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Paleomagnetism of Cryogenian Kitoi mafic dykes in South Siberia: implications for Neoproterozoic paleogeography

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1. Introduction

According to most Neoproterozoic paleogeographic models, the Rodinia supercontinent finally amalgamated at 1000-900 Ma and started to break up at 800-750 Ma, although the exact timing of these events and the precise configuration of Rodinia are controversial (e.g., Hoffman, 1991; Dalziel, 1997; Pisarevsky et al., 2003; Li et al., 2008). The role and place of Siberia in these events is a key part of this long-lasting controversy. Most workers suggest that Siberia was juxtaposed with the northern margin of Laurentia controversy (e.g., Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Rainbird et al., 1998; Pisarevsky et al., 2008; but see Sears and Price, 2000), but a more precise reconstruction is hindered by the lack of early and middle Neoproterozoic paleomagnetic data.

Although reliable ca. 1500-1450 Ma and ca. 1050-950 Ma paleomagnetic data from Siberia and Laurentia (Table 2; see also Pavlov, 1994; Ernst et al., 2002; Veselovsky et al., 2006) support coherent movement of these two continents during most of Mesoproterozoic, they also suggest a paleolatitudinal separation, implying the presence of some other continental block(s) in between (Wingate et al., 2009). The apparent absence of any exposures of the giant 1267 Ma Mackenzie igneous event in Siberia supports this inference (Gladkochub et al., 2006a, b; Pisarevsky et al., 2008). However, the 710-730 Ma mafic igneous rocks along the southern margin of Siberia (Neimark et al., 1990; Rytsk et al., 2002; Ernst et al., 2012) may be related to the Laurentian 723 Ma Franklin giant igneous event. If so, at ca. 720 Ma Siberia may

have been closer to Laurentia than it was in Mesoproterozoic, a hypothesis that would have major implications for Neoproterozoic reconstructions and for models of Rodinia breakup. Some reliable ca.790-720 Ma paleomagnetic data from both continents are therefore needed to test this hypothesis. Sklyarov et al. (2003) reported a 743 ± 47 Ma Sm–Nd isochron age and a 758 ± 4 Ma ^{40}Ar-^{39}Ar plateau age for mafic dykes along the Kitoi river in the Sharyzhalgai massif of the southern Siberia (Fig. 1) which may be related to the Franklin event. A pilot study of these dykes (Konstantinov, 2006) demonstrated the presence of a stable paleomagnetic remanence. In this paper we present results of a 2009 field study in which we carried out a detailed paleomagnetic sampling of the Kitoi dykes with the purpose of obtaining a highly reliable Cryogenian paleomagnetic pole for Siberia.

2. Geology and sampling.

The Siberian craton (Fig. 1a) is a Paleoproterozoic collage of mostly Archean granulite-gneiss and granite-greenstone complexes (Rosen et al., 2005) surrounded by major Phanerozoic suture zones (Zonenshain et al., 1990; Parfenov, 1991). The basement is exposed only in two shields, Aldan-Stanovoy and Anabar, and in some outcrops of the Olenek (north), Kan, Biryusa, Sharyzhalgai, and Baikal (south-west) inliers (Fig. 1; Gladkochub et al., 2006a).

Several Proterozoic mafic dyke swarms and some associated sills are located along the western shore of Lake Baikal and at the basement inlier of the Archean Tungus superterrane, known as the Sharyzhalgai metamorphic massif (Fig. 1a). The Sharyzhalgai massif is composed of Archean tonalite-trondhjemite-granodiorite (TTG) series, Archean and Paleoproterozoic granite-gneisses, metavolcanic and metasedimentary rocks, including granulites. These rocks are intruded by ca. 2530 Ma Kitoi granitoids (Gladkochub et al., 2005) and ca. 1850 – 1870 Ma Sayan and Shumikha granites (Donskaya et al., 2002; Levitskii et al., 2002; Didenko et al., 2003;

Poller et al., 2004). Most of the Sharyzhalgai massif, including our study area, is located far from the Main Sayan Fault and from the Baikal rift, so no tilting or block rotations related to Phanerozoic tectonism occurred here. Mafic intrusions of two different magmatic episodes have been described (Sklyarov et al., 2003).

Dykes related to the first magmatic episode are rare. They are composed of medium grained sub-alkaline gabbro-dolerites that are sub-vertical in orientation (Sklyarov et al., 2003; Gladkochub et al., in press). These dykes are slightly deformed and metamorphosed, containing minerals typical of greenschist facies. One of these dykes has been recently dated at 1864 ± 4 Ma by U-Pb (zircon, TIMS; Gladkochub et al., in press).

The dykes (or sheets) associated with the second episode are abundant in the Sharyzhalgai massif. These dykes are commonly 1.5-3.0 m wide, shallowly (25-35°) dipping to SW, and are composed mostly of unaltered fine-grained gabbro-dolerite of tholeiitic composition (Fig. 1b; Sklyarov et al., 2003). Some of the dykes can be mapped up to 7–8 km in length, but aeromagnetic data suggest that individual dykes may attain a length of 12–15 km (Sklyarov et al., 2003). Similarities in mineralogy, geochemistry, petrology and structural orientation (Sklyarov et al., 2003) suggest that these dykes are coeval and are derived from a single mantle source. One of these dykes (K5, Fig.1) was dated at 758 ± 4 Ma (^{40}Ar-^{39}Ar, plagioclase) and 743 ± 47 Ma (Sm-Nd, whole rock-mineral) by Sklyarov et al. (2003) and these data suggest a ca. 760 Ma age for the intrusions.

In 2009 we collected paleomagnetic samples from eleven Sharyzhalgai ca. 760 Ma shallow-dipping dykes and from two vertical Late Paleoproterozoic (episode 1) dykes in outcrops along the Kitoi River. Cross-cutting relationships between older and younger dykes were observed in one location (Fig.1b) which was sampled for the paleomagnetic bake contact test. In total we collected 178 oriented cores from 13

dykes and host rocks. Both solar and magnetic compasses were used to determine the orientation.

3. Analytical methods

Remanence behaviour was determined by detailed stepwise alternating field (AF) demagnetisation (≤ 20 steps, up to 100 mT), using an AGICO LDA-3A tumbling demagnetiser and the 2G cryogenic magnetometer in the University of Edinburgh. Thermal stepwise demagnetisation (≤ 20 steps, to 600°C), using a Magnetic Measurements MMTD1 furnace was also applied. Magnetic mineralogy was investigated from demagnetisation characteristics and, in selected samples, from measuring the variation of susceptibility versus temperature (20 to 700°C) using the AGICO Kappabridge MFK-FA with the CS3 apparatus. Parts of the collection were studied in the paleomagnetic laboratory of Utrecht University (Netherlands). Magnetisation vectors were isolated using Principal Component Analysis (Kirschvink 1980).

All minerals were analysed using a modified MAR-3 microprobe in the Geological Institute SB RAS (Ulan-Ude) using standard conditions of analysis (operators Karmanov and Kanakin). See Table 1 of Sklyarov et al. (2003) for details.

4. Magnetic mineralogy and rock magnetism

Microprobe studies of ca. 760 Ma dykes indicate the presence of mostly homogeneous titanomagnetite in the Cryogenian gabbro-dolerites (Sklyarov et al., 2003). This observation is supported by magnetic susceptibility versus temperature curves (Fig. 2a) Curie temperatures are distributed between 500° and 570°C, which corresponds to a titanium-poor titanomagnetite $Fe_{3-x}Ti_xO_4$ with $x \approx 0.05$-0.10 (Fig. 3.11 in Dunlop and Özdemir, 1997). Konstantinov (2006) reached similar conclusions in his preliminary studies of these dykes using differential

thermomagnetic analysis (DTA) and analyses of coercivity spectra. Hopkinson peaks (Fig. 2) indicate the presence of paleomagnetically highly stable single-domain (SD) or pseudo-single-domain (PSD) grains.

The 1864 Ma vertical dykes show similar distribution of Curie temperatures also indicating SD or PSD titanium-poor titanomagnetite (Fig.2b) and DTA analyses led to the same conclusion (Konstantinov, 2006).

