlier paper.

81

82 **GEOLOGIC SETTING**

83 The Siberian craton, which assembled at about 1900 Ma (Rosen, 2003), is
84 largely covered by Phanerozoic sedimentary rocks. Precambrian rocks,
85 both crystalline and sedimentary, are exposed around the craton's margins
86 as well as two shield areas or uplifts: Anabar in the northwest, and Aldan
87 in the southeast (Figure 1). Both shield areas (i.e., exposed crystalline
88 basement) are mantled by sedimentary cover and inferred to represent
89 larger, internally coherent blocks. Whereas the Aldan block exposes much
90 of its pre-Phanerozoic basement architecture, the Anabar block is almost
91 entirely covered. In the north-central Anabar block, a gentle domal uplift
92 exposes the Anabar Shield and an annular ring of Mesoproterozoic
93 (Riphean) sedimentary rocks that are invaded by numerous mafic
94 intrusions. Geophysical surveys (e.g., Rosen et al., 1994; Glebovitsky et al.,
95 2008) extend the inferred basement architecture of the Anabar block
96 beyond its uplifted shield regions, under its sedimentary cover (also
97 described by Pisarevsky et al., 2008). There is increasingly compelling

98 paleomagnetic evidence for a 20-25° relative rotation between the Anabar
99 and Aldan blocks during Devonian formation of the Vilyuy rift system
100 (Pavlov and Petrov, 1997; Smethurst et al., 1998; Gallet et al., 2000, Pavlov
101 et al., 2008). Aside from this deformation, the Siberian cratonic interior
102 has remained tectonically stable other than emplacement of Devonian-
103 Triassic kimberlites and the particularly voluminous Permian-Triassic
104 “traps” (largely mafic, both extrusive and intrusive; Nikishin et al., 2010).

105 The Anabar uplift, which is the study area of this work, is a broad cratonic
106 arch with Paleoproterozoic crystalline basement (shield) encircled by
107 nonconformably overlying, nearly horizontal and regionally
108 unmetamorphosed, Paleo-Mesoproterozoic sedimentary rocks (Figure 1).
109 The sedimentary succession begins with clastic strata of the Mukun Group,
110 transitioning upsection to carbonates of the Billyakh Group (Figures 1, 2).
111 The lowest clastic layers contain detrital zircons as young as 1681 ± 28 Ma
112 ($n=8$; Khudoley et al., 2015), providing a maximum constraint for the onset
113 of sedimentation. Mafic sills intrude the stratigraphy at several levels, and
114 there are numerous mafic dykes as well. The most common ages for dated
115 intrusions are ca. 1500-1470 Ma (reviewed by Gladkochub et al., 2010a;
116 new data presented in Ernst et al., 2016b), the latter figure being shared by
117 mafic magmatism in the Olenëk uplift about 600 km to the east (Wingate
118 et al., 2009); but many Anabar intrusions are suspected to be related to the
119 Permian-Triassic traps (Bogdanov et al., 1998).

120

121 **METHODS**

122 In this study, paleomagnetic samples were collected from both the lower
123 clastic and upper carbonate stratigraphic units of the Riphean succession,
124 and from numerous mafic intrusions, some of them directly dated by U-Pb
125 ages on baddeleyite (Ernst et al., 2016b). We report data from six raft
126 trips in the northern flank (Fomich River) and western flank (Kotuy,
127 Dzhogdzhoh, Magan, Ilya, and Kotuykan Rivers) of the Anabar dome, where
128 strata everywhere dip less than 5 degrees. The sites were mainly block-
129 sampled, except for portable-drilled samples on the upper reaches of the
130 Kotuykan River. Orientation was achieved by magnetic compass and
131 clinometer, occasionally supplemented by solar compass and indicating

132 local magnetic variations that match expected IGRF values to within a few
133 degrees. Representative samples from a subset of the sites were
134 investigated by optical and scanning-electron microscopy.

135 Demagnetization was performed within shielded chambers in the
136 following paleomagnetic laboratories: Institute of Physics of the Earth
137 (Moscow), Institut de Physique du Globe (Paris) and Yale University (New
138 Haven). Following measurement of the natural remanent magnetization
139 (NRM), all samples were thermally demagnetized up to 580-680°C with an
140 average of 12-15 steps to isolate the components of the natural remanent
141 magnetization. The measurements were made using a 2G-Enterprise
142 cryogenic magnetometer (Paris, Yale), and an AGICO JR-6 spinner
143 magnetometer (Moscow); heating was done in homemade non-magnetic
144 ovens (Paris), a MMTD-80 (Magnetic Measurements Ltd.) thermal
145 demagnetizer (Moscow), and a TD-48 (ASC Scientific) thermal
146 demagnetizer (Yale). Some specimens were pre-treated by low-
147 temperature immersion in liquid nitrogen to remove multi-domain
148 magnetic components (Borradaile et al., 2004), but we found that such
149 procedure had little effect on the quality of data acquired during the
150 subsequent high-temperature demagnetization. Directional data were fit
151 in almost all cases with least-squares lines, but occasionally least-squares
152 planes or great circles, according to routines developed by Kirschvink
153 (1980) and Enkin (1994). Reconstructions were made using the GPlates
154 freeware package (Williams et al., 2012).

155

156 **RESULTS**

157 About half of the samples yielded well resolved components of the NRM
158 (Table 1). Most of those samples contained only one or two components
159 (Figures 3-6), with one clearly defined characteristic remanence
160 magnetization (ChRM). Within the sedimentary rocks distant to mapped
161 intrusions, which were red-colored, unblocking temperatures extend as
162 high as ~680°C, indicating near-stoichiometric hematite as the remanence
163 carrier (Figure 3). Within mafic rocks, unblocking temperatures extend as
164 high as ~580°C, indicating low-Ti titanomagnetite as the carrier (Figures
165 4-6). Some mafic specimens display two components of magnetization

166 that are nearly antipodal, (e.g., Fomich site 17, Dzhogdzhho trap sites 9-07
167 and 13-00) indicating either intrinsic self-reversal behavior (e.g., Krása et
168 al., 2005; Gapeev and Gribov, 2008), remanence acquisition over a
169 protracted interval of time spanning a geomagnetic field reversal, or a
170 spurious artifact associated with stepwise heating (Shcherbakov et al.,
171 2015).

172 Site-mean directions are listed in Table 1. We applied data quality filters
173 on the number of least-squares lines and/or circles (the latter counting
174 half, total per site >4) and Fisher's (1953) 95% confidence radius (α_{95}
175 <20°). Characteristic remanence directions vary according to lithology
176 (Figure 7). Sedimentary rocks that are distant (i.e., more than a few
177 hectometers) to mapped intrusions, in general, yield either S-down or N-
178 up ChRMs. There is a systematic shift in declination between the lower
179 sedimentary horizons and the upper units, but the directional shift does
180 not occur along the boundary between the Mukun and Billyakh Groups.
181 Instead, the shift is localized between the Burdur and Labaztakh
182 Formations, within the upper part of the Mukun Group, where a
183 disconformity is recognized regionally (Figure 2). The "older sedimentary"
184 directional group contains only one polarity, whereas the "younger
185 sedimentary" group contains two polarities.

186 Within intrusive units, ChRMs fall into four distinct groups: (1) a steep,
187 two-polarity group with W-up and E-down directions, (2) a moderate-
188 inclination component with mainly N-down directions but a single site of
189 opposite S-up polarity, (3) a shallow NE direction, mainly downward, from
190 the Fomich River, and (4) a shallow SW direction, upward, from the
191 western Anabar region plus the stratigraphically uppermost site of Fomich
192 River. Group 1 likely represents intrusions from the Permian-Triassic
193 Siberian trap large igneous province, based on similarity of directions to
194 published results (Pavlov et al., 2011). Group 2 is termed the "enigmatic"
195 component, and will be discussed at length, below. Groups 3 and 4 are
196 broadly antipodal, but a formal significance test (McFadden and McElhinny,
197 1990) reveals that antiparallelism can be rejected at the 95% confidence
198 level (i.e., the two groups "fail" the reversal test by standard measure;
199 although they are within antiparallelism at slightly more lax 99%
200 confidence limits). Some of the departure from antipolarity is due to a

declination offset, which may be tempting to interpret as due to vertical-axis rotation between the west Anabar and Fomich areas, but continuity of exposure and near-horizontality of strata in both regions argue against such an interpretation. In addition, the lone Group 4 direction (SW-up) from Fomich has similar declination to the remainder of Group 4 directions from west Anabar. An alternative explanation for the negative reversal test is a significant age difference between the two polarities of remanence, with Siberian plate motion during the intervening time interval. Two U-Pb dated sills with the Group 4 remanence in west Anabar have ages of 1503 ± 2 and 1502 ± 2 Ma, whereas the Group 3 sill in Fomich area has a U-Pb age of 1483 ± 17 Ma (Ernst et al., 2016b). Following this interpretation, we treat the Group 3 and 4 directions as distinct from each other in our analysis.

