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Paleomagnetism and U-Pb age of the 2.4 Ga Erayinia mafic dykes in the south-western Yilgarn, Western Australia: paleogeographic and geodynamic implications

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Abstract

We present results from a paleomagnetic study of the previously undated Erayinia dykes intruding the south-western Yilgarn Craton. The U-Pb TIMs baddeleyite age of these dykes is now 2401 ± 1 Ma, which is about 10 m.y. younger than the 2418 – 2410 Ma Widgiemooltha dyke swarm. The paleomagnetic study isolated a stable primary remanence with steep downward direction, and the paleomagnetic pole (22.7°S, 150.5°E, A_{95}=11.4°) is similar, but not identical to that of the previously studied Widgiemooltha dykes. We interpret this difference as the result of the movement of the Yilgarn Craton toward the pole at ~ 1 °/m.y angular speed, which is comparable with tectonic plates' velocities during the Phanerozoic. Paleomagnetic polarities of Widgiemooltha and Erayinia dykes suggest that at least one geomagnetic reversal occurred between these two magmatic events. The estimated amplitude of geomagnetic secular variations at c. 2400 Ma is slightly higher than predicted by the existing models for the last 5 m.y. at the c. 64° latitude. The paleomagnetic data and patterns of c. 2.6 – 2.1 Ga mafic dyke swarms permit the recently suggested reconstruction of the Paleoproterozoic supercontinent.

Keywords: Paleomagnetism, U-Pb TIMs age, Paleoproterozoic, Yilgarn Craton, mafic dykes, supercontinent.

1. Introduction

The popular hypothesis of supercontinental cycles (e.g. Condie and Aster, 2010; Nance and Murphy, 2013 and references therein) predicts the assembly of a supercontinent in Siderian time (2.5 – 2.3 Ga). This supercontinent is usually called Kenorland (Williams et al., 1991), but Bleeker (2003) suggested the existence of the Sclavia supercraton, while another supercraton, Superia, which included the Superior, Karelia and Hearne cratons, has been postulated by Bleeker and Ernst (2006). Söderlund et al (2010) provided some evidence that the Zimbabwe and Yilgarn cratons could also have formed part of Superia. On the other hand, Condie et al. (2009) demonstrated that the global distribution of U-Pb ages of subduction-related granitoids and of detrital zircon suggest slowing down or even cessation of the plate tectonics between 2.45 and 2.20 Ga. If true, this would be inconsistent with the formation of a supercontinent during the Siderian time. As paleomagnetism is the only method for quantitatively formulating and verifying pre-Mesozoic continental reconstructions, and the only tool for analysing the ancient geomagnetic field, any new paleomagnetic data from well-dated Siderian rocks provide important clues for a better understanding of the abovementioned models. However, Early Proterozoic paleomagnetic data are scarce. Evans and Pisarevsky (2008) included only five reliable 2500-2300 Ma paleomagnetic poles from four cratons (Dharwar, Karelia, Yilgarn and Superior) into their synthesis.

One of the most prominent Siderian dyke swarms in the world is the ca. 2420-2410 Ma Widgiemooltha swarm in Western Australia, which extends west to east across the Yilgarn Craton and includes dykes of both ENE and E-W trends (Fig. 1.a) (e.g., Hallberg, 1987; Parker et al. 1987; Nemchin and Pidgeon, 1998; Ernst and Buchan, 2001; Claoué-Long and Hoatson, 2009a, b). Evans (1968) and Smirnov et al. (2013) reported a coherent and high-quality paleomagnetic results from the Widgiemooltha swarm.

Another prominent swarm in the south-eastern Yilgarn Craton is the c. 1210 Ma Fraser swarm of the Marnda Moorn Large Igneous Province (Wingate et al., 2000; Pidgeon and Nemchin, 2001; Pisarevsky et al., 2003; Wang et al., 2014) (Fig. 1a). One of the Fraser dykes has been studied paleomagnetically (Pisarevsky et al., 2003) and the paleomagnetic pole is close to the paleopoles of c. 1200 Ma metamorphic rocks of the Albany-Fraser Orogen (Pisarevsky and Harris, 2001; Pisarevsky et al., 2003). Recently a more detailed paleomagnetic study of the Mandra Moorn dykes supported these results (Pisarevsky et al., 2014).