5. Paleomagnetic analysis

5.1. 760 Ma dykes

The intensity of the natural remanent magnetization (NRM) of Cryogenian gabbro-dolerites ranges from 20 mA/m to 2.5 A/m, and their magnetic susceptibility from ~2 to 90×10^{-4} SI units. After removal of a low-stability, randomly oriented overprint, thermal (Fig. 3a), AF demagnetisations (Fig. 3b) and a combination of both (Fig. 3c) of the Cryogenian gabbro-dolerites reveal a stable shallow eastward unipolar characteristic magnetisation ChRM. Unblocking temperatures are in most cases between 550 and 590°C typical for the titanium-poor titanomagnetite and magnetite. The relatively high coercivities of these gabbro-dolerites are indicative of SD or PSD titanomagnetite and magnetite - typically 60 to 100 mT was required for the AF demagnetization (Fig.3b). Mean ChRM directions for each dyke are shown in Table 1 (entries 1-11). Remanence directions from all dykes, except for K9, show reasonably well grouping with $\alpha_{95} < 16°$. The mean direction for ten dykes (dyke K9 was excluded) is: D = 80.8°, I = -12.1°, k = 42.8, $\alpha_{95} = 7.8°$. The corresponding paleomagnetic pole of 1.1°N, 21.8°E (A_{95}=7.4°) falls far from any younger Siberian paleopole (McElhinny and Lock, 1996; Smethurst et al., 1998; Pisarevsky, 2005; Shatsillo and Pavlov, 2006; Metelkin et al., 2012), suggesting that the ChRM of studied gabbro-dolerites is primary.

5.2. Paleoproterozoic dykes

The remanence of nearly vertical Paleoproterozoic dykes is also stable (Fig. 4a), but its directions are rather scattered (Table 1) and vary significantly from dyke to dyke (Table 1; Fig.5b). The K4 dyke is exposed only near the contact of the cross-cutting 760 Ma K3 dyke. The remanence directions of all (except two) K4 samples are similar to the remanence direction of the K3 dyke. The remanence directions of dykes K6 and K7 apparently represent two geomagnetic polarities, but the mean directions are not antipodal (Table 1). This disparity may reflect either a significant time difference in their magnetisations, or a high level of geomagnetic secular variations. In either case the corresponding paleopoles (entries 14-16 in Table 1) should be considered as Virtual Geomagnetic Poles (VGPs), which may reflect positions of geomagnetic rather than geographic pole at the time of the dyke's emplacement.

6. Contact tests

We collected ten samples from the 1864 Ma dyke K4 within 102 cm from its contact with the shallow dipping 760 Ma dyke K3. Eight of these samples were collected within 70 cm from the contact and yield the remanence direction similar to the mean remanence direction of dyke K3 (Table 1, entry 12; Fig. 4b; Fig. 5a), shown as a star in Fig. 5. However, the remanence directions of two K4 samples collected at >70 cm from the contact are steeper and are close to the inverted mean direction for another 1865 Ma dyke K7. We tentatively interpret these data to provide a positive contact test and evidence for the primary remanences of both sets of dykes.

We collected fourteen samples from host gneisses within 1 m from dykes K3, K5, K8, K9, K12, K13 and K14 and thirty one samples from host gneisses far from their contacts with dykes. Half of the unbaked gneiss samples are paleomagnetically unstable, but the other half yield a scattered bipolar remanence (Table 1, entry 17; Fig. 4c; Fig. 5b). After an inversion of downward directions, this remanence has a

loose grouping with a mean direction of D=13°, I=-67° (α_{95}=24°). The age of this remanence is unclear, but its direction is significantly different from that of the 760 Ma dykes (Table 1; Fig.5b). All baked rocks yield stable remanence close to that of the 760 Ma dykes (Table 1, entry 13; Fig. 4d; Fig. 5b). We interpret these data as evidence for the primary remanence of 760 Ma dykes, but cannot classify it as the full positive contact test because of the scattered remanence of the unbaked host rocks.

7. Discussion

Our new 760 Ma paleomagnetic pole suggests an equatorial position of the Siberian craton rotated by about 90° clockwise compare to its present-day orientation. This pole provides a test for published Neoproterozoic continental reconstructions. Most of these reconstructions imply contiguity between Siberia and Laurentia during at least some part of the Proterozoic, but the precise configuration and timing have been widely debated (e.g. Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Rainbird et al., 1998; Sears and Price, 2000; Gallet et al., 2000; Pisarevsky and Natapov, 2003; Gladkochub et al., 2006b; Pisarevsky et al., 2008; Wingate et al., 2009). Paleomagnetic tests (Pisarevsky and Natapov, 2003; Pisarevsky et al., 2008) indicate that (i) reconstructions with 'tight' fit between Laurentia and Siberia (Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Rainbird et al., 1998; Sears and Price, 2000) are not supported by 1050-950 Ma paleomagnetic data and (ii) Laurentia and Siberia could have moved coherently during that time only if Siberia has been located NW of Laurentia with significant 'gap' between them that was presumably occupied by some yet unknown piece(s) of the continental crust. Possibly those pieces included some fragments of Arctic Alaska (Rainbird et al., 1996).

Wingate at al. (2009) reported a new ca 1475 Ma Siberian paleomagnetic pole. This pole together with coeval Laurentian pole of Meert and Stuckey (2002) suggest that the distant position of Siberia with respect to Laurentia may be valid between ca.

1500 and 1000 Ma. This distant relationship might explain an apparent absence of any traces of the giant 1267 Ma Mackenzie igneous event in Siberia (Gladkochub et al., 2006b; Pisarevsky et al., 2008).

Notably, these hypotheses assume that Siberian craton behaved as a rigid coherent continent since Mesoproterozoic to present time. Gurevich (1984) analysed Early Paleozoic Siberian paleomagnetic data and suggested that there was a significant mismatch between poles from SW Siberia (Aldan block) and poles from NW Siberia (Anabar-Angara block), which implies a clockwise rotation between two blocks during the opening of the v-shaped Vilyui syneclise in Devonian times. Pavlov et al. (2008) provided more geophysical, geological and paleomagnetic evidence for such rotation and reported the best estimation of Euler rotation parameters. Using these parameters we modified the shape of the pre-Devonian Siberia (figs. 6-8). This restoration also caused the rotation of ca. 1050-950 Ma Siberian poles (Pavlov et al., 2000, 2002; Gallet et al., 2000) from the Aldan block (Table 2). These readjustments provide a tighter fit of ca.1500-950 Ma coeval Siberian and Laurentian poles, but still require a distant position of Siberia with respect to Laurentia (Fig. 6).

There are no reliable ca. 760 Ma Laurentian poles (Table 2), but the closeness of precisely dated 778 ± 2 Ma Tzesotene Sills (TS) and Gunbarrell Dykes (GD) poles to precisely dated 723+4/-2 Ma Franklin Dykes (FD) pole and less precisely dated Uinta Formation (UF) pole (Table 2) suggest a little movement of Laurentia between ca. 780-720 Ma. Hence we reconstructed the ca. 760 Ma position of Siberia and Laurentia using our new Kitoi pole and the middle point between Laurentian 778 ± 2 Ma and 723+4/-2 Ma poles (Tables 1 and 2; Fig. 7). This reconstruction implies that after ca.1000 Ma Siberia obliquely moved closer to Laurentia to its new position at 760 Ma (Fig. 7). The exact timing of this movement is not constrained. However, it could be associated with the 780 Ma Gunbarrel magmatic event (Harlan et

al., 2003) which reflects rifting along the western margin of Laurentia (e.g., Hoffman, 1999; Powell et al., 1994) and the first stage in the breakup of Rodinia (Li et al., 2008 and references therein).