214

215 **BAKED-CONTACT TESTS**

216 We performed several baked-contact tests (BCTs), to the extent allowable
217 by available outcrops along the rivers.

218 (1) Fomich River, site 3-04. A 50m-wide dyke, and Burdur Formation
219 sedimentary rocks in the exocontact, both give NE-shallow up Group 3
220 directions. Burdur host rocks at this site are magnetically unstable.
221 However, site 4-04, only six km away, has the “younger sedimentary”
222 Labaztakh direction. This is not a complete BCT, though it is suggestive of
223 primary remanences. The baked sediment direction matches precisely the
224 dyke direction, not the Group 3 mean, suggestive of instantaneous baking
225 of the host rocks rather than recording a regional magnetic overprint.

226 (2) Fomich River, site 24-04. A 30m-wide dolerite dyke has a direction
227 that is clearly within Group 3, but has scatter slightly larger than our cutoff
228 filter ($\alpha_{95} > 18^\circ$). Contact rocks were altered and thus were not sampled,
229 but fresh Kotuykan Formation limestone 100-350m away yielded a stable
230 “younger sedimentary” direction. Although not a complete baked-contact
231 test, the data suggest lack of pervasive remagnetization in the region.

232 (3) Fomich River, site 25-04. A 10m-wide dyke carries the SW-shallow,
233 Group 4 direction (determined by 4 least-squares lines plus 2 planes), but

234 Kotuykan Formation green and red variegated limestone strata 40m and
235 150 m away bear the S-down younger sedimentary direction. The dyke's
236 exocontact rocks are green limestone yielding an anomalous WSW-shallow
237 direction. Although this direction is closer to the dyke remanence than
238 that of the distant host rocks, the aggregate data are only suggestive of a
239 positive BCT.

240 (4) Upper Kotuykan River, site O-08. A subvertical dyke with exposed (i.e.,
241 minimum) width of 25m intrudes Mukun Group sediments that were
242 sampled at distances of 5m, 10m, and 20m from the contact; all subsites
243 share a Permian-Triassic Group 1 direction. No distant host rock was
244 sampled, so the test is incomplete.

245 (5) Upper Kotuykan River, site 181-08. A ~15m-wide dyke and its
246 exocontact have the same SW-shallow Group 4 direction. Distant host
247 rocks were sampled about 500m away, but their response to thermal
248 demagnetization was chaotic; so the test is incomplete.

249 (6) Ilya River, site 37-07. A 12m-wide dyke plus exocontact, plus distant
250 Burdur Fm host rock, all give the SW-up Group 4 direction. The "distant"
251 host rock samples were collected at 2m and 10m away from the contact, so
252 the zone of directional concordance only slightly exceeds the canonical
253 half-dyke-width rule for contact remagnetization. The presence of a N-
254 down Group 2 direction at site 36-07, only 1.2 km away, argues against
255 widespread regional overprinting.

256 (7) Middle Kotuykan River, site 39-07. A 20m-wide dyke has a NE-shallow
257 Group 3 direction shared by the distant host rock (Kotuykan Formation
258 gray siltstone, 720m away from the contact). The dyke's exocontact has a
259 direction intermediary between the Group 2 and 3 directions, but with a
260 large a_{95} value so it is excluded from both means. The baked-contact test
261 is considered to be inconclusive.

262 (8) Dzhogdzho River, site 5-07. A 3-4m wide mafic dyke has a steep-up
263 Group 1 (Permian-Triassic) direction. Its exocontact has the same steep-
264 up direction, but the distant host rock (Kotuykan red dolomite) has a N-
265 down Group 2 direction, as does the red dolomite at the next site, ~400m
266 away. In addition, site 4-07 (dolerite sill) is also only ~600m distant from
267 the baked-contact test, and has a SW-up Group 4 ChRM. The combined

268 results from these sites suggest that both the N-down Group 2 direction
269 and the SW-up Group 4 direction pre-date the Permian-Triassic intrusion,
270 which itself carries a primary Group 1 remanence.

271 (9) Dzhogdzho River, site 11-07 (sill with U-Pb age of 1501.6 ± 1.9 Ma).
272 Both intrusion and exocontact have same SW-up Group 4 direction. Mafic
273 intrusions of various ages are pervasive in this region of the lower
274 Dzhogdzho River, so it was not possible to find host sedimentary rocks
275 unaffected by their influence and the test is thus incomplete.

276 To summarize, none of the baked-contact tests conclusively demonstrate a
277 primary remanence for either the N-D “enigmatic” Group 2 ChRM direction
278 or the NE/SW shallow ChRM directions of Groups 3 and 4. However, there
279 are strong suggestions of primary remanence in Group 3 (Fomich River
280 sites 3 and 24); and Groups 2 and 4 are both likely older than Permian-
281 Triassic (Dzhogdzho River site 5-07)—assuming that each group contains
282 a pure, uncontaminated representation of the local geomagnetic field at
283 some time in the past. There remains the possibility that any of those non-
284 trap ChRM groups, particularly the N-down Group 2 direction, could be a
285 mixture of other components, as discussed next.

286

287 **INTERPRETATION OF CHARACTERISTIC REMANENCE DIRECTIONS**

288 Based on the information presented above, either the dominantly N-down
289 Group 2 direction or the nearly antipodal Group 3 and 4 directions could
290 plausibly be primary. The Group 3 and 4 data are similar to those
291 reported from nearly coeval rocks in the Olenëk uplift in northeastern
292 Siberia (Wingate et al., 2009) and to some directions obtained from dykes
293 of the eastern Anabar uplift (Ernst et al., 2000). Among all groups,
294 multiply sampled intrusions yield site-mean directions that are well
295 clustered relative to the entire spread of data, implying a positive “secular
296 variation test” as one would expect from sampling thermal-remanent
297 magnetizations (TRMs) from quickly cooled intrusions (Halls, 1986).
298 Groups 2-4 are distributed throughout large areas of our sampling region,
299 although Group 2 is restricted to the west Anabar subregion (upper
300 Kotuykan to Dzhogdzho Rivers). Within Groups 3 and 4, a rough
301 correlation with stratigraphy may be evident, with Group 3 among the

302 lower levels of sill intrusion, and Group 4 among the higher levels (Figures
303 1, 2).

304 The first class of explanations for the difference between the N-down
305 “enigmatic” Group 2 component and the NE/SW shallow Groups 3 and 4
306 components assumes that they all accurately record the local geomagnetic
307 field at the time of remanence acquisition, recording excursions of either
308 Siberian APW or the mid-Proterozoic geodynamo. We suspect an APW
309 explanation is unlikely, because Group 2 is identified in the Upper
310 Kotuykan River sill site VR1-5 (1493 ± 9 Ma) whereas Group 4 is found in
311 sills of the same age, within error: Dzhogdzho River site 11-07 (1502 ± 2
312 Ma) and Kotuy River sites 16-07 to 25-07 (1503 ± 2 Ma). Stretching the age
313 uncertainties to their limits, one would require 49° of APW in a span of
314 only 21 million years, corresponding to a minimum 26 cm/yr rate of
315 continental motion. A slight age difference between directional groups
316 could perhaps in principle be detectable by subtle geochemical variations,
317 and indeed there are two distinct trace-element geochemical groups of
318 intrusions described by Ernst et al. (2016b); however, those two groups do
319 not correspond to the paleomagnetic directional groups (Table 1). If the
320 paleomagnetic discrepancy is to be explained by a geomagnetic excursion,
321 then the enigmatic Group 2 more likely records the anomalous field
322 because it is less abundant across the field area. Nonetheless, it then
323 becomes puzzling why the excursion would be observed in so many rocks
324 spread across ~ 3000 km², including not only mafic intrusions but also
325 redbeds, the latter presumably bearing a thermochemical remanence
326 unlikely to be acquired at precisely the same time. Most troubling for this
327 class of explanation, however, is the fact that both Group 2 and Group 4
328 directions are found at different sites within the same intrusion, for
329 example Dzhogdzho sites 15-00 (Gr. 2), 11-07 (Gr. 4) and 16-00 (Gr. 4). A
330 similar discrepancy exists at Dzhogdzho sites 1-07 (Gr. 4) and 2-07 (Gr. 2),
331 both from the same intrusion, although the 2-07 ChRM is the only
332 southerly-upward polarization of the Group 2 set—one could choose to
333 consider it as a marginal member of Group 4, but then the discrepancy
334 between it and 1-07 from the same intrusion remains a challenge for APW
335 or geomagnetic explanations of all the directional discordances in our
336 dataset.