Interestingly, paleomagnetic directions of the Widgiemooltha and Fraser dykes are relatively close (the angular difference is 28°). However, both sets of data are supported by precise rock dating and robust baked contact tests, so any later remagnetization of Widgiemooltha dykes by Fraser dykes is ruled out.

In 2006 we collected geochronological and paleomagnetic samples from nine E-NE trending dykes (hereafter called Erayinia dykes) in the area of the conjunction of the Widgiemooltha and Fraser swarms, about 86 km ESE of Kambalda, WA. Although they are of similar trend to the Widgiemooltha dykes, these dykes are uniformly much thinner (all less than 4 m). At the time of our sampling these dykes were not dated and it was not clear if these dykes belonged to the Widgiemooltha or Fraser swarms.

2. Geology and sampling

The study area is located about 50 km northwest of the south-eastern margin of the Yilgarn Craton, in the Kurnalpi Terrane of the Eastern Goldfields Superterrane (Fig. 1b). The area is dominated by northwest-trending belts of Archean metasedimentary rocks, mafic volcanic and intrusive rocks and large granitic intrusions. The <1737 Ma (Hall and Jones, 2005) Woodline Formation overlies the Archean basement rocks in the southern part of the study area. Multiple mafic dykes were found in the area and have been assigned to the east-northeast trending ca. 2420-2410 Ma Widgiemooltha dyke swarm (e.g. Nemchin and Pidgeon, 1998) and the northeast-trending ca. 1210 Ma Fraser Dyke Swarm (Wingate et al., 2000).

A prolonged deformation history is identified for this area and comprises: Archean D_1 recumbent folding and development of a bedding-parallel foliation in places (Jones, 2006); upright folding during the Late Archean D_2 event (Nelson, 1997; Davis and Maidens, 2003; Weinberg et al., 2003) as a result of east-west compression; tightening of the upright folds and development of major north-northwest oriented Late Archean D_3 shear zones during continued east-west compression (Jones, 2006); and 2660-2620 Ma brittle D_4 faulting during northeast-southwest directed compression (Nelson, 1997; Swager, 1997; Swager et al., 1997). A D_5 event produced open upright northeast-oriented folds in the Mesoproterozoic Woodline Formation as a result of northwest-southeast directed compression during the Albany-Fraser orogeny (Jones, 2006).

Archean units in this area are typically lower to middle greenschist facies, but amphibolite facies rocks are observed in the eastern part of the study area and in localised shear zones. Peak metamorphic conditions in the Archean units are considered to be during the D_2 event, likely contemporaneous with the bulk of granite emplacement at approximately 2660-2640 Ma (Witt, 1991; Nelson, 1997; Swager, 1997, Mikucki and Roberts, 2003). The Woodline Formation displays lower greenschist facies conditions (M_5) associated with the D_5 event (Jones, 2006).

A series of major NNW oriented shears extend through the study area that separate broad packages of folded Archean rocks and extend south to the Cundeelee Fault which marks the northeast-trending contact between the Yilgarn Craton and the Albany Fraser Orogen.

Eight dykes and some country-rock were sampled, all located within the Erayinia 100K geological map sheet (Jones, 2007, see Fig. 1b). Seven of the sampled dykes occur in the western part of the sheet, while one dyke (ER10) intrudes the Archean granite in the eastern part of the map sheet (Fig. 1b).

Dyke ER03 is composed of fine-grained dolerite. It intrudes Archean mafic/ultramafic schists along a direction of 072°. The dyke ranges in width from 0.5 to 1.5 meters, and seems to be truncated by two NNW-oriented fractures displacing the dyke over a distance of 0.5 meters and ascribed to D_5 deformation. The contact between the host rock and the dyke is abrupt, but the grain size of the dolerite is too small for the identification of a chilled margin. The samples have been taken from the dyke and from Archean amphibolite and serpentinite country rock immediately east of the dyke outcrop.

Dyke ER04 is composed of small to medium grained dolerite. The dyke is 4 m thick, it intrudes a strongly schistose succession of Archean mafic and felsic volcanic rocks along a direction of 091°. The host rock shows a prominent subvertical cleavage along 180°, while the dolerite is undeformed. Samples were taken from the dyke and from parts of the contact and host rock.