Our paleomagnetic data suggest that modifications to recently published Neoproterozoic reconstructions are required to accommodate the oblique (clockwise) convergence of Siberia relative to Laurentia in addition to the separation of Australia/South China from Laurentia (Li et al., 2008). Taken together, these relative motions require that Siberia, Laurentia and Australia/South China are on three different plates, implying the existence of a triple point between them. Fig. 8 shows a possible scenario for this event, one which can be tested against the tectonothermal evolution of several adjacent continental blocks. The approximately orthogonal separation of Australia/South China from both Laurentia and Siberia suggests that the plate boundaries between them were oceanic ridges. However, the oblique convergence between Laurentia and Siberia implied by the paleomagnetic data suggests that the plate boundary between these continents was a transform fault that accommodated the relative dextral (clockwise) motion between them.

The scenario presented in Figure 8 implies nearly orthogonal convergence between Baltica and Siberia, implying the existence of a subduction zone between them. However, the arc that may record this convergence has not been identified. As the leading edge of Siberia has no record of arc magmatism, we place Siberia on the lower plate, although it is possible that an unknown continental block may have been positioned between Siberia and Baltica in which case the polarity of subduction is unclear.

The new, closer position of Siberia and Laurentia suggests that some traces of the giant ca. 723 Ma Franklin magmatic event might occur in southern Siberia. There were no ca. 723 Ma magmatic bodies reported from southern Siberia until recently. However, Ernst et al. (2012) published a ca. 725 Ma age (U-Pb, ID-TIMS,

baddeleyite) of the Dovyren pluton in the Baikal-Patom margin of the Siberian craton (Fig. 1). On the other hand, to our knowledge, no igneous rocks coeval to ca. 760-740 Ma Biryusa sills (Gladkochub et al., 2006) and Kitoi dykes (Sklyarov et al., 2003) were reported from northern Laurentia. The latter can be explained either by the local extend of the ca. 760-740 Ma magmatism in southern Siberia, or by a passing of Siberia-Laurentia system over the mantle plume between ca. 760 Ma (causing some minor magmatism in southern Siberia) and 725 Ma, eventually causing the giant Franklin magmatic event, involved the southern margin of Siberia (725 Ma Dovyren pluton, Ernst et al., 2012) (Fig. 8). The data used by Sklyarov et al. (2003) to define the Sm-Nd isochron for the ca. 760 Ma mafic dykes yield εNd (t) values ranging from -3.5 to -3.9, suggesting the dykes were derived from an enriched subcontinental mantle (EM1) source characterized by time-integrated depletion of Sm relative to Nd (e.g. Bell and Simonetti, 1996). This signature contrasts with the more radiogenic signature of the Franklin dykes (e.g. Shellnutt et al., 2004), an evolution that might reflect a stronger asthenospheric component to plume-related magmatism with time. In both scenarios the Franklin magmatic pulse could cause a new rifting along the Arctic margin of Laurentia (Rainbird, 1993). We suggest that this rifting caused an opening of the Paleo-Asian Ocean and a dramatic change in the movement of Siberia, eventually resulting in almost 180° rotation of Siberia by the Early Cambrian, as indicated by abundant, but not always precisely dated Ediacaran and Cambrian paleomagnetic data from Siberia (e.g. Kirschvink and Rozanov, 1984; Pisarevsky et al., 2000, 1997; Pavlov and Gallet, 1998; Gallet et al., 2003; Shatsillo and Pavlov, 2006; Pavlov et al., 2008 and references therein). The ca. 720 Ma Franklin magmatic event could have increased of the speed of Siberia away from the plume and slowed down or even reversed the movement of Laurentia, a scenario analogous to the process started by the Reúnion plume at 60-55 Ma (Cande and Stegman, 2011). Franklin plume activity may have resulted in the fan-like opening of the Palaeo-Asian

Ocean and initiated the clockwise rotation of Siberia. Details of this rotation are beyond the scope of this study and will be published elsewhere.

8. Conclusions

According to our analysis the relative movement between Laurentia and Siberia could occur during the first stage of the breakup of Rodinia between 0.80 and 0.75 Ga, which amalgamated at ca. 1.0 Ga. We propose that the dextral transpressive motion of Siberia relative to Laurentia between 0.78 and 0.76 Ga implied in Fig. 8 may be indirectly related to the rifting along the western Laurentian margin (Fig. 8). This motion also may cause subduction and strike-slip motions between Siberia, Greenland and Baltica, but corresponding arc complexes have not yet been identified.

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Figure captions

Fig. 1. (a) Precambrian tectonic and paleogeographic elements of the Siberian Craton; (b) geology of the study area and sampling localitie.

Fig. 2. Magnetic susceptibility (κ) versus temperature curves; (a) 760 Ma dyke; (b) 1865 Ma dyke.

Fig. 3. Demagnetisations of the 760 Ma dykes. In orthogonal plots, open (closed) symbols show magnetisation vector endpoints in the vertical (horizontal) plane; curves show changes in intensity during demagnetisation. Stereoplots (equal-angle projection) show upwards (downwards) pointing palaeomagnetic directions with open (closed) symbols; (a) thermal demagnetisation; (b) AF demagnetisation; (c) combination of AF and thermal demagnetisations.

Fig. 4. Demagnetisations of the 1865 Ma dykes and country gneiss; (a) 1865 Ma dyke K6; (b) 1865 Ma dyke K4, 5 cm from the contact with 760 Ma dyke K3; (c) country gneiss distal from dykes; (d) country gneiss, 10 cm from 760 Ma dyke K5.

Fig. 5. Baked contact tests; (a) contact between 760 Ma dyke K3 and 1865 Ma dyke K4 (squares denote mean remanence directions of the 1865 Ma dyke K6 and K7, the latter is inverted); (b) remanence directions of baked and unbaked gneiss. Star denotes the mean remanence direction of ten 760 Ma dykes.

Fig. 6. New paleomagnetically supported reconstruction of Laurentia and Siberia at 1000 Ma. Laurentia is rotated to the absolute framework about a pole at 10.32°N, 142.27°W by -25.33°. Siberia is rotated to Laurentia about a pole at 69.95°N,

133.23°E by +127.05°. Southeastern Siberia (Aldan block) is rotated to northwestern Siberia about a pole at 62°N, 117°E by +23° (Pavlov et al., 2008). Acronyms for paleopoles are as in Table 2.

Fig. 7. Displacement of Siberia with respect to Laurentia after 1000 Ma: (a) paleogeographic reconstruction in Laurentian coordinates, at 760 Ma Siberia is rotated to Laurentia about a pole at 69.66°N, 78.92°E by + 130.99° ; (b) paleomagnetic poles (polar projection).

Fig. 8. 780 Ma (a), 760 Ma (b) and 725 Ma (c) reconstructions of Laurentia, Siberia, South China and Australia. Rotation parameters: (a) Laurentia is rotated to the absolute framework about a pole at 16.11°N, 59.52°E by +87.4°, Siberia is rotated to Laurentia about a pole at 69.95°N, 133.23°E by +127.05°; (b) Laurentia is rotated to absolute framework about a pole at 10.28°N, 67.42°E by +90.91°, Siberia is rotated to Laurentia about a pole at 69.66°N, 78.92°E by +130.99°; (c) Laurentia is rotated to absolute framework about a pole at 6.37°N, 78.52°E by +83.24°, Siberia is rotated to Laurentia about a pole at 69.66°N, 78.92°E by +130.99°. Rotation parameters for Australia and South China are as in Li et al. (2008).