337 A second class of explanations for the Group 2-4 directional discordance
338 invokes rock-magnetic artifacts of either anisotropy or component mixing.
339 Anisotropic effects are unlikely because none of the sampled rocks are
340 visibly anisotropic as would be necessary to account for the $\sim 30^\circ$
341 directional discordance. The Group 2 direction, being N-down directed at
342 Northern Hemisphere sites, is inherently suspect as being contaminated
343 by a viscous remanent magnetization (VRM) acquired in the present Earth
344 field, perhaps partially overprinting Group 3 northeasterly ChRMs. This
345 seems unlikely, however, because (a) Group 2 samples exhibited straight-
346 line demagnetization trajectories that would require coincidentally
347 identical unblocking spectra between the two components, (b) Group 2
348 sites were typically Fisher-distributed, with no preferred elongation
349 direction at either the within-site or between-site hierarchical level, (c)
350 Site 15-00 has a Group 2 direction but the adjacent sites 14-00 and 16-00
351 (the former possibly and the latter definitely from the same intrusion)
352 have SW-seeking ChRM directions (Group 4) rather than NE-seeking
353 Group 3 directions, and (d) Group 2 directions in red dolomite (sites 5-07
354 and 6-07) and red sandstones (site 105sed-08) render a VRM
355 interpretation unlikely because those redbed sites are unlikely to contain
356 multi-domain magnetite, the typical carrier of VRMs.

357 The enigmatic Group 2 direction could alternatively be interpreted as a
358 contaminated partial overprint from Permian-Triassic traps. It is noted
359 that 8 out of 11 of the Group 2 sites are located within 7 km of a site
360 bearing a Permian-Triassic Group 1 direction. However, the polarity of
361 nearest Group 1 site does not always match that of the proximal Group 2
362 site. Also, it seems improbable that all five sites in the single sill at the
363 base of the succession along the upper Kotuykan River (VR1-5, dated by U-
364 Pb on baddeleyite at 1493 ± 9 Ma) would be partially remagnetized by a
365 trap intrusion where none is recognized in that area.

366 Although most samples yielded single-component behavior, some
367 examples were observed of Group 2 partial overprinting on either a
368 sedimentary ChRM (Figure 3, sample 99), or one the Group 3 or Group 4
369 characteristic remanences (Figure 5, sample 185; Figure 6, sample 7247).
370 There were only rare instances of a Group 3 or Group 4 component

371 unblocking at lower temperatures than a Group 2 component (Figure 6,
372 sample 7247).

373 Petrographic and rock-magnetic results (Figure 8) may shed some
374 additional light on the origin of Group 2 remanence, although the data are
375 far from definitive. Group 2 samples tend to be finer-grained than those of
376 Groups 3 and 4, with pyroxene and glassy matter completely overprinted
377 by epidote and chlorite, and creation of fine-grained opaque minerals on
378 the chloritized pyroxene. Groups 3 and 4 tend to be coarser-grained, with
379 ophitic and poikilo-ophitic textures. Partial to complete saussuritization
380 affects plagioclase, and pyroxene is variably altered along grain
381 boundaries to amphibole, chlorite, and epidote. On the whole, samples
382 from Groups 3 and 4 tend to be less altered than samples from Group 2.

383 In backscattered scanning electron microprobe (SEM) imagery, Groups 3
384 and 4 show variability of Fe-oxide phases, both in grain size and in
385 morphology. Group 2 samples tend to have larger amalgamations of Fe-
386 oxide-bearing grains with oxy-exsolution features. Group 1 Fe-oxide
387 grains are smaller and lack distinctive internal structure. In all samples,
388 the presence of high-temperature oxidation and solid solution decay is
389 supported by SEM observations and microprobe analyses, and these can
390 be considered as evidence for a primary magmatic origin of the most of
391 magnetic minerals. Groups 3 and 4 show sufficient variability of magnetic
392 mineralogy to corroborate the idea that recording of the ambient
393 geomagnetic field occurred over enough time to average paleosecular
394 variation.

395 Hysteresis parameters of studied samples, summarized on the plotting
396 convention of Day et al. (1977), show that they contain single-domain and
397 pseudo-single-domain (SD/PSD) magnetic particles, and can be considered
398 as stable magnetic carriers over geological timescales (Figure 8A). The
399 Group 3 and 4 samples exhibit the greatest variability in hysteresis
400 parameters, whereas Groups 1 and 2 are confined to the central part of the
401 PSD field. This may indicate support for briefly emplaced and relatively
402 homogeneous magnetic mineralogy for each of those two directional
403 groups (Permian-Triassic and the enigmatic group). Thermomagnetic
404 curves of bulk susceptibility versus temperature (Figure 8B) all indicate
405 dominant presence of near-stoichiometric magnetite, with Hopkinson

406 peaks at temperatures immediately below 580°C. These curves show
407 more variable behavior for Groups 3 and 4, with some curves largely
408 reversible and others irreversible. Group 2 samples are dominated by
409 nearly reversible thermomagnetic behavior, whereas Group 1 shows
410 consistently irreversible behavior.

411 Altogether, we favor the Group 3 and Group 4 magnetizations as most
412 likely to represent primary magnetizations among the ca. 1500 Ma
413 intrusions around the Anabar Shield. This interpretation is mainly due to
414 (a) greater abundance relative to the enigmatic Group 2 component, (b)
415 various possible explanations for the Group 2 component including
416 modest degrees of remagnetization or acquisition during geomagnetic
417 excursions, and (c) an overall smooth progression of paleomagnetic poles
418 through the stratigraphic succession, from the older Riphean sedimentary
419 units, to the younger sedimentary units, and finally to the Group 3 and 4
420 results (Figure 9).

421 In addition to these arguments in favor of the Group 3 and 4 data
422 representing the Siberian craton at ca. 1500 Ma, we note the consistency of
423 the Group 3 and 4 poles with that of the nearly coeval Sololi-Kyutingde
424 pole from the Olenëk area to the east (Wingate et al., 2009; Figure 9). Our
425 new data are similar to some results from eastern Anabar dykes (Ernst et
426 al., 2000; Figure 9), but our poles differ from the Kuonamka mean pole of
427 the same study, which was assigned an age of 1503 ± 5 Ma based on U-Pb
428 dating of one of the dykes. Figure 9 shows how the five-dyke Kuonamka
429 mean lies between the dated dyke's VGP and both the Olenëk pole and our
430 new results. We follow Evans and Mitchell (2011) in interpreting the
431 dated Kuonamka dyke's anomalous remanence—relative to the vastly
432 more abundant Olenëk dataset of Wingate et al. (2009) and now also our
433 northern and western Anabar results—as representing either a
434 geomagnetic excursion or, perhaps, hitherto unrecognized (and if so,
435 dramatic) rotations of Siberia at ca. 1500 Ma.

436

437 **TECTONIC RECONSTRUCTION**

438 As noted above, the primary goal of this study is to determine whether
439 new paleomagnetic data from Siberia can elucidate its position relative to

Laurentia during mid-Proterozoic time. Our new Group 3 and Group 4 poles, dated at 1483 ± 17 and 1503 ± 2 Ma, respectively, can be compared to mid-Proterozoic poles from Laurentia (Table 2), in particular the St. Francois Mountains igneous province result from Meert and Stuckey (2002). Our new poles conform to earlier suggestions of a juxtaposition between the southern Siberian and northern Laurentian margins (Figure 10). Our new poles are substantially discordant to the St. Francois Mountains pole in the Siberia-Laurentia reconstruction models of Sears and Price (1978, 2000, 2003).

The question of whether the Siberia-Laurentia fit was loose (Pisarevsky and Natapov, 2003; Pisarevsky et al., 2008) or tight (Pavlov et al., 2002; Metelkin et al., 2007; Evans and Mitchell, 2011) during mid-Proterozoic time is not addressed directly by our new poles, because they fall atop the coeval Laurentian poles about equally well in either of the two reconstructions (compare Figure 10a and b). Other Proterozoic poles from Siberia may aid in answering this question, however. Figure 10 shows Siberian and Laurentian poles from the interval 1750 to 700 Ma (Table 2). Either reconstruction accommodates the poles in a single APW path with reasonable consistency, but the most important difference occurs in the 1100-1000 Ma datasets. In a loose-fitting reconstruction (Figure 10a), the Linok and Uchur-Maya poles (Malgina to Kandyk) fall along the 1090-1000 Ma portion of the Laurentian APW path; whereas in the tight-fitting reconstruction (Figure 10b), the same Siberian poles correspond to slightly older Laurentian APW ages beginning closer to 1100 Ma. The youngest of these Siberian poles, Kandyk sills (Pavlov et al., 2002) is well dated at ca. 990 Ma, and accords moderately well with Grenvillian intrusive poles of about the same age from Laurentia (Warnock et al., 2000; Brown and McEnroe, 2012)—especially when considering that the paleohorizontal datums of Grenvillian intrusions are not well established—and also recognizing the caveat that internal Grenville terranes may be substantially allochthonous (Halls, 2015). The older Siberian poles from that interval, Linok and Malgina, are not precisely dated. The Malgina Formation (within the Kerpyl Group) has a Pb/Pb isochron age of 1043 ± 14 Ma (Ovchinnikova et al., 2001), but it is recognized that such a value represents early diagenesis rather than deposition (Kaurova et al., 2010). Recent U-Pb detrital zircon results

476 provide firm maximum constraints on sedimentation, with the youngest
477 population in basal strata of the Kerpyl Group dated at 1120 ± 17 Ma
478 (Khudoley et al., 2015). With such age constraints, both the loose-fitting
479 and tight-fitting reconstruction options remain viable.