Fine grained dolerite dykes ER05, ER06 and ER07 are nearly parallel running along trends between 085° and 100°. They intrude the Archean metavolcanic schist. The host rocks are strongly deformed, with a subvertical schistosity developed along 155 to 160°. The dykes range in width from 0.2 to 0.5 meters. Where the contact with the host metavolcanic units can be observed, it is sharp, but no chilled margin is apparent.

Dyke ER08 is about 100 meters south of the dykes ER05-07. The dyke is 1 m thick and also comprises of very fine grained dolerite, and runs along a direction of 165°.

1 m-thick medium-grained dolerite dyke ER09 intrudes the sub-vertically dipping mafic metavolcanic schist. The dyke and the mafic schists are both cut by a 50-cm-wide aplite dyke intruding along the host-rock foliation, but lacking internal deformation. Samples were taken from both the dolerite dyke, mafic schist country rock and the aplite dyke.

Dyke ER10 is exposed at the border of a small salt lake running along 073°. The country coarse biotite granites with a clear biotite foliation are exposed north of the dyke. The southern contact between the dyke and the host rock is covered by lake sediments, and the thickness of the dyke can therefore not be determined. Where the contact is observed, it appears sharp. The biotite granite is strongly weathered, and samples were only collected from the dolerite dyke.

Altogether we collected 70 oriented blocks samples, both sun and magnetic compasses were used for the orientation.

3. Geochronology

Sample ER04A2 was collected from the thickest ER04 dyke for geochronological analysis (Table 1, Fig. 2). Previous attempts at dating this sample have included laser ^{40}Ar-^{39}Ar heating on plagioclase separates and zirconolite in polished section. The laser ^{40}Ar-^{39}Ar data on plagioclase separates were characterized by large amounts of excess argon and therefore did not yield useful results. Zirconolite, although identified in polished section using Back Scatter Electron Microscopy, was too small to allow analysis on the SHRIMP, and analysis spots therefore intersected both zirconolite and adjacent minerals (plagioclase), leading to spurious data.

Mineral separation using the technique of Söderlund and Johansson (2002) yielded some tens of dark brown, needle-shaped baddeleyite grains. The best quality grains were handpicked under a binocular microscope and combined into three fractions with 4 to 5 grains in each. The grains were transferred using a micropipette into Teflon dissolution bombs and washed successively in

3 N nitric acid and water. A trace of a mixed 236-233U - 205Pb isotopic solution was added. The sample was completely dissolved in HF: HNO_3 (10:1) at 190°C over three days. The samples were dried down on hot plate before converted to chlorides by adding 10 drops of 6.2 N HCl and 1 drop 0.25 N H_3PO_4. After evaporation the samples were loaded together with silica gel onto outgassed single Re filaments and analysed in a Thermo Scientific Triton thermal ionisation multicollector mass spectrometer at the Museum of Natural History in Stockholm. The intensities of all isotopic masses were analysed using a Secondary Electron Multiplier (SEM) in peak-switching mode. Initial common Pb was corrected for using the model composition of Stacey and Kramers (1975). The mass discrimination correction of Pb is constant at 0.1% per atomic mass unit. Total procedural blank was 1 pg Pb and 0.1 pg U. Decay constants are those of Jaffey et al. (1971). All age errors quoted in the text and Table 1, and error ellipses in the concordia diagram, are given at the 95% confidence level. Plotting and age calculations are from Ludwig (2003).

All fractions are moderately discordant with one fraction (Bd-2) touching the Concordia line (Fig. 2). Regression yields upper and lower intercept of 2401 ± 3 Ma and -4 ± 390 Ma, respectively, whereas their weighted $^{207}Pb/^{206}Pb$ dates yield a more precise result of 2401 ± 1 Ma (Fig. 2). The latter is favoured for dating the crystallisation of this sample.