Table

Table 1. Paleomagnetic directions and poles, dolerite dykes, Kitoi River, South Siberia

#	Dyke	Locality	N/n	Slat (°N)	Slong (°E)	Decl. (°)	Incl. (°)	k	α_{95} (°)	Plat (°N)	Plong (°E)	D_p (°)	D_m (°)
Neoproterozoic (~760 Ma) dykes													
1	K1	Alangar	19/17	52°19.57’	102°50.92’	89.8	-13.6	10.6	11.5	5.3	17.2	6.0	11.7
2	K2	“	9/7	52°19.75’	102°50.56’	80.9	-35.2	15.7	15.8	9.9	31.9	10.5	18.2
3	K3	Proval	16/8	52°14.26’	102°47.72’	76.3	-12.3	15.3	14.6	-3.4	27.5	7.6	14.6
4	K5	“	11/9	“	“	80.7	0.0	26.4	10.2	-5.7	20.2	5.1	10.2
5	K8	“	13/11	52°13.99’	102°47.46’	76.8	-8.9	28.1	8.8	-4.5	26.0	4.5	8.9
6	K9*	Kholomkha	14/7	52°11.41’	102°46.54’	61.2	-12.3	9.4	20.8	-12.0	39.8	10.2	21.2
7	K10	“	6/6	“	“	83.4	3.1	36.3	11.1	-5.3	17.1	5.7	11.3
8	K11	“	8/8	“	“	81.8	-2.8	44.8	8.4	-3.9	20.1	4.2	8.4
9	K12	“	10/6	“	“	78.8	-24.8	40.3	10.7	3.5	29.5	6.2	11.5
10	K13	“	15/10	“	“	86.4	-5.5	23.0	10.3	0.0	17.3	5.2	10.3
11	K14	“	5/5	“	“	72.7	-20.5	41.4	12.0	-1.9	32.9	6.6	12.6
	Mean for 10 dykes		***126/94***			***80.8***	***-12.1***	***39.7***	***7.8***	***1.1***	***22.4***	A_{95}***=7.4°***	
Baked rocks													
12	K4**	“	10/8	52°14.26’	102°47.72’	83.4	-5.7	30.0	11.2	-1.2	19.1	5.6	11.2
13		Baked gneiss	14/14			82.5	1.4	18.7	9.4	-5.1	18.3	4.7	9.4
	Mean for 1-5,7-13		***150/116***			***81.3***	***-10.4***	***42.8***	***6.7***	***0.4***	***21.8***	A_{95}***=6.1°***	
Paleoproterozoic (1864 Ma) dykes													
14	K4[§]	Proval	2/2	52°14.26’	102°47.72’	101.0	-51.8	-	-	31.5	26.4	-	-
15	K6	“	11/9	“	“	197.7	-44.4	13.4	14.6	60.6	249.0	11.5	18.4
16	K7	“	9/7	“	“	254.0	46.0	7.5	23.6	12.3	41.9	19.3	30.2
Unbaked host rocks													
17			31/15			12.9	-66.6	3.6	23.8	12.0	94.2	32.3	39.2

N/n=number of demagnetised /used samples; Slat, Slong=locality latitude and longitude; Decl, Incl =site mean declination, inclination; k =best estimate of the precision parameter of Fisher (1953); α_{95}= the semi-angle of the 95% cone of confidence; Plat, Plong = latitude, longitude of the paleopole; D_p ,D_m =the semi-axes of the cone of confidence about the pole at the 95% probability level.

* excluded from the overall mean

** samples remagnetised by K3 dyke

[§] not remagnetised by K3 dyke

Table

Table 2. Laurentian and Siberian ca. 1475 Ma, ca. 1080-1000 Ma and ca. 780-720 Ma palaeomagnetic poles.

#		Rockname	Age (Ma)	Plat (°N)	Plong (°E)	A_{95} (°)	Reference
				Laurentia			
1	SF	St.Francois Mountains	1476 ± 16	-13.2	219.0	6.1	Meert and Stuckey, 2002
2	LS	Lake Shore Traps	1087 ± 2	22.2	180.8	4.5	Diehl and Haig, 1994;Davis and Paces, 1990
3	FS	Freda Sandstone	1050 ± 30	2.2	179.0	4.2	Henry et al., 1977; Wingate et al., 2002
4	NS	Nonesuch Shale	1050 ± 30	7.6	178.1	5.5	"
5	CS	Chequamegon Sandst.	1020 ± 30	-12.3	177.7	4.6	McCabe and Van der Voo , 1983
6	JS	Jacobsville Sandstone	1020 ± 30	-10.0	184.0	4.2	Roy and Robertson, 1978
7	HI	Haliburton Intrusion	1030-1000	-32.6	141.9	6.3	Warnock et al., 2000
8	TS	Tzesotene Sills	778 ± 2	1.6	137.8	5.0	Park et al., 1989
9	GD	Gunbarrell Dykes	778 ± 2	13.9	129.4	8.2	Harlan et al., 1997
10	UF	Uinta Formation	800-750	0.8	161.3	4.7	Weil et al., 2006
11	FD	Franklin Dykes	723+4/-2	6.7	162.1	3.0	Denyszyn et al., 2009
				Siberia			
12	KS	Kyutingde, Sololi intrusions, Siberia	1473 ± 24	33.6	253.1	10.4	Wingate et al., 2009
13	MF	Malgina Formation*	1043±14	-15.4	248.8	2.6	Gallet et al., 2000; Ovchinnikova et al., 2001
14	KF	Kumakha Formation*	1040-1030	-3.2	221.4	7.0	Pavlov et al., 2000
15	MF	Milkon Formation*	~1025	5.1	216.3	3.8	"
16	NF	Nelkan Formation*	1025-1015	-4.4	238.8	6.3	"
17	IF	Ignikan Formation*	1015-1005	-5.3	221.8	7.4	"
18	KA	Kandyk Formation*	1000-950	7.0	196.7	4.3	Pavlov et al., 2002
19	UK	Ust-Kirba Formation*	<KA	2.3	253.1	10.4	"
20	KD	Kitoi Dykes	758 ± 4	-0.4	201.8	6.1	This study

*poles rotated to NW Siberia by 23° anticlockwise , Euler's pole is 62°N, 117°E (Pavlov et al., 2008)