480 We are left, then, with the somewhat unsatisfactory conclusion that
481 according to Mesoproterozoic paleomagnetic poles, both the loose-fitting
482 and tight-fitting reconstructions of Siberia and Laurentia are possible.
483 Each has its prediction of the ages of Kerpyl Group strata, via comparison
484 to well dated Laurentian poles. However, there is one more pole
485 comparison that may shed additional light on this dichotomy of ideas.
486 Recent paleomagnetic study of 758 ± 4 Ma Kitoi dykes, in SW Siberia
487 (Pisarevsky et al., 2013), produced an excellent match with Laurentian
488 poles in a tight-fitting reconstruction, and a rather poor match in the loose-
489 fitting reconstruction (Figure 10). According to the authors of that study,
490 Siberia migrated from a loose fit to a tight fit during ca. 780-760 Ma
491 dextral transform motion associated with Rodinia breakup. The model
492 helps explain synchronicity of ca. 725-Ma mafic magmatism in both
493 southern Siberia and northern Laurentia (Ernst et al., 2016a), but it calls
494 for mid-Neoproterozoic strike-slip relative motion that is not particularly
495 evident along either margin. We propose a simpler model in which the
496 coincidence of Kitoi poles with those of mid-Neoproterozoic Laurentia
497 merely represents the near-final stages of the long-lived pairing between
498 the two cratons in their tight juxtaposition, and that the cratons began
499 separating at the time of the 725-Ma magmatism. Our preferred
500 reconstruction (Figure 10b) is chosen to optimize both the cratonic
501 marginal outlines and paleomagnetic poles from the entire 1.7-0.7 Ga
502 interval, and to honor many geological comparisons between the two
503 cratons throughout that history (Evans and Mitchell, 2011; Ernst et al.,
504 2016a).

505 If our model of billion-year tectonic stability (within the resolution of
506 paleomagnetic data) between Siberia and northern Laurentia is correct,
507 then all high-quality paleomagnetic poles must conform to a common APW
508 path between the two blocks for that interval of time. As shown in Figure
509 10, our model accommodates the Mesoproterozoic-Neoproterozoic poles
510 from both cratons. Several recent paleomagnetic and geochronologic

511 results from late Paleoproterozoic rocks, however, warrant additional
512 discussion. In the Ulkan graben, rocks from both volcanosedimentary
513 units and intrusive granitoids yielded paleomagnetic poles (Didenko et al.,
514 2015). The volcanosedimentary pole from the Elgetey Formation, dated at
515 1732 ± 4 Ma, passes both fold and intraformational conglomerate tests, but
516 it is highly discordant to other poles from the Siberian craton and is thus
517 interpreted by the authors as having been deflected by local rotations
518 during graben development. The granitoid pole, with an estimated age of
519 1719 Ma (Didenko et al., 2015) is more consistent with other granitoid-
520 derived poles from southern Siberia (Didenko et al., 2009), but none of
521 those granitoid-based data have reliable estimates of paleohorizontal. Due
522 to this lack of structural control, neither Ulkan result can be considered as
523 a robust estimate of Siberia's paleogeography at ca. 1730-1720 Ma. In
524 southwestern Siberia, mafic rocks of the Nersa complex were once
525 considered entirely Neoproterozoic-Cambrian in age (Gladkochub et al.,
526 2006), but one mafic sill that yielded a paleomagnetic pole (Metelkin et al.,
527 2005) is now dated by U-Pb on baddeleyite at ca. 1640 Ma (Ernst et al.,
528 2016a). That pole, with its new age constraint, actually fits well atop the
529 common Siberia-Laurentia APW path in either the loose or tight fit (Figure
530 10).

531

532 CONCLUSIONS

533 We produce new paleomagnetic poles from the northern and western
534 margins of the Anabar Shield, Siberia. Our data, when compared to
535 similarly aged poles from Laurentia, allow a tight-fitting juxtaposition
536 between the two cratons, slightly modified from that of Rainbird et al.
537 (1998) and Evans and Mitchell (2011) and internally stable for about a
538 billion years (1.7-0.7 Ga). The alternative, loose-fitting reconstruction
539 between southern Siberia and northern Laurentia (e.g., Pisarevsky et al.,
540 2003, 2008) requires transform motion between the cratons during
541 Rodinia breakup (Pisarevsky et al., 2013); whereas our model
542 accommodates all of the high-quality poles from both cratons without any
543 internal motions. Both models make specific predictions regarding the
544 ages of sedimentation of Riphean strata that have yielded high-quality

545 paleomagnetic poles, and thus further geochronology of those successions
546 may assist in distinguishing which reconstruction is viable.

547

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558

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873 **FIGURE CAPTIONS**

874 Figure 1. Regional map of Siberian craton (A), highlighting the location of
875 Anabar Shield study areas (B, C). Paleomagnetic sampling sites are color-
876 coded according to characteristic remanent magnetization (ChRM) group.
877 Filled=normal polarity, open=reversed polarity (see text for justification).

878 Figure 2. Schematic stratigraphic column (not to scale) for the
879 northwestern flank of the Anabar Shield. Vertical lines represent
880 unconformities. Circles represent sedimentary paleomagnetic sampling
881 horizons. These, and approximate mafic sill levels (with U-Pb ages from
882 Ernst et al., 2016b), are color-coded for ChRM group and polarity
883 interpretation as in Figure 1. Other ages are discussed in the text.

884 Figure 3. Orthogonal demagnetization diagrams and equal-angle
885 stereonet plots of sedimentary samples from sites distant to mapped
886 intrusions. Upper row: younger sedimentary succession from Fomich
887 River valley, Labastakh Formation (left) and Kotuykan Formation (right).
888 Lower row: older sedimentary succession from the Western Anabar region,
889 Ust-II'ya Formation (left) and Burdur Formation (right). In all orthogonal
890 demagnetization plots, closed symbols lie within the horizontal projection
891 and open symbols lie within the vertical projection. NRM=natural
892 remanent magnetization. All temperatures are in °C.

893 Figure 4. Representative orthogonal demagnetization diagrams and equal-
894 area stereonet plots of (A) sites inferred to be of Permian-Triassic age
895 based on steep west-up or east-down Group 1 remanence direction, and
896 (B) sites carrying the enigmatic north-down or south-up Group 2 direction.
897 Symbols as in Figure 3.

898 Figure 5. Representative orthogonal demagnetization diagrams and equal-
899 area stereonet plots of sites carrying the northeast-shallow Group 3
900 characteristic remanence direction. Symbols as in Figure 3.

901 Figure 6. Representative orthogonal demagnetization diagrams and equal-
902 area stereonet plots of sites carrying the southwest-shallow Group 4
903 characteristic remanence direction. Symbols as in Figure 3.

904 Figure 7. Equal-area stereographic projection of all site means reported in
905 this study, color coded by remanence grouping as in Table 1 (color-coded

as in Figure 1). Solid symbols are in the lower hemisphere; open symbols are in the upper hemisphere. Each irregular envelope surrounds multiple sites collected from the same intrusion. U-Pb baddeleyite ages are in Ma (Ernst et al., 2016b). Site 2-07 is discussed in text. S=sedimentary site within Group 2. Star is the present dipole field direction for the sampling area.

Figure 8. Rock-magnetic data from representative samples of the four directional groups, color-coded as in Figure 1. (A) Plot of hysteresis parameters (M_{rs}/M_s = ratio of saturation remanence to saturation magnetization; B_{cr}/B_c = ratio of coercivity of remanence to coercivity) from samples plotted against the canonical fields (Day et al., 1977) of single-domain (SD), pseudo-single-domain (PSD) and multi-domain (MD) magnetite. (B) Selected samples from each of the four characteristic remanence (ChRM) directional groups, showing SEM backscattered imagery (scale bar = 20 μm wide for all images; the bar for VR1-08 is almost too narrow to see, as the field of view is $\sim 3\text{mm}$ wide), and bulk susceptibility versus temperature for heating and cooling.