4. Paleomagnetic analysis

Remanence composition was determined by detailed stepwise alternating field (AF) demagnetization (≤26 steps, up to 160 mT) using and the 2G-755R cryogenic magnetometer. Stepwise thermal demagnetization (≤20 steps, to 600°C), using the 2G-600 automated degaussing system Magnetic Measurements thermal demagnetizer was also applied. To monitor possible mineralogical changes during heating, magnetic susceptibility was measured in selected samples after each heating step using a Bartington MS2 susceptibility meter. Magnetic mineralogy was investigated from demagnetization characteristics and, in selected samples, from detailed variation of susceptibility versus temperature (20° to 700°C) obtained using the

Bartington meter in conjunction with an automated Bartington furnace. Magnetization vectors were isolated using Principal Component Analysis (Kirschvink, 1980). All vectors were defined with a minimum of four data points and a maximum angular deviation (MAD) of 10 degrees

The intensity of the natural remanent magnetization (NRM) of Erayinia dolerite ranges from

20mA/m to 20 A/m, and their magnetic susceptibility from ∼3 to 150 × 10−4 SI units.

Susceptibility versus temperature curves (Fig. 3) show that Curie points are close to 585°C, indicative of magnetite as the main magnetic carrier. Well-defined Hopkinson peaks (Fig. 3), indicate that the remanence is carried mostly by highly stable single-domain (SD) particles and is likely to be primary. The dominance of SD magnetite is also supported by high coercivity of the studied samples: in many cases even after applying AF demagnetization with 120 mT amplitude a significant part of remanence was not destroyed (Fig. 4c). Thermal demagnetization curves do not indicate a presence of hematite (Fig. 4b).

Both thermal and AF demagnetizations of the dolerites isolated a stable steep downward ENE characteristic remanence (Fig. 4) with the mean direction of D = 77.6°, I = 75.9°, k = 70.2, α_{95} = 6.3° (Fig. 5; Table 2). Only one paleomagnetic polarity (downward) has been found.

In attempt to carry out a baked contact test we collected 15 block samples of host rocks at various distances from dykes ER03, ER04, ER05 and ER06. Unfortunately AF and thermal demagnetizations demonstrated that they are either magnetically unstable, or show random remanence directions inconsistent within each sampled block. Samples from the aplite dyke cutting across ER09 dyke also do not carry a stable remanence. Only one sample collected within 1 m distance of the contact of the thickest dyke ER04 contains a stable and internally consistent remanence with D=67.3°, I=67.2° direction, which is statistically indistinguishable from the mean remanence direction of the dyke (Table 2, entry 2). This directional similarity supports the primary nature of the remanence, but this is not a full contact test.

5. Discussion

The 2401 ± 1 Ma U-Pb baddeleyite age of the ER04 dyke rules out a possibility for the Erayinia dykes to be part of the ~1210 Ma Marnda Moorn magmatic event. However, the newly established age of the Erayinia dykes is also ~ 10 m.y. younger than the age of the Widgiemooltha swarm. The latter has been dated by various methods including U-Pb baddeleyite ages of 2418 ± 3 Ma (Nemchin and Pidgeon, 1998), 2410.3 ± 2.1 Ma (French et al., 2002) and 2410.6 +2.1/-1.6 Ma (Doehler and Heaman, 1998). Smirnov et al. (2013) recently published the new paleomagnetic pole for the dykes of 8.2°S, 156.0°E (A_{95} = 10.9°) supported by the baked contact test. Interestingly, all dykes studied by Smirnov et al. (2013) have a steep upward remanence. Evans (1968) previously studied five Widgiemooltha dykes and four of them also have a steep upward remanence. The poles of the two studies are nearly identical (Fig. 6), which is not surprising. However, Smirnov et al. (2013) studied more dykes and demonstrated a robust positive contact test. The only case of the steep downward (‘reverse’) remanence has been reported form site H of Evans (1968) – a small dyke in the gold mine about 400 m underground. This dyke was not dated, but supposed to belong to the Widgiemooltha swarm (Evans, 1968), but we cannot exclude the possibility that this dyke is younger and closer in age to the Erayinia dykes.