Figure

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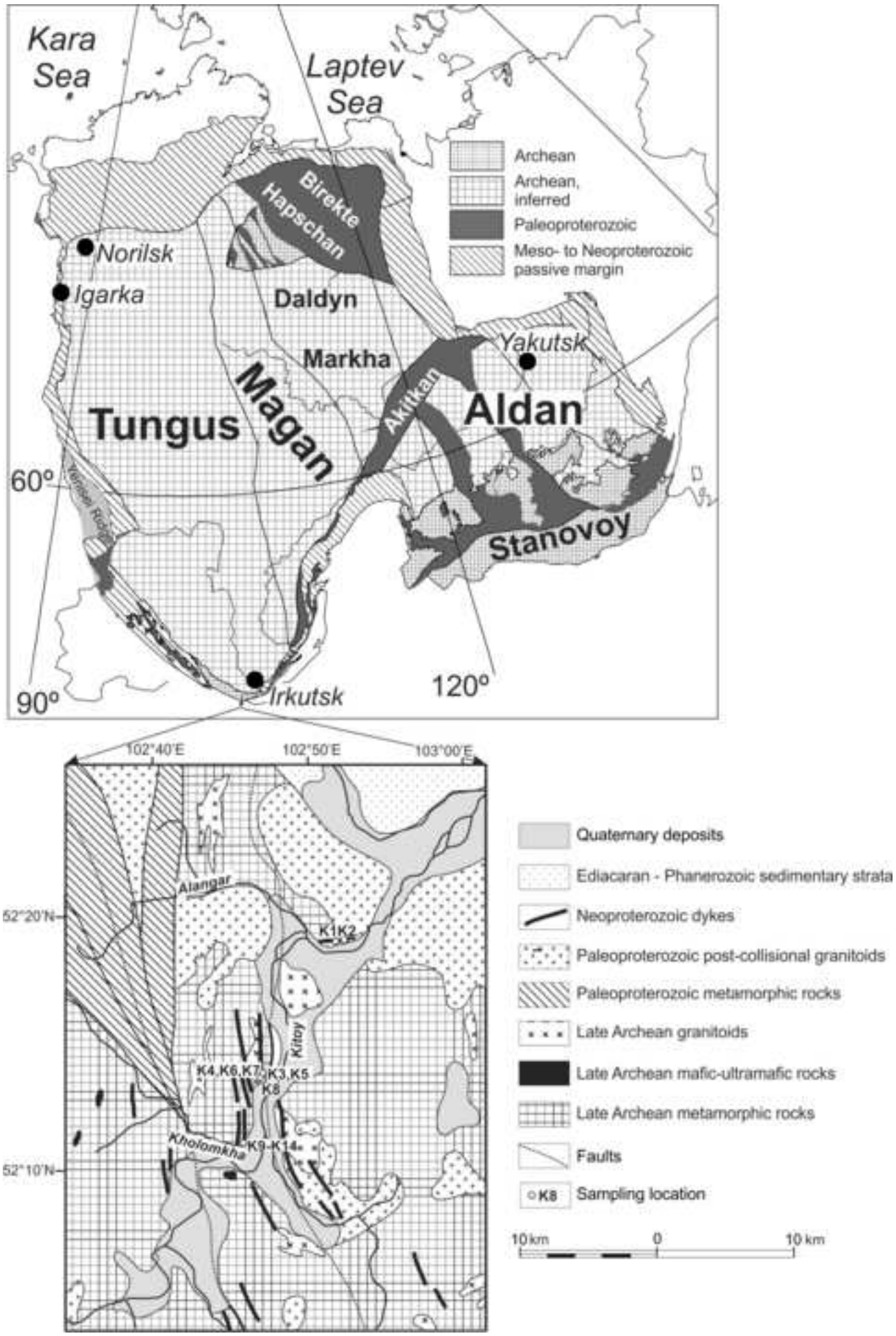
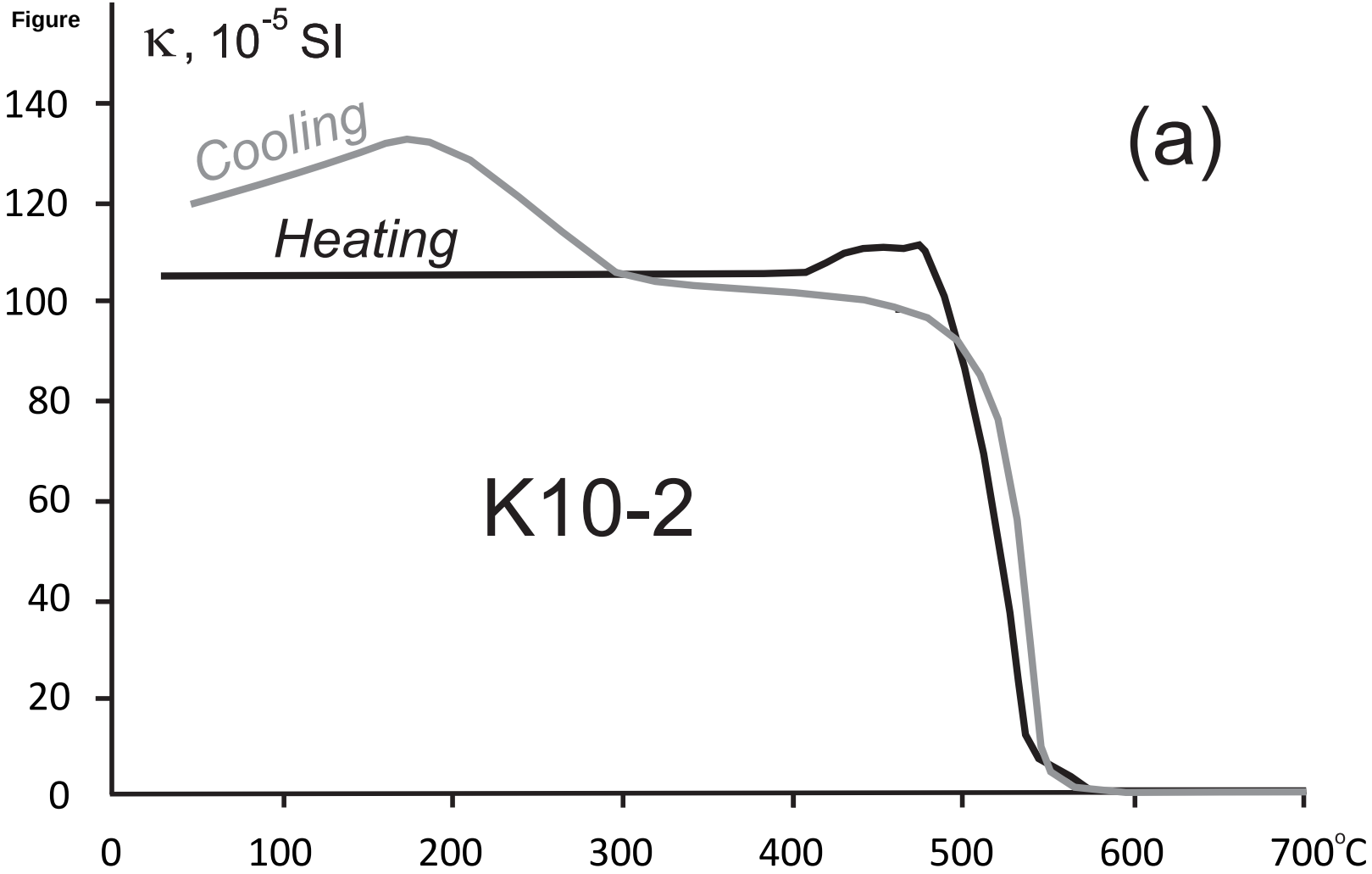