Figure 9. New paleomagnetic poles generated in this study, compared to selected published results. Pole abbreviations follow Table 2, plus P-Tr (Permian-Triassic). Aldan block and its generalized ca. 1070-1000 Ma pole path (pink) have been restored to the Anabar reference frame in pre-Devonian time (Pavlov et al., 2008; Euler parameters from Evans, 2009). The individual site-mean virtual geomagnetic poles from Ernst et al. (2000) have italicized numeric labels and U-Pb ages. Dark squares are selected Paleozoic running-mean Siberian (Anabar frame) poles from Cocks and Torsvik (2007).

Figure 10. Alternative reconstructions of Siberia in the present North American reference frame. In both models, Aldan is first restored to Anabar for pre-Devonian time (Euler parameters $60^\circ, 115^\circ, 25^\circ$) according to Evans (2009). (A) Loose fit adopted from Pisarevsky et al. (2014) (Anabar to North America $70^\circ, 133^\circ, 127^\circ$). (B) Long-lived, tight fit proposed in this study (Anabar to North America $77^\circ, 098^\circ, 137^\circ$). Pole abbreviations are identified in Table 2. Baltica is restored to Laurentia ($47.5^\circ, 001.5^\circ, 49^\circ$) according to Evans and Pisarevsky (2008).

Graphical Abstract

Table 1. Paleomagnetic data from the northern and western margins of the Anabar Shield, Siberia.

Site abbr.	River section	Lithology	Weight	Lat.(°N)	Long.(°E)	n/N	GDec	GInc	k	a95	Plat(N)	Plong(E)	U-Pb geochronology or geochemistry
<i>Older sediments</i>													
1-04	Fomich	Burdur Fm., pink sandstone	0(PLF)	71.2067	107.2928	0/15	359.3	75.1	45.7	7.2	----	----	
2-04	Fomich	Burdur Fm., pink-cherry sandstone	0(PLF)	71.2425	107.1817	0/15	351.8	78.0	43.0	5.9	----	----	
3-04(H)	Fomich	Upper Burdur Fm., distant host rocks to 04-3(D)	0(scst)	71.2767	107.1442	0/10	unstable	----	----	----	----	----	
13sed-08	Upper Kotuykan	Il'ya Fm., red sandstone	1	70.5016	106.1270	12/31	165.7	30.9	19.8	10.0	-02.3	119.8	
44sed-08	Upper Kotuykan	Burdur Fm., chocolate, cherry-colored ss.	1	70.563	105.883	20/30	156.1	30.0	10.1	10.8	-01.8	128.8	
74sed-08	Upper Kotuykan	Burdur Fm., red sandstone	1	70.5697	105.8727	6/15	173.5	30.1	28.4	12.8	-03.1	112.1	
89sed-08	Upper Kotuykan	Burdur Fm., red sandstone	1	70.6468	105.9104	10/16	167.1	19.2	9.4	16.6	-09.0	118.8	
34-07	Ilya	Il'ya Fm., red sandstone	0(scst)	70.3138	105.8413	0/13	unstable	----	----	----	----	----	
1-00	Magan	Burdur Fm., sandstone	0(scst)	69.97	105.47	0/67	unstable	----	----	----	----	----	
<i>mean</i>						4 sites	165.6	27.7	92.9	9.6			
											K=113	A95=8.7	
<i>Younger sediments</i>													
4-04	Fomich	Labaztakh Fm., cherry-colored siltstone	1	71.3194	107.0375	20/20	016.7	-28.0	80.0	3.7	-3.0*	90.9*	
24-04(H)	Fomich	Kotuykan Fm., gray limestone 100-350m away from	1	71.6403	107.7739	7/31	194.4	35.2	21.3	13.4	01.6	094.2	
25-04(H)	Fomich	Kotuykan Fm., variegated limestone 150m away fro	1	71.6708	108.0250	11/22	193.0	33.5	12.5	13.4	00.4	095.7	
7-07	Dzhogdzho	Kotuykan Fm., red dolostone	0(scst)	70.234	104.172	4/11	scattered	----	----	----	----	----	
2-00	Magan	Labaztakh Fm., red sandstone	0(scst)	70.07	104.92	0/20	unstable	----	----	----	----	----	
3-00	Magan	Labaztakh Fm., sandstone	0(scst)	70.05	104.95	0/7	unstable	----	----	----	----	----	
4-00	Magan	Labaztakh Fm., sandstone	0(scst)	70.07	104.92	0/16	unstable	----	----	----	----	----	
5-00	Magan	Labaztakh and Ust-II'ya Fms., sandstone	0(scst)	70.07	104.92	0/12	unstable	----	----	----	----	----	
6-00	Magan	Ust-II'ya Fm.	0(scst)	70.07	104.90	0/10	unstable	----	----	----	----	----	
7-00	Magan	Ust-II'ya Fm.	0(scst)	70.07	104.88	0/14	unstable	----	----	----	----	----	
8-00	Magan	Ust-II'ya Fm., sandstone	0(scst)	70.07	104.88	0/16	unstable	----	----	----	----	----	
9-00	Magan	Lowest part of Ust-II'ya Fm., sandstone	0(scst)	70.07	104.93	0/17	unstable	----	----	----	----	----	
<i>mean</i>						3 sites	194.7	32.2	393.0	6.2			
											K=553	A95=5.2	
<i>Steep W-up/E-down "Permian-Triassic" (Group 1)</i>													
0-08(D)	Upper Kotuykan	Dolerite sill	0.5	70.6880	105.8291	8/12	271.5	-68.9	214.1	3.8	47.9*	171.4*	
0-08(C,H)	Upper Kotuykan	Exocontact and host rocks to 0-08(D)	0.5	70.6880	105.8291	21/23	276.4	-72.5	136.6	2.7	51.1*	163.5*	
M-08	Upper Kotuykan	Mafic sill	1	70.7022	105.6473	13/15	257.8	-76.4	64.6	5.2	61.6*	169.3*	
5-07(D)	Dzhogdzho	3-4m wide mafic dyke, trending 045°	0.5	70.2331	104.1851	6/10	010.9	-77.3	82.0	7.4	46.2*	97.7*	
5-07(C)	Dzhogdzho	Exocontact to 5-07(D)	0.5	70.2331	104.1851	4/10	359.5	-70.4	47.5	13.5	34.8*	104.5*	
7-07	Dzhogdzho	Kotuykan Fm., red dolostone (remagnetized by near	1	70.234	104.172	9/10	079.7	70.5	19.6	11.9	53.4	176.7	
13-00	Dzhogdzho	Mafic dyke, trending 030°	1	70.5025	104.4367	9/15	071.2	81.0	26.5	10.2	68.6	156.1	
9-07	Dzhogdzho	Weathered mafic dyke, 15m wide, trending 030°	1	70.5028	104.4396	17/21	118.3	79.8	51.7	5.0	56.4	137.1	
10-07	Dzhogdzho	Mafic sill, 4m thick	1	70.5028	104.4396	6/12	222.2	-71.3	168.6	5.2	66.8*	211.4*	
<i>mean</i>						7 sites	089.3	78.4	48.9	8.7			
											K=15.1	A95=16.1	
<i>N-down/S-up "enigmatic component" (Group 2)</i>													
VR1-08	Upper Kotuykan	Large (>10m thick), fresh mafic sill at river level	0.2	70.5155	106.1041	8/8	023.0	67.7	65.0	6.9	67.5	245.8	
VR2-08	Upper Kotuykan	Same sill as VR1, sampled ~3m higher	0.2	70.515	106.102	8/8	032.8	67.3	98.3	5.6	64.6	232.1	
VR3-08	Upper Kotuykan	Same sill as VR2, sampled ~2m higher	0.2	70.515	106.101	8/8	044.2	63.8	41.8	8.7	57.1	221.9	