The paleomagnetic study of the Erayinia swarm, which we present here, revealed only steep downward (‘negative’) remanence, which is nearly, but not precisely antipodal to the ‘positive’ Widgiemooltha direction of Smirnov et al. (2013) – the reversal test of McFadden and McElhinny (1990) is negative. As the Erayinia swarm is about 10 m.y. younger than the Widgiemooltha swarm, at least one geomagnetic reversal occurred between ~ 2410 and ~ 2400 Ma. The ~11° angular distance between Widgiemooltha and Erayinia poles (Fig. 6) reflects the movement of the Yilgarn Craton toward the geographic pole. It gives a minimal constraint on the angular velocity of the Yilgarn Craton between 2410 and 2400 Ma at ~ 1 °/m.y., which is comparable with similar estimations for the angular plate velocities in the Phanerozoic (Torsvik et al., 2012). This does not support the hypothesis of a slowing down or even cessation of plate tectonics between 2.45 and 2.2 Ga as suggested by Condie et al. (2009).

Smirnov and Tarduno (2004) analysed paleomagnetic data from c. 2.5 Ga dykes from the Superior and Karelian cratons and a c. 2.7 Ga volcanic of the Pilbara Craton. They demonstrated that the pattern of geomagnetic secular variations in Archean estimated by the between-site angular dispersion of the paleomagnetic directions are similar to that of the last 5 m.y. (Constable and Parker, 1988). The between-site angular dispersion of the paleomagnetic directions of the Erayinia dykes is 15.4°, which is slightly higher than c. 10-12° predicted by the model of Constable and Parker (1988) for the latitude of 63° (see Figure 3a of Smirnov and Tarduno, 1988).

Bleeker and Ernst (2006), and Ernst and Bleeker (2010) suggested the existence of the c. 2.5-2.1 Ga Superia supercraton from the study of Large Igneous Provinces (LIPs) patterns. Superia incorporated the Superior, Kola-Karelia, Wyoming and Hearne cratons. Nilsson et al. (2010) suggested that the North Atlantic Craton (or Nain Craton of Hoffman, 1989) was also a part of Superia. Söderlund et al. (2010) suggested that the Zimbabwe and Yilgarn cratons could also have formed part of Superia. On the other hand Smirnov et al. (2013) proposed a connection between northeastern Yilgarn and southern Zimbabwe (Zimgarn) at 2410 Ma by matching their new Widgiemooltha pole and the coeval Sebanga Poort Dyke pole from Zimbabwe (Jones et al., 1975 and Mushayandebvu et al., 1995 re-interpreted by Smirnov et al., 2013; Table 3). The latter is the VGP (Virtual Geomagnetic Pole), because only one dyke has been studied and geomagnetic secular variations have not been averaged.

For the paleomagnetic testing of these ideas reliable c. 2.4 Ga paleomagnetic poles for the suggested constituents of Superia are required. Unfortunately, no reliable c. 2.4 Ga paleopoles from Superior, Wyoming, North Atlantic and Hearne cratons have been published. However, there is such pole from Kola-Karelia. Mertanen et al. (2006) reported a paleomagnetic study of Paleoproterozoic dykes in Russia and Finland. They argued that there are two distinct remanence components in these dykes – the 2.40 Ga D component and the 2.45 Ga D’ component. Recently Salminen et al. (2014) reassigned the younger age of 2.3 Ga for the D’ component, but provided an additional support for the 2.4 Ga D component. Using nine poles from Tables 1 and 2 of Mertanen et al. (2006) and the WD dyke pole of Salminen et al. (2014) we calculated the mean D-pole at 16.7°S, 250.5°E (A_{95} = 8.9°) and use this pole for the paleomagnetic testing of the Superia and Zimgarn reconstructions (Table 3). Apart from poles obtained in their own study, Mertanen et al. (2006) used the results of Krasnova and Gooskova (1990), Fedotova et al. (1999) and Mertanen et al. (1999).

Fig. 7a shows the position of Zimgarn (reconstructed according to Euler rotation parameters of Smirnov et al., 2013) with respect to Superior-Kola-Karelia as suggested by Söderlund et al. (2010). This and other reconstructions in Fig. 7 show positions of continents at 2.4 Ga in the Kola-Karelian reference frame. Being rotated accordingly, 2.40 - 2.41 Ga poles from Yilgarn and Zimbabwe fall far away from the Kola-Karelian mean D-pole (Fig. 7a; Table 3). This means that existing paleomagnetic data do not support the suggestion of Söderlund et al. (2010) that Zimbabwe and Yilgarn were part of Superia around 2.4 Ga if they were connected in the Zimgarn fit of Smirnov et al. (2013). Fig. 7b shows the closest position of Zimgarn with respect to Superia if we rotate the 2.4 Ga Erayinia pole of this study exactly to the position of the coeval Kola-Karelian D-pole. We also show the closest position to Superia and the paleomagnetically permissive position of Zimgarn – the circles of confidence of the Kola-Karelian D-pole and Erayinia pole are touching each other (Fig. 7c). Hence if we accept the Zimgarn model of Smirnov et al. (2013), Zimbabwe and Yilgarn were not part of Superia.