Figure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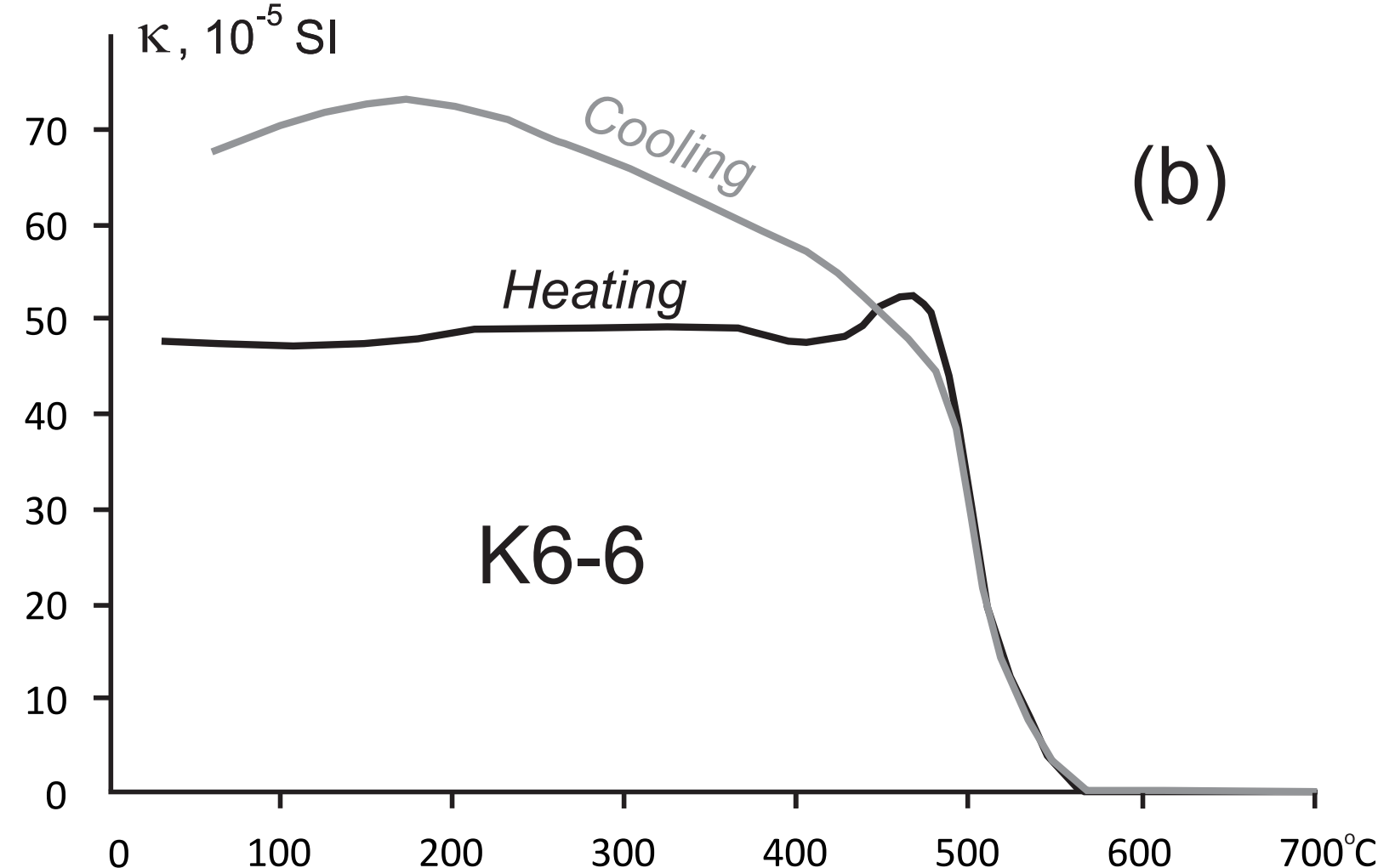
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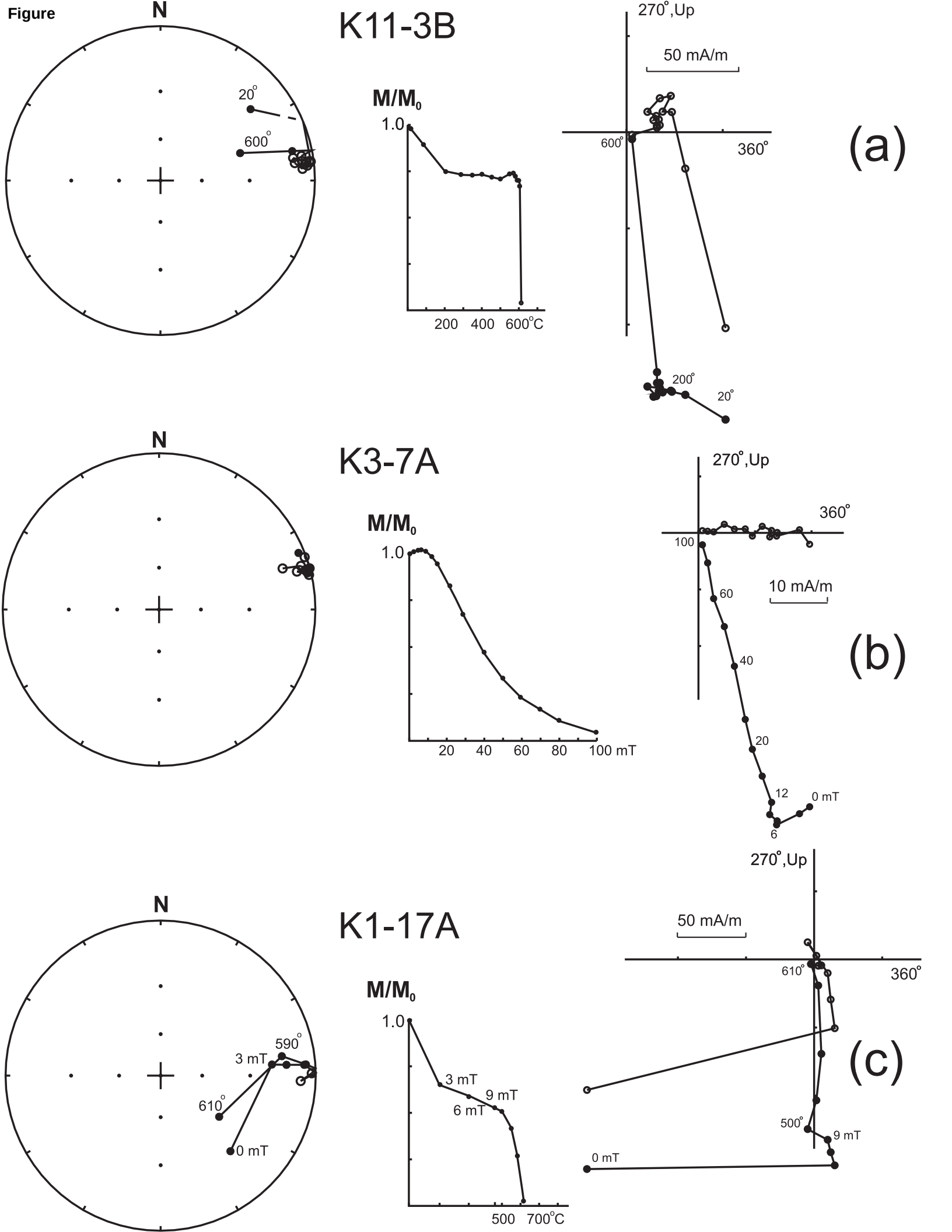
Figure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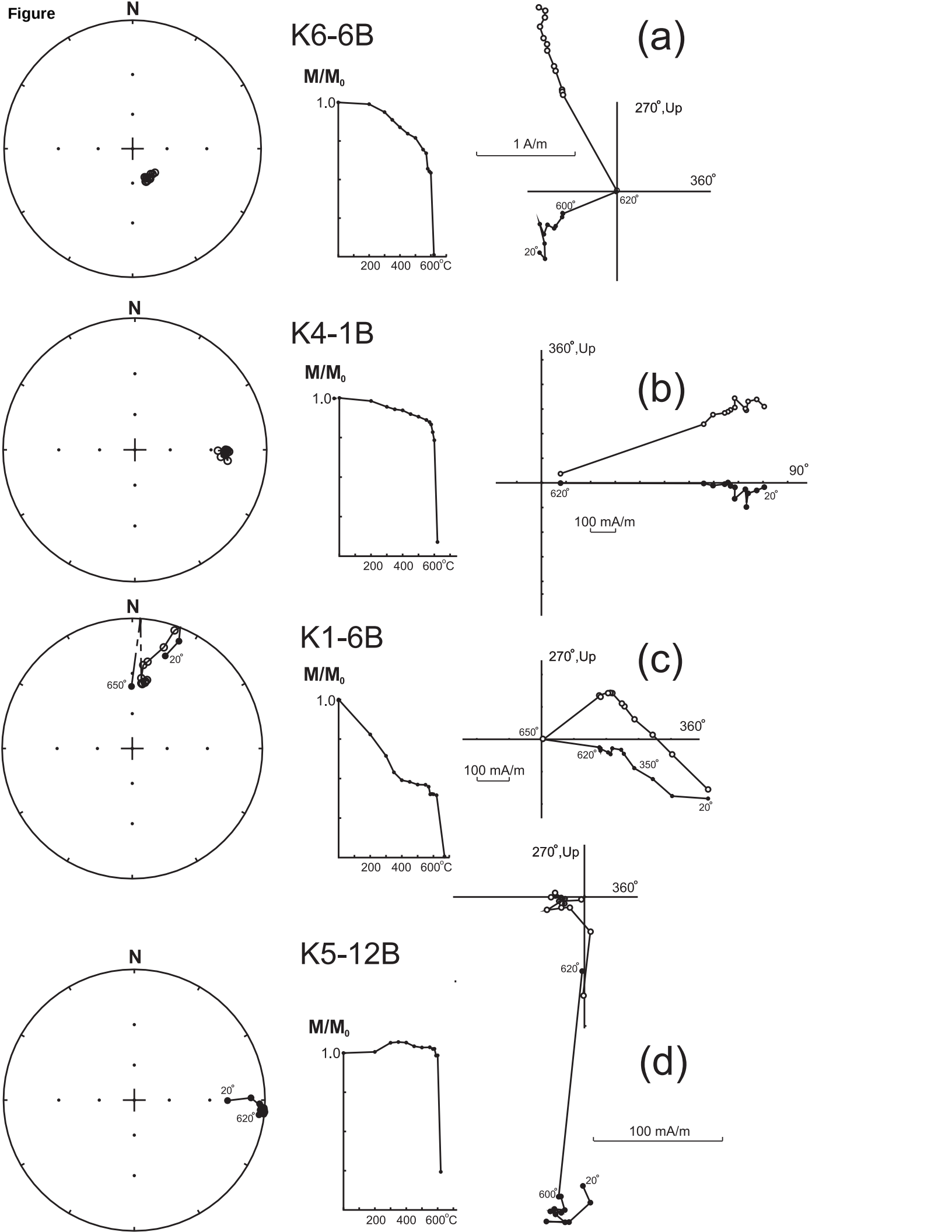
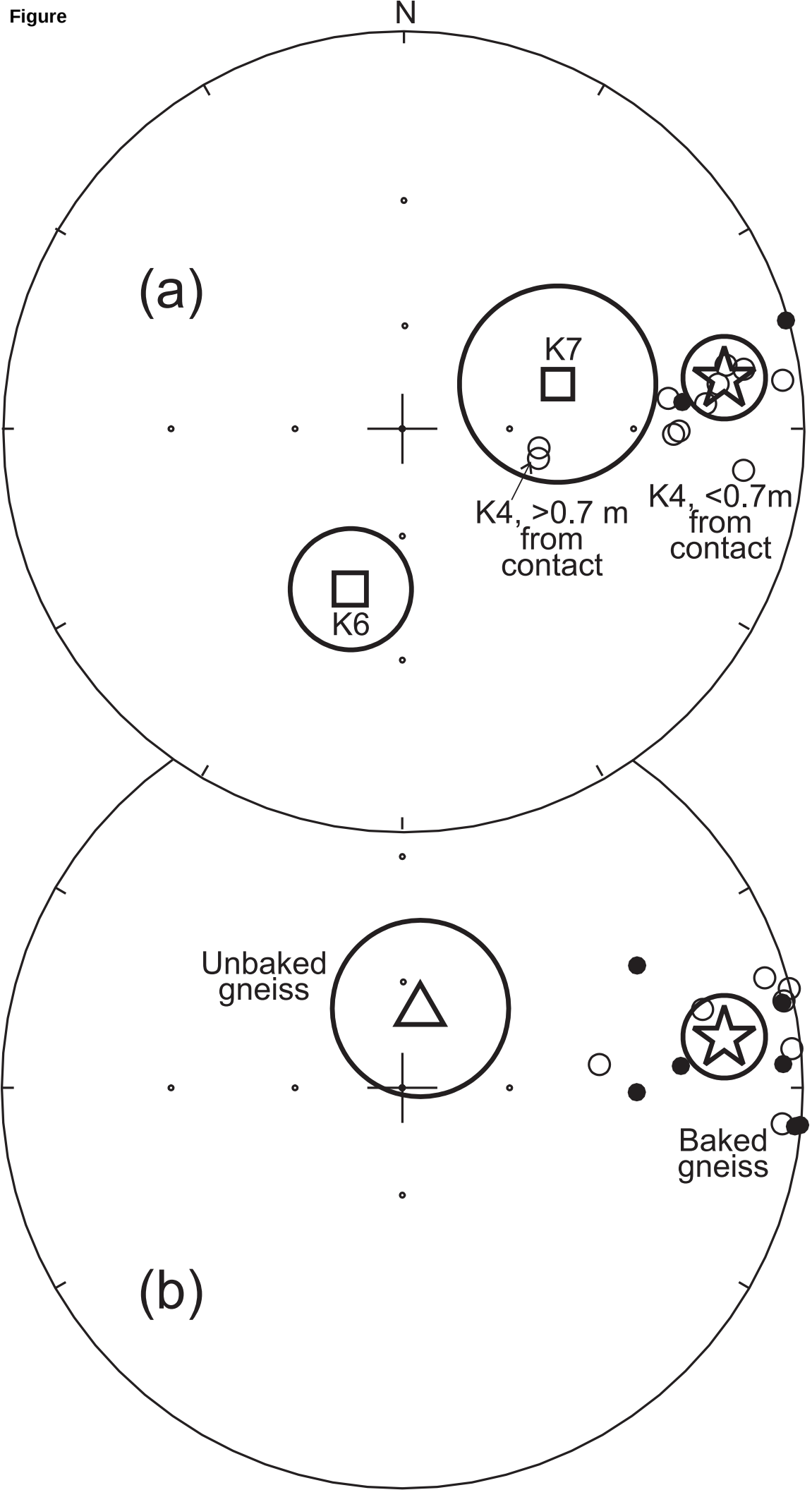
(c)