VR4-08	Upper Kotuykan	Same sill as VR3, sampled ~2m higher	0.2	70.515	106.099	7/8	013.9	64.7	46.6	8.9	65.2	263.0	1493±9 Ma (same sill, 400m away)
VR5-08	Upper Kotuykan	Same sill as VR4, at its fine-grained margin	0.2	70.5192	106.0625	8/8	028.7	65.8	91.5	5.8	63.7	239.6	1493±9 Ma (same sill, 1100m away)
105sed-08	Upper Kotuykan	Ilya and Burdur Formations, redbeds	1	70.653	105.932	10/12	028.5	42.8	124.3	4.3	41.3	250.7	
E-08	Upper Kotuykan	Mafic sill or dyke, trending E-W, crossing river valley	1	70.697	105.642	14/15	026.7	53.3	35.7	6.7	50.4	249.8	
36-07	Ilya	Coarse, dark green mafic body, 50m of exposure	1	70.4240	105.5732	10/15	022.2	60.0	91.2	5.1	58.4	252.6	
38-07	Ilya	Mafic sill(?) at least 18m thick	1	70.4851	105.4752	9/10	008.6	52.0	41.7	8.1	51.8	273.7	
11-00	Magan	Mafic sill, mapped as P-Tr	1	70.3111	104.4033	11/11	356.9	57.7	108.4	4.4	58.0	289.0	
2-07	Dzhogdzho	Fine, green-black gabbro-dolerite sill >15m thick	1	70.1953	104.1407	13/16	186.5	-54.2	20.4	9.4	54.4*	275.0*	
5-07(H)	Dzhogdzho	Kotuykan Fm., red dolostone host to 5-07(D)	1	70.2331	104.1851	3/28	352.6	60.0	10.6	16.6	60.4	295.6	
6-07	Dzhogdzho	Kotuykan Fm., red dolostone	1	70.2346	104.1749	9/9	329.2	58.3	35.4	11.4	54.9	327.9	
15-00	Dzhogdzho	Same large mafic sill as 11-07 and 16-00 (Group 4)	1	70.4878	104.5219	5/15	037.7	56.2	46.7	11.3	50.9	233.6	
18-00	Dzhogdzho	Weathered dyke, trending 025°	0(scatter)	70.5228	104.4242	0/15	unstable	-----	-----	-----	-----	-----	
4-01	Dzhogdzho	Mafic dyke <1m wide, trending 025°	1	70.53	104.37	8/8	316.4	70.1	68.0	6.8	64.9	356.5	
19-00	Dzhogdzho	Mafic dyke, trending 030°	0(scatter)	70.5417	104.3683	0/15	unstable	-----	-----	-----	-----	-----	
mean						11 sites	009.6	59.4	30.7	8.4	60.1	271.9	
											15.8	A95=11.8	

NE-shallow (Group 3)

3-04(D)	Fomich	50m wide dolerite dyke, trending 300°	0.5	71.2767	107.1442	14/15	032.3	-05.0	59.7	5.2	13.3	253.9	
3-04(C)	Fomich	Contact rocks to 04-3(D), upper Burdur Fm.	0.5	71.2767	107.1442	9/15	034.2	-03.2	56.0	6.9	13.8	251.8	
5-04	Fomich	Dolerite sill	0.5	71.3422	106.9244	10/15	024.5	22.6	16.9	12.1	28.6	259.4	Geochemistry group I; 1483±17 Ma
6-04	Fomich	Dolerite sill (same as 04-6)	0.5	71.3408	106.9278	14/14	024.3	17.9	16.2	10.2	26.0	260.0	
7-04	Fomich	Dolerite sill	0.25	71.3772	106.8511	13/15	024.1	07.0	26.5	8.2	20.4	261.1	
8-04	Fomich	Dolerite sill (same as 04-7)	0.25	71.3786	106.8400	14/15	020.9	16.7	16.5	10.1	25.8	263.8	
9-04	Fomich	Dolerite sill (same as 04-7)	0.25	71.3636	106.8056	15/15	020.6	04.0	23.6	8.0	19.4	264.9	Geochemistry group I
10-04	Fomich	Dolerite sill (same as 04-7)	0.25	71.3658	106.8142	9/15	009.1	16.5	14.6	13.9	26.8	276.7	
11-04	Fomich	Dolerite sill	0.5	71.3747	106.7314	10/15	015.8	09.0	21.0	10.8	22.4	269.7	
12-04	Fomich	Dolerite sill (same as 04-11)	0.5	71.3717	106.7281	10/10	024.1	-01.2	83.1	5.3	16.4	261.5	
13-04	Fomich	Dolerite sill (same as 04-12)	0(scatter)	71.3722	106.7161	9/10	001.7	-06.3	7.0	20.9	15.5	285.0	
14-04	Fomich	Dolerite	1	71.3928	106.5356	7/11	023.3	12.6	27.1	11.8	23.4	261.2	
15/16-04	Fomich	Dolerite sill	1	71.409	106.380	9/22	039.3	07.2	9.4	17.7	17.8	244.8	Geochemistry group II
24-04(D)	Fomich	30m wide dolerite dyke, trending 005°	0(scatter)	71.6403	107.7739	7/15	024.6	-08.6	11.5	18.6	12.4	262.6	Geochemistry group II
D-08	Upper Kotuykan	Gabbro-dolerite sill	1	70.7005	105.6013	11/11	039.7	09.1	13.4	12.9	19.2	243.2	
39-07(D)	Upper Kotuykan	20m wide dolerite dyke, trending 320°	1	70.6059	104.9124	14/14	035.7	34.8	27.9	7.7	34.4	243.0	
39-07(C)	Upper Kotuykan	Baked contact rocks to 39-07(D)	0(scatter)	70.6059	104.9124	4/12	010.8	56.3	16.8	23.1	55.8	269.5	
39-07(H)	Upper Kotuykan	Host rocks to 39-07(D), Kotuykan Fm.	1	70.6059	104.9124	6/9	020.0	30.6	29.7	12.5	34.5	261.5	
mean						9 sites	028.3	14.1	27.4	10.0	23.9	255.3	
											K=48.0	A95=7.5	

SW-shallow (Group 4)

17-04	Fomich	Dolerite sill (Tunbl>500°C)	1	71.4317	106.2567	7/11	217.6	-35.0	58.4	8.0	-33.5	062.6	
25-04(D)	Fomich	10m wide dolerite dyke, trending 045°	0(scatter)	71.6708	108.0250	(4+2c)/10	225.0	19.8	11.9	21.0	-02.9	063.8	
25-04(C)	Fomich	Exocontact to 25-04(D); green limestone	0(anom)	71.6708	108.0250	9/9	251.6	06.1	195.5	3.7	-02.8	036.5	
181-08(DC)	Upper Kotuykan	Dolerite dyke (trending NNW) and baked contact rocks	1	70.6333	105.2690	12/32	206.9	-11.6	24.3	9.0	-23.0	076.0	
I-08	Upper Kotuykan	5m wide dolerite dyke	1	70.5895	104.9653	11/12	215.7	-19.7	77.3	5.2	-25.6	065.4	
40-07	Upper Kotuykan	Dolerite sill, at least 18m thick	0.5	70.5670	104.5259	14/16	223.9	-24.2	80.2	4.5	-26.1	055.6	
41-07	Upper Kotuykan	Dolerite sill, same as 40-07	0.5	70.5634	104.5381	10/12	223.1	-27.6	26.1	9.6	-28.3	055.9	
37-07(D)	Ilya	12m wide dolerite dyke, trending 290°	1	70.4206	105.5630	11/12	232.8	-17.1	36.4	7.7	-20.1	048.6	
37-07(C)	Ilya	Baked contact rocks to 37-07(D)	0(scatter)	70.4206	105.5630	4/7	231.4	-21.8	25.0	18.7	-22.9	049.2	