However a juxtaposition of Superior, Zimbabwe, Yilgarn and Kola-Karelia at c. 2.4 Ga is possible (Fig. 8) if we assume that Zimbabwe has been adjacent not to the eastern, but to the western Yilgarn. In this figure Karelia/Kola and Superior craton are juxtaposed as in Bleeker and

Ernst (2006). Zimbabwe is adjacent to Superior as discussed by Söderlund et al., (2010) and western Yilgarn is attached to southern Zimbabwe. The acceptable overlap of the c. 2.4 Ga poles (Table 3) for this reconstruction is shown in Figure 8a. However, this reconstruction should be considered with caution, because of the low quality of the paleopole from Zimbabwe (it is a VGP) and the poor age constraints for the Kola-Karelian pole. New high-quality paleomagnetic data are necessary to confirm this test.

Additional support for this reconstruction is provided by the distribution of dyke swarms in the interval 2.5 - 2.4 Ga (Fig. 8b). The position of Kola-Karelia with respect to the southern Superior Craton is approximately that of Bleeker and Ernst (2006) and features the ca. 2100 Ma dykes of Kola-Karelia (Vuollo and Huhma, 2005) trending toward the suggested plume centre for the fanning 2125 - 2100 Ma Marathon dykes (Halls et al., 2008) of the Superior craton. In addition, 2446 +/- 6 Ma gabbronorite dykes (U-Pb) of Kola-Karelia trend toward the 2480 - 2450 Ma Matachewan plume centre of the Superior craton. In Kola-Karelia there is an intermixed NW trending swarm of low-Ti tholeiites which Vuollo and Huhma (2005) also interprets to be c. 2450 Ma, but the dating only requires a minimum age of 2378 Ma. There are NE trending dykes of boninitic-noritic composition which only have a minimum age of 2395 Ma. Similar trending gabbronorite dykes further south, the Avdeevskiy and Shalskiy dykes have U-Pb baddeleyite ages of c. 2504 Ma (Bleeker et al., 2008). These 2505 Ma dykes in Kola-Karelia are linked with the 2515 ± 3 Ma Mistassini plume centre of the Superior Craton (age from Hamilton, 2009).

Söderlund et al. (2010), dated three NW-NNW trending dykes in the Zimbabwe Craton and these yielded U-Pb baddeleyite ages of 2512 +/- 2 Ma (Crystal Springs dyke), 2470 +/- 1 Ma (Mtshingwe dyke), and the 2408 +/- 2 Ma (Sebanga Poort dyke). Based on these ages, Söderlund et al. (2010) suggested a link with the magmatism in the Superior craton. Specifically the 2512 Ma Crystal Springs dyke can be linked with the 2515 Ma Mistassini swarm of the Superior craton and the 2470 Ma Mtshingwe dyke can be linked to a magmatic pulse of the 2450-2480 Ma Matachewan radiating swarm. The 2408 Ma Sebanga Poort dyke can be linked to the poorly studied Du Chef swarm of which has been provisionally dated as 2408 ± 2 Ma (Krogh, 1994). In addition there is a link with the Widgiemooltha and swarm of the Yilgarn Craton (ages discussed above). Overall the Widgiemooltha swarm shows a weak convergence toward the east side and we have provisionally interpreted a plume centre position (marked by a star) on the eastern side of the craton. In this reconstruction the 2510 Ma Sebanga Poort dyke in Zimbabwe would represent a continuation of the Widgiemooltha/Erayinia swarm(s).