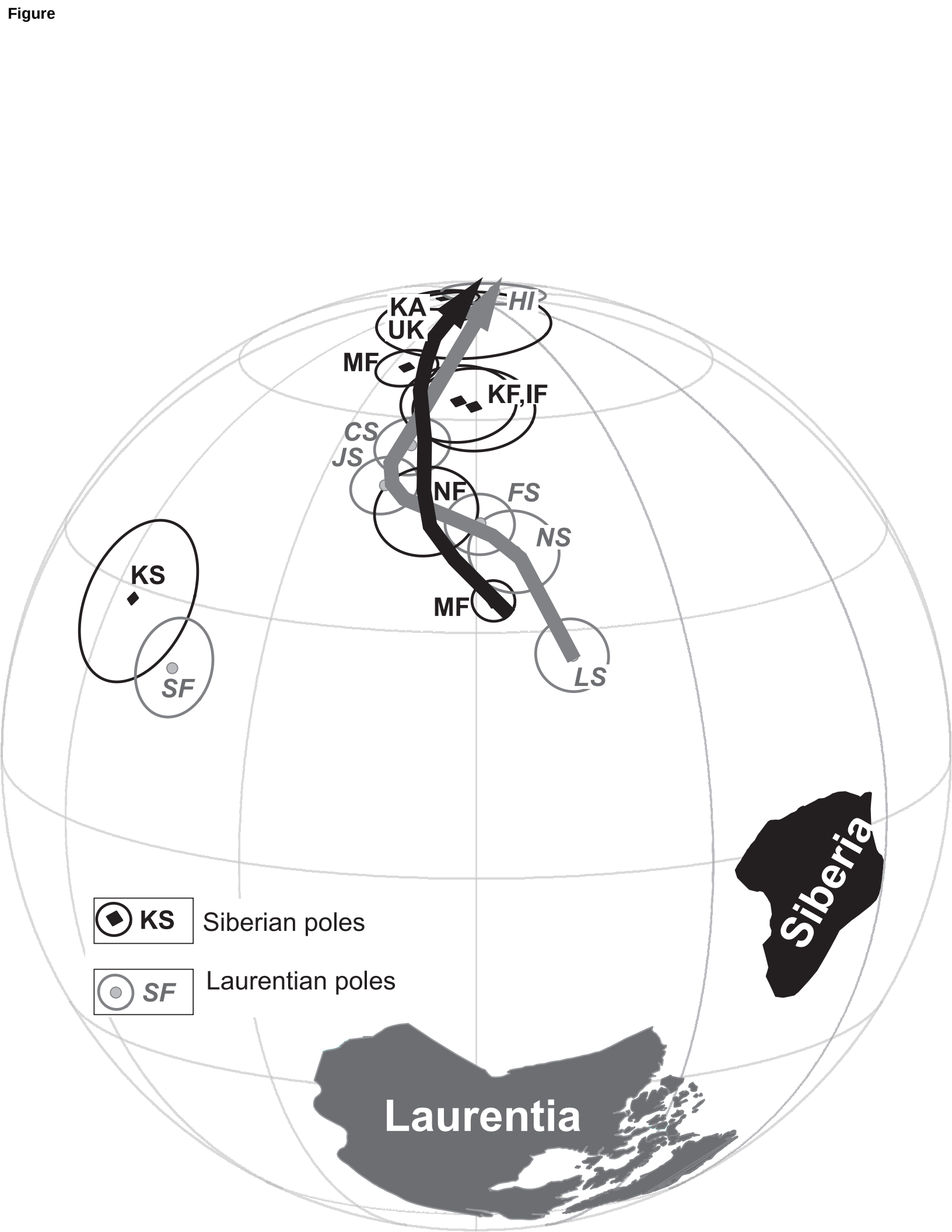
Figure


N
K6-6B
M/M0
1.0
200 400 600°C
270°,Up
1 A/m
360°
620°
600°
20°
(a)
N
K4-1B
M/M0
1.0
200 400 600°C
360°,Up
(b)
90°
620°
20°
100 mA/m
N
K1-6B
M/M0
1.0
200 400 600°C
270°,Up
(c)
650°
360°
620°
350°
100 mA/m
20°
270°,Up
360°
620°
N
K5-12B
M/M0
1.0
200 400 600°C
20°
620°
(d)
100 mA/m
600°
20°