37-07(H)	Ilya	Host rocks to 37-07(D), lower Burdur Fm.	0(few)	70.4206	105.5630	(1+3c)/9	230.5	-25.6	194.3	9.0	-25.3	049.5	
10-00	Magan	Mafic intrusion	1	70.2358	104.6681	7/15	227.8	-18.8	17.0	15.1	-22.4	052.5	
1-07	Dzhogdzho	Dolerite sill, at least 10m thick	1	70.1847	104.1219	13/15	214.1	-22.3	51.6	5.8	-27.6	065.8	
3-07	Dzhogdzho	Dolerite sill with differentiated center	1	70.1929	104.1194	16/24	224.0	-20.3	44.8	5.6	-24.3	055.6	ca.1770 Ma, zircon (xenocr.)
4-07	Dzhogdzho	Fine-grained mafic sill	1	70.2281	104.1778	17/27	211.7	-17.8	32.3	6.4	-25.7	069.0	
12-00	Dzhogdzho	Mafic dyke, trending 300°	0(scst)	70.3869	104.3358	0/12	unstable	-----	-----	-----	-----	-----	
8-07	Dzhogdzho	Mafic intrusion	0(few)	70.3094	104.3128	(3+2c)/15	212.1	-18.2	52.3	11.4	-25.7	068.7	
3-01	Dzhogdzho	Dolerite sill	1	70.47	104.45	13/15	219.0	-33.9	44.8	6.3	-33.1	059.0	
14-00	Dzhogdzho	Dolerite sill, maybe same as 11-07 and 16-00?	1	70.4878	104.4889	5/16	222.5	-20.2	108.7	7.4	-24.4	057.6	
11-07(S)	Dzhogdzho	Dolerite sill, same as 16-00	0.333	70.4964	104.5335	9/10	246.3	-30.4	79.7	5.8	-23.2	031.6	Transitional geochemistry; 1502±2 Ma
11-07(C)	Dzhogdzho	Baked contact rocks to 11-07(S)	0.333	70.4964	104.5335	5/11	246.9	-31.9	44.0	11.7	-23.9	030.7	
16-00	Dzhogdzho	Dolerite sill, same as 11-07 and perhaps 14-00	0.333	70.5117	104.5292	6/15	251.1	-32.1	66.2	7.5	-22.7	026.5	
17-00	Dzhogdzho	Dolerite dyke (mapped as P-Tr), trending 030°	1	70.5153	104.5022	12/15	228.9	-28.5	40.0	6.9	-27.3	049.6	
20-00	Lower Kotuykan	Dolerite	0(few)	70.5761	104.2278	(2+1c)/11	223.5	-35.6	40.7	23.0	-33.0	053.6	
12-07	Lower Kotuykan	Dolerite sill	1	70.5626	104.0303	7/15	219.9	-06.8	112.1	5.7	-18.1	061.7	
13-07	Lower Kotuykan	5m thick dolerite sill intruding Ust-Mastakh dolost	1	70.5634	103.8909	16/25	212.6	18.4	22.9	7.9	-07.0	071.5	
6-01	Lower Kotuykan	~10m thick dolerite sill intruding Ust-Mastakh dolo	1	70.53	103.91	9/20	224.2	-19.2	40.5	8.2	-23.4	055.5	
7-01	Lower Kotuykan	5-10m thick dolerite sill intruding Ust-Mastakh dolo	0(scst)	70.53	103.91	0/15	unstable	-----	-----	-----	-----	-----	
8-01	Lower Kotuykan	Dolerite sill at base of high cliff	1	70.52	103.88	9/15	213.6	-15.6	18.5	12.3	-23.9	067.0	
14-07	Lower Kotuykan	Dolerite sill, 40m above river level	1	70.5194	103.8554	10/11	214.5	-15.6	68.0	5.9	-23.7	066.1	Geochemistry group I
16-07	Kotuy	Large, continuous dolerite sill	0.1	70.3088	103.5395	8/8	212.2	-24.9	129.1	4.9	-29.4	067.0	
17-07	Kotuy	Large, continuous dolerite sill	0.1	70.3115	103.5385	4/8	219.0	-22.1	130.1	8.1	-26.4	060.0	
18-07	Kotuy	Large, continuous dolerite sill	0.1	70.3149	103.5373	6/8	208.3	-21.4	27.4	13	-28.2	071.7	
19-07	Kotuy	Large, continuous dolerite sill	0.1	70.3170	103.5392	7/8	203.6	-26.0	40.2	9.6	-31.5	076.4	
20-07	Kotuy	Large, continuous dolerite sill	0.1	70.3214	103.5416	5/8	213.9	-23.5	65.4	9.5	-28.2	065.3	
21-07	Kotuy	Large, continuous dolerite sill	0.1	70.3238	103.5424	6/8	206.2	-26.0	72.2	7.9	-31.1	073.5	
22-07	Kotuy	Large, continuous dolerite sill	0.1	70.3271	103.5430	4/11	217.4	-23.5	55.8	12.4	-27.5	061.6	1503±2 Ma
23-07	Kotuy	Large, continuous dolerite sill	0.1	70.3311	103.5411	(5+1c)/8	197.2	-22.5	19.3	15.9	-30.4	083.9	
24-07	Kotuy	Large, continuous dolerite sill	0.1	70.3378	103.5369	5/8	216.5	-22.4	59.7	10	-27.1	062.7	Geochemistry group I
25-07	Kotuy	Large, continuous dolerite sill	0.1	70.3443	103.5363	7/8	205.1	-18.4	40.0	9.7	-27.1	075.5	
26-07	Kotuy	Dolerite sill	1	70.3926	103.4287	8/15	206.6	-26.0	73.8	6.5	-31.0	072.9	
27-07	Kotuy	15m wide alkaline dyke, trending 060°	1	70.4261	103.4277	5/15	201.8	-21.9	38.3	12.5	-29.4	078.7	
mean						21 sites	218.7	-20.0	30.7	5.8	-25.3	061.4	
											K=48.6	A95=4.6	

Notes: in site abbreviations, (D)=dyke, (S)=sill, (C)=exocontact, (H)=distant host; for zero weights, (anom=anomalous), (few)= n<5, (PLF)=present local field, (scst)= a95>18°; n/N = # of samples in mean direction/number analyzed (c=great circles); GDec, GInc = mean ChRM in geographic coordinates (degrees); k, a95 = Fisher's (1953) precision parameter, radius(°) of the 95% cone of confidence for the mean direction; Plat, Plong = virtual geomagnetic pole latitude, longitude (*=polarity inverted); Geochemistry groups and U-Pb baddeleyite ages are from Ernst et al. (2016b).

* Plat, Plong listed as antipole of the mean direction given in the table.

Table 1. Paleomagnetic data from the northern and western margins of the Anabar Shield, Siberia.

<u>Site abbr.</u>	<u>River section</u>	<u>Lithology</u>	<u>Weight</u>	<u>Lat.(°N)</u>
<u>Older sediments</u>				
1-04	Fomich	Burdur Fm., pink sandstone	0(PLF)	71.2067
2-04	Fomich	Burdur Fm., pink-cherry sandstone	0(PLF)	71.2425
3-04(H)	Fomich	Upper Burdur Fm., distant host rocks to 04-3(D)	0(scatter)	71.2767
13sed-08	Upper Kotuykan	Il'ya Fm., red sandstone	1	70.5016
44sed-08	Upper Kotuykan	Burdur Fm., chocolate, cherry-colored ss.	1	70.563
74sed-08	Upper Kotuykan	Burdur Fm., red sandstone	1	70.5697
89sed-08	Upper Kotuykan	Burdur Fm., red sandstone	1	70.6468
34-07	Ilya	Il'ya Fm., red sandstone	0(scatter)	70.3138
1-00	Magan	Burdur Fm., sandstone	0(scatter)	69.97
<i>mean</i>				
<u>Younger sediments</u>				
4-04	Fomich	Labaztakh Fm., cherry-colored siltstone	1	71.3194
24-04(H)	Fomich	Kotuykan Fm., gray limestone 100-350m away from d	1	71.6403
25-04(H)	Fomich	Kotuykan Fm., variegated limestone 150m away from	1	71.6708
7-07	Dzhogdzho	Kotuykan Fm., red dolostone	0(scatter)	70.234
2-00	Magan	Labaztakh Fm., red sandstone	0(scatter)	70.07
3-00	Magan	Labaztakh Fm., sandstone	0(scatter)	70.05
4-00	Magan	Labaztakh Fm., sandstone	0(scatter)	70.07
5-00	Magan	Labaztakh and Ust-Il'ya Fms., sandstone	0(scatter)	70.07
6-00	Magan	Ust-Il'ya Fm.	0(scatter)	70.07
7-00	Magan	Ust-Il'ya Fm.	0(scatter)	70.07
8-00	Magan	Ust-Il'ya Fm., sandstone	0(scatter)	70.07
9-00	Magan	Lowest part of Ust-Il'ya Fm., sandstone	0(scatter)	70.07
<i>mean</i>				
<u>Steep W-up/E-down "Permian-Triassic" (Group 1)</u>				
0-08(D)	Upper Kotuykan	Dolerite sill	0.5	70.6880
0-08(C,H)	Upper Kotuykan	Exocontact and host rocks to 0-08(D)	0.5	70.6880
M-08	Upper Kotuykan	Mafic sill	1	70.7022
5-07(D)	Dzhogdzho	3-4m wide mafic dyke, trending 045°	0.5	70.2331
5-07(C)	Dzhogdzho	Exocontact to 5-07(D)	0.5	70.2331
7-07	Dzhogdzho	Kotuykan Fm., red dolostone (remagnetized by nearby)	1	70.234
13-00	Dzhogdzho	Mafic dyke, trending 030°	1	70.5025
9-07	Dzhogdzho	Weathered mafic dyke, 15m wide, trending 030°	1	70.5028
10-07	Dzhogdzho	Mafic sill, 4m thick	1	70.5028

Table 2. Paleomagnetic poles shown in Figures 9 and 10.