The North Atlantic Craton can also be included in this reconstruction. It has been placed along the NE side of the Superior Craton (Nilsson et al., 2010), This reconstruction was done only on the basis of matching dykes swarms and flood basalt events between North Atlantic and NE Superior cratons, however, this reconstruction is not constrained by paleomagnetic data and the North Atlantic Craton is only located by a label as a placeholder in Fig. 8b. The locations of Wyoming and Hearne cratons after Bleeker and Ernst (2006) and Ernst and Bleeker (2010) are similarly labelled in Fig. 8b.

The final aspect to consider is the Great Dyke of Zimbabwe LIP (2575 Ma) (Söderlund et al., 2010). This is a dyke-like layered intrusion is about 550 km long and from 1-13 km wide and based on gravity is underlain by a feeder dyke up to 1 km in width (Podmore and Wilson, 1987). It extends across the Zimbabwe Craton from NNE to SSW and is accompanied by two parallel major mafic dykes (e.g. Wilson et al., 1987). The Great Dyke reaches the NNE edge of the craton and likely continues on whichever crustal block was adjacent at that time. At its SSW end the Great Dyke has split into a number of smaller dykes that reach to the edge of the craton, and similarly are expected to continue into whatever block was formerly adjacent on that side. Magmatism coeval to the Great Dyke has not been yet found on any crustal blocks anywhere in the world. However, the reconstruction shown in Fig. 8 makes a prediction as to where that continuation of the Great Dyke and its two companion mafic dykes might be found. In Fig. 8b the NNE end of the Great Dyke trends near to the south Yilgarn, and so if present in the Yilgarn would be on its southern side, but possibly buried under younger cover rocks. The extrapolated trend of the southern end of the Great Dyke would intersect the edge of Superior Craton. However, as mentioned above, before reaching the southern edge of the Zimbabwe Craton the Great Dyke has become a regular dyke swarm; so some still undated dykes in SE Superior Craton could potentially be related to the Great Dyke of Zimbabwe.

6. Conclusions

- Our new well-dated 2401 ± 1 Ma Erayinia paleopole for the Yilgarn Craton is similar, but not identical to the 2410 - 2420 Ma Widgiemooltha pole of Smirnov et al. (2013).
- The angular difference between these two poles suggest the angular velocity of the Yilgarn Craton between 2410 - 2420 and 2400 Ma at ~ 1 °/m.y., which is comparable with similar estimations for the angular plate velocities in the Phanerozoic (Torsvik et al., 2012).
- Paleomagnetic remanence polarities of Widgiemooltha and Erayinia dykes suggest that at least one geomagnetic reversal occurred between two magmatic events.
- The estimated amplitude of the geomagnetic secular variations at c. 2400 Ma is slightly higher than predicted by the existing models for the last 5 m.y. at the c. 64° latitude.
- A 2.4 - 2.5 Ga reconstruction of Kola-Karelia, Zimbabwe and Yilgarn cratons near the southern and southeastern Superior Craton is supported by paleomagnetic and dyke trend data.
- Yilgarn, Kola-Karelia, Zimbabwe, North Atlantic, Hearne and Wyoming cratons could be parts of the Paleoproterozoic supercontinent.

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Figure captions

Fig.1. Geological sketch of the southern Yilgarn (a) and geological map of the sampling area (b).

Fig. 2. U-Pb age of the Erayinia dyke ER04.

Fig. 3. Analyses of Curie points using magnetic susceptibility versus temperature curves: (a) dyke ER05; (b) dyke ER06.

Fig. 4. Examples of thermal and alternating-field (AF) demagnetization of Erayinia dykes. In orthogonal plots, open (closed) symbols show magnetization vector endpoints in the vertical (horizontal) plane; curves show changes in intensity during demagnetization. Stereoplots (equal-angle, lower-hemisphere projection) show upwards (downwards) pointing paleomagnetic directions with open (closed) symbols.

Fig. 5. Stereoplot (equal-angle, lower-hemisphere projection) of mean directions of Erayinia dykes.

Fig. 6. Paleomagnetic poles of Erayinia dykes (ER) and Widgiemooltha dykes (W68 – Evans, 1968; W13 – Smirnov et al., 2013).