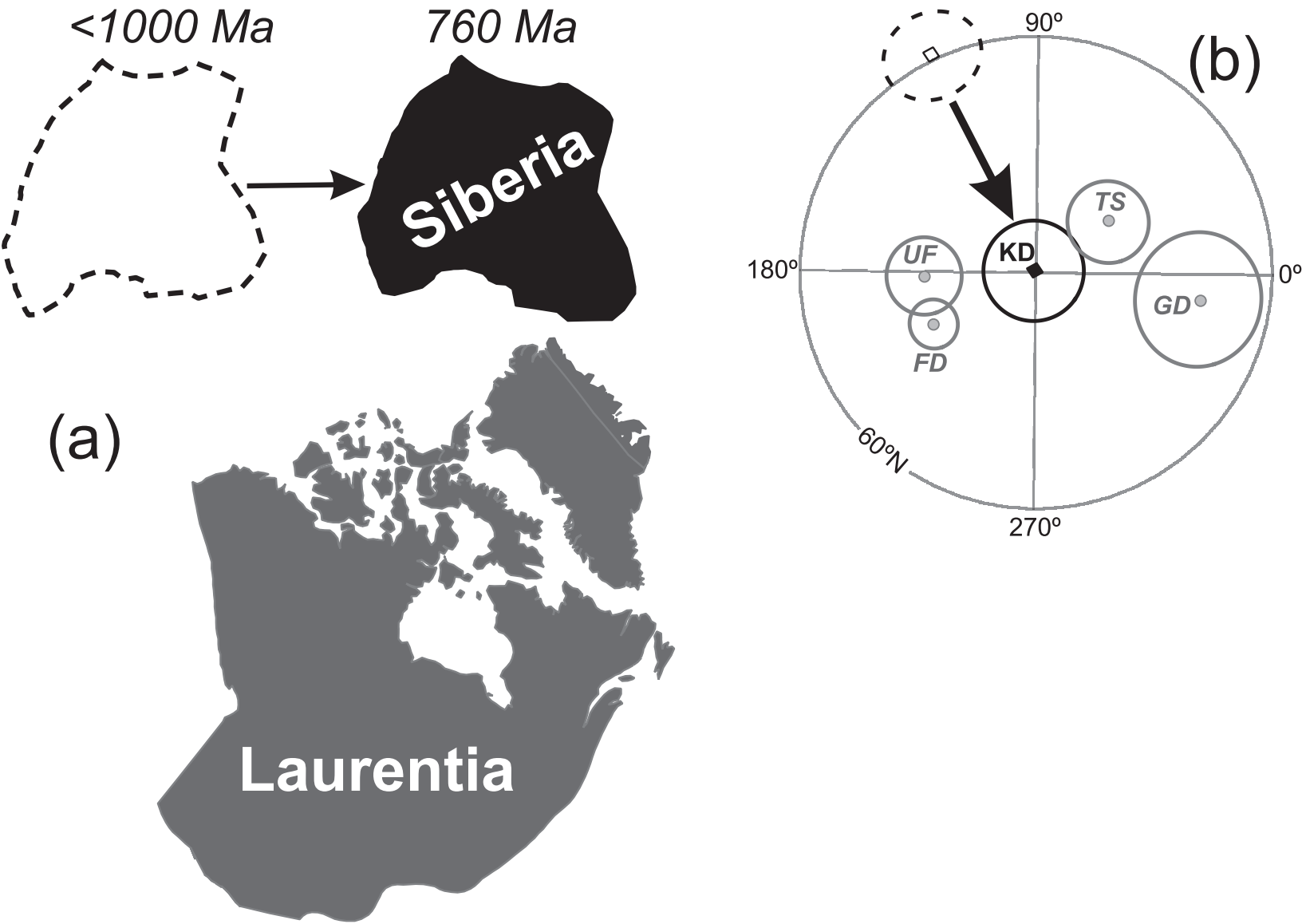
Figure


N
(a)
K7
K6
K4, >0.7 m
from
contact
K4, <0.7m
from
contact
Unbaked
gneiss
Baked
gneiss
(b)

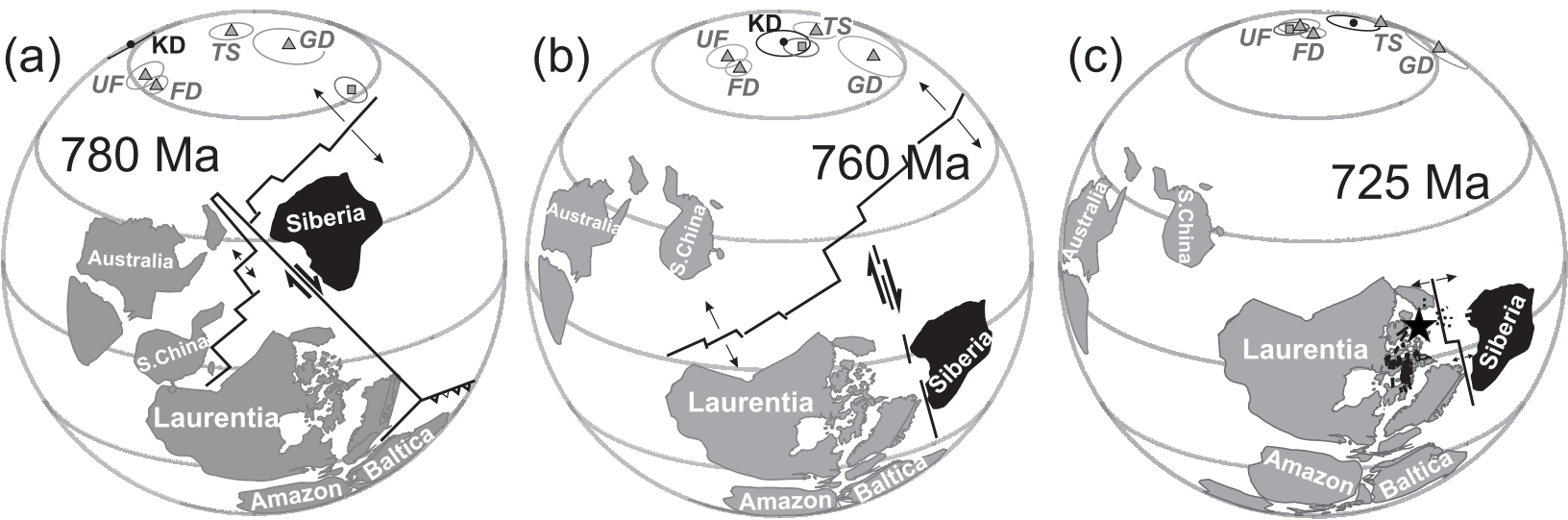
Figure


KA
UK
HI
MF
KF,IF
CS
JS
NF
FS
NS
MF
LS
KS
SF
KS Siberian poles
SF Laurentian poles
Siberia
Laurentia

Figure


<1000 Ma
760 Ma
Siberia
(a)
Laurentia
(b)
90º
180º
0º
270º
60ºN
KD
UF
FD
TS
GD

Figure


(a)
KD
TS
GD
UF
FD
780 Ma
Siberia
Australia
S.China
Laurentia
Amazon
Baltica
(b)
KD
TS
UF
FD
GD
760 Ma
Australia
S.China
Siberia
Laurentia
Amazon
Baltica
(c)
UF
FD
TS
GD
725 Ma
Australia
S.China
Laurentia
Siberia
Amazon
Baltica