<i>Craton</i> /rock unit	code	Age (Ma)	Pole(°N,°E)	A ₉₅ (°)	1234567 Q	References
<i>Siberia (Anabar ref. frame)</i>						
Nersa complex A	Nersa	1641±8	−23, 130	12	1111110 6	Metelkin et al., 2005; Ernst et al., 2016a
Ilya-Burdur	Ily-Bur	1690-1500	−04, 120	9	0110100 3	<i>this study</i> ; Khudoley et al., 2015
Labaztakh-Kotuykan	Lab-Kot	< Ily-Bur	−00, 094	5	0110111 5	<i>this study</i>
West Anabar intrusions	WAnab	1503±2	−25, 061	5	1111100 5	<i>this study</i> ; Ernst et al., 2016b
North Anabar intrusions	NAnab	1483±17	−24, 075	8	1110100 4	<i>this study</i> ; Ernst et al., 2016b
Sololi-Kyutingde	Sol-Kyu	1473±24	−34, 073	10	1111100 5	Wingate et al., 2009
Malgina Fm	Malg	< 1120	15, 070 †	3	0111111 6	Gallet et al., 2000; Khudoley et al., 2015
Linok Fm	Linok	= Malgina	15, 076	8	0111111 6	Gallet et al., 2000; age from correlation
Kartochka Fm *	Kart	ca. 1050?	19, 036	12	0111101 5	Gallet et al., 2012; age interpolated from APWP
Mil'kon Fm	Milk	ca. 1050?	−06, 039 †	3	0111101 5	Pavlov and Gallet, 2010; age interpolated
Kandyk Fm	Kand	ca. 990	−09, 019 †	4	1111100 5	Pavlov et al., 2002
Kitoi mafic sheets	Kitoi	758±4	01, 022	7	1111101 6	Pisarevsky et al., 2013
<i>Laurentia</i>						
Cleaver dykes	Cleav	1740+5/-4	19, 277	6	1111101 6	Irving et al., 2004
Melville Bugt dykes	Melv	1638-1619	03, 261 ††	9	1110111 6	Halls et al., 2011
Western Channel diabase	WCh	ca. 1592	09, 245	7	1101101 5	Irving et al., 1972; Hamilton and Buchan, 2010
St Francois Mtns	StFr	1476±16	−13, 219	6	1111101 6	Meert and Stuckey, 2002
Michikamau intr. comb.	Mich	1460±5	−02, 218	5	1111011 6	Emslie et al., 1976
Spokane Fm	Spok	1470-1445	−25, 216	5	1111101 6	Elston et al., 2002
Snowslip Fm	Snow	1463-1436	−25, 210	4	1111111 7	Elston et al., 2002
Purcell lava	Purc	1443±7	−24, 216	5	1111101 6	Elston et al., 2002
Abitibi dikes	Abit	1141±2	49, 216	14	1111111 7	Ernst & Buchan, 1993; excl. A1 (Halls et al., 2008)
Logan sills	Logan	1111±3	47, 218	4	1111111 7	Lulea Working Group, 2009
Osler R – lower 3rd	OsR1	1111-1108	41, 219	4	1110111 6	Swanson-Hysell et al., 2014a
Mamainse Point R1a	MPR1a	1111-1105	50, 227	5	1111111 7	Swanson-Hysell et al., 2014b
Osler R – middle 3rd	OsR2	1110-1103	43, 211	8	1111111 7	Swanson-Hysell et al., 2014a
Osler R – upper 3rd	OsR3	1105±2	43, 202	4	1111111 7	Swanson-Hysell et al., 2014a
Mamainse Point R1b	MPR1b	1110-1100	38, 206	4	1111111 7	Swanson-Hysell et al., 2014b
Mamainse Point N1+R2	MPmid	1100.4±0.3	36, 190	5	1111111 7	Swanson-Hysell et al., 2014b
North Shore Volcanics N	NSVN	1102-1095	36, 182	3	1110111 6	Tauxe and Kodama, 2009
Chengwatana Volcanics	Cheng	1095±2	31, 186	8	1110111 6	Kean et al., 1997; Zartman et al., 1997
Portage Lake Volcanics	PLV	1095±3	27, 178	5	1111101 6	Hnat et al., 2006
Mamainse Point N2	MPN2	1100-1094	31, 183	3	1111111 7	Swanson-Hysell et al., 2014b

Cardenas basalts+intrus.	Card	1091±5	32, 185	8	1110101 5	Weil et al., 2003
Lake Shore Traps	LST	1087±2	23, 186	4	1111101 6	Kulakov et al., 2013
Nonesuch Fm	None	ca. 1065?	08, 178	6	0110100 3	Symons et al., 2013; age interpolated from APWP
Freda Fm	Freda	ca. 1055?	02, 179	4	0110100 3	Henry et al., 1977; age interpolated
Jacobsville Fm (A+B)	JacAB	ca. 1040?	-09, 183	4	0110110 4	Roy and Robertson, 1978; age interpolated
Chequamegon Fm	Cheq	ca. 1035?	-12, 178	5	0110100 3	McCabe and Van der Voo, 1983; age interpolated
Haliburton A	Hal-A	1015±15	-33, 142	6	1110000 3	Warnock et al., 2000
Adirondack fayalite granite	Ad-fay	ca. 990	-28, 133	7	1110010 4	Brown and McEnroe, 2012
Adirondack metam. anorth.	Ad-met	ca. 970	-25, 149	12	1110010 4	Brown and McEnroe, 2012
Adirondack microcl. gneiss	Ad-mic	ca. 960	-18, 151	10	1110010 4	Brown and McEnroe, 2012
Tsezotene sills	Tzes	780±2	02, 138	5	1110111 6	Park et al., 1989
Wyoming Gunbarrel dikes	WyGB	780±3	14, 129	8	1110101 5	Lulea Working Group, 2009
Uinta Mtn sandstone	Uinta	ca. 750	01, 161	5	1110110 5	Weil et al., 2006
Franklin LLP (authochth.)	Frank	ca. 720	07, 162	3	1111110 6	Denyszyn et al., 2009

Notes:

* Unit weight given to each section (N=2).

† Euler rotation parameters of pre-Devonian Aldan block to Anabar-Angara: 60, 115, 25 (Evans, 2009).

†† Euler rotation parameters of Greenland to North America: 67.5, 241.5, -13.8 (Roest and Srivastava, 1989)

The seven quality criteria and "Q" factor are described by Van der Voo (1990).

A Regional map of the Aldan Shield and surrounding areas. The map shows the distribution of geological units: Cretaceous (green), Jurassic (blue), Perm./Triassic (pink), Riph./Paleozoic (yellow), and Pre-Riphean (red). Key features include the Anabar Shield, Aldan Shield, and the Aldan River. The map is oriented with North at the top.

B Detailed map of the Aldan Shield, showing the distribution of mafic dykes and sills (green circles) and the locations of geochronology sites (stars). The map is oriented with North at the top. The legend indicates:
 - V-E: Vendian-Cambrian
 - P-T: Permian-Triassic
 - R.M: Billyakh Group
 - R.mk: Mukun Group
 - Pt1: Paleoproterozoic basement

C Detailed map of the Aldan Shield, showing the distribution of mafic dykes and sills (green circles) and the locations of geochronology sites (stars). The map is oriented with North at the top. The legend indicates:
 - V-E: Vendian-Cambrian
 - P-T: Permian-Triassic
 - R.M: Billyakh Group
 - R.mk: Mukun Group
 - Pt1: Paleoproterozoic basement

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Figure 2

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Figure 3

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Figure 4

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Figure 5

Sample 122 (site 7-04)

Sample 185 (site 12-04)

Sample DD7 (site D-08)

Sample 193 (site 12-04)

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Figure 6

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Figure 7

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Figure 1: ChRM data for Group 1, Group 2, and Group 3.

Panel A: Scatter plot of Mrs/Ms vs Bcr/Bc. The y-axis (Mrs/Ms) ranges from 0.0 to 0.6. The x-axis (Bcr/Bc) ranges from 1 to 4. The plot is divided into three regions: SD (Single Domain), PSD (Partial Single Domain), and MD (Multi-Domain). Data points are categorized by color: green (Group 3.4), purple (Group 2), and pink (Group 1). Sample labels include 3-04(D), 16-00, D-08, 3-04(D), D-08, VR1, VR1, M-08, E-08, I-08, E-08, 13-07, and I-08. Two micrographs show mineral grains with magnetic inclusions.

Panel B: ChRM GROUP 4. Two ChRM curves are shown for samples 16-00 and 13-07. The y-axis is Susceptibility (1e-6 SI) and the x-axis is Temperature (°C). Arrows indicate the direction of the magnetic field.

Panel C: GROUP 3. Two ChRM curves are shown for samples 3-04(D) and D-08. The y-axis is Susceptibility (1e-6 SI) and the x-axis is Temperature (°C). Arrows indicate the direction of the magnetic field.

Panel D: GROUP 2. Two ChRM curves are shown for samples VR1-08 and E-08. The y-axis is Susceptibility (1e-6 SI) and the x-axis is Temperature (°C). Arrows indicate the direction of the magnetic field.

Panel E: GROUP 1. Two ChRM curves are shown for samples M-08 and M-08. The y-axis is Susceptibility (1e-6 SI) and the x-axis is Temperature (°C). Arrows indicate the direction of the magnetic field.

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Figure 9

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Figure 10

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