Fig. 7. Paleomagnetic test for the Superia reconstruction at 2.4 Ga (in the Kola-Karelian reference frame); blue - Superior craton; green – Kola-Karelia and mean D-pole (Table 3); orange – Yilgarn, Erayinia (E) and Widgiemooltha (W) pole (Table 3)); red – Zimbabwe and Sebanga pole (Table 3). Superior is rotated to Kola-Karelia about an Euler pole (+ is anticlockwise) at 75.08°N, 240.52°E, +101.47°. Zimbabwe is rotated to Yilgarn at 47°S, 77°E, -157° (Smirnov et al., 2013). Black arrows denote directions to the present north. (a) reconstruction of Söderlund et al. (2010), Yilgarn rotated to Kola-Karelia at 5.18°N, 127.94°W, +240.84°; (b) reconstruction of Zimgarn and Superia with exact fit of Erayina and D-pole, Yilgarn rotated to Kola-Karelia at 31.88°N, 133.00°E, -109.37°; (c) the closest paleomagnetically permissive position of Zimgarn to Superia, Yilgarn rotated to Kola-Karelia at 26.76°N, 134.64°E, -137.23°.

Fig. 8. Alternative reconstruction of Superia with Zimbabwe connected to the western Yilgarn (after Söderlund et al., 2010) in absolute framework (Table 4). (a) paleomagnetically permissive reconstruction; (b) dyke swarms’ pattern in the Paleoproterozoic supercontinent; stars denote suggested position of the mantle plumes.

- We dated previously undated dyke swarm in Australia at 2401 Ma
- We present a new paleomagnetic pole from these dykes
- We present a new reconstruction for the Paleoproterozoic supercontinent

Table 1. U-Pb TIMS data

Analysis no. (number of grains)	U/ Th	Pbc/ Pbtot1)	^{206}Pb/ ^{204}Pb	^{207}Pb/ ^{235}U	± 2s % err	^{206}Pb/ ^{238}U	± 2s % err	^{207}Pb/ ^{235}U	^{206}Pb/ ^{238}U	^{207}Pb/ ^{206}Pb	± 2s % err	Concord- ance
			raw2)	[corr]3)				[age, Ma]				
Bd-1 (5 grains)	4.3	0.017	3272.6	9.4614	0.20	0.44306	0.20	2383.8	2364.3	2400.5	1.0	0.985
Bd-2 (4 grains)	4.8	0.080	670.3	9.5956	0.43	0.44924	0.42	2396.8	2391.9	2400.9	2.2	0.996
Bd-3 (5 grains)	5.9	0.042	1353.9	9.4499	0.40	0.44201	0.37	2382.7	2359.6	2402.5	2.7	0.982

1) Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).

2) measured ratio, corrected for fractionation and spike.

3) isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (1 pg Pb and 0.1 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.

Table 2. Paleomagnetic directions and poles, Erayinia dykes, SE Yilgarn, Western Australia

#	Dyke	N/n	Slat (°S)	Slong (°E)	Decl. (°)	Incl. (°)	k	α_{95} (°)	Plat (°S)	Plong (°E)	D_p (°)	D_m (°)
Erayinia area												
1	ER03	9/9	31.22635	122.54177	23.7	75.9	34.6	8.9	6.4	133.0	15.1	16.4
2	ER04	9/5	31.20882	122.50004	62.9	67.2	31.8	13.8	7.4	157.9	19.0	22.9
3	ER05	10/9	31.20991	122.49923	73.7	73.1	42.2	8.0	18.6	154.2	12.8	14.3
4	ER06	10/10	31.20991	122.49923	59.6	72.1	13.9	13.4	11.6	151.0	20.9	23.7
5	ER07	6/6	31.20991	122.49923	114.4	79.5	27.9	12.9	37.5	146.0	23.5	24.6
6	ER08	5/5	31.21082	122.49881	129.2	80.2	230.0	5.1	41.8	142.3	9.4	9.8
7	ER09	8/5	31.21163	122.49905	81.8	74.8	38.4	12.5	23.4	153.5	20.7	22.8
8	ER10	7/4	31.17700	122.86223	103.1	69.9	34.4	15.9	32.2	165.7	23.5	27.3
	Mean for 8 dykes				***77.6***	***75.9***	***70.2***	***6.3***	***22.7***	***150.5***	***A_{95}=11.4***	
					(63.6° paleolatitude)							

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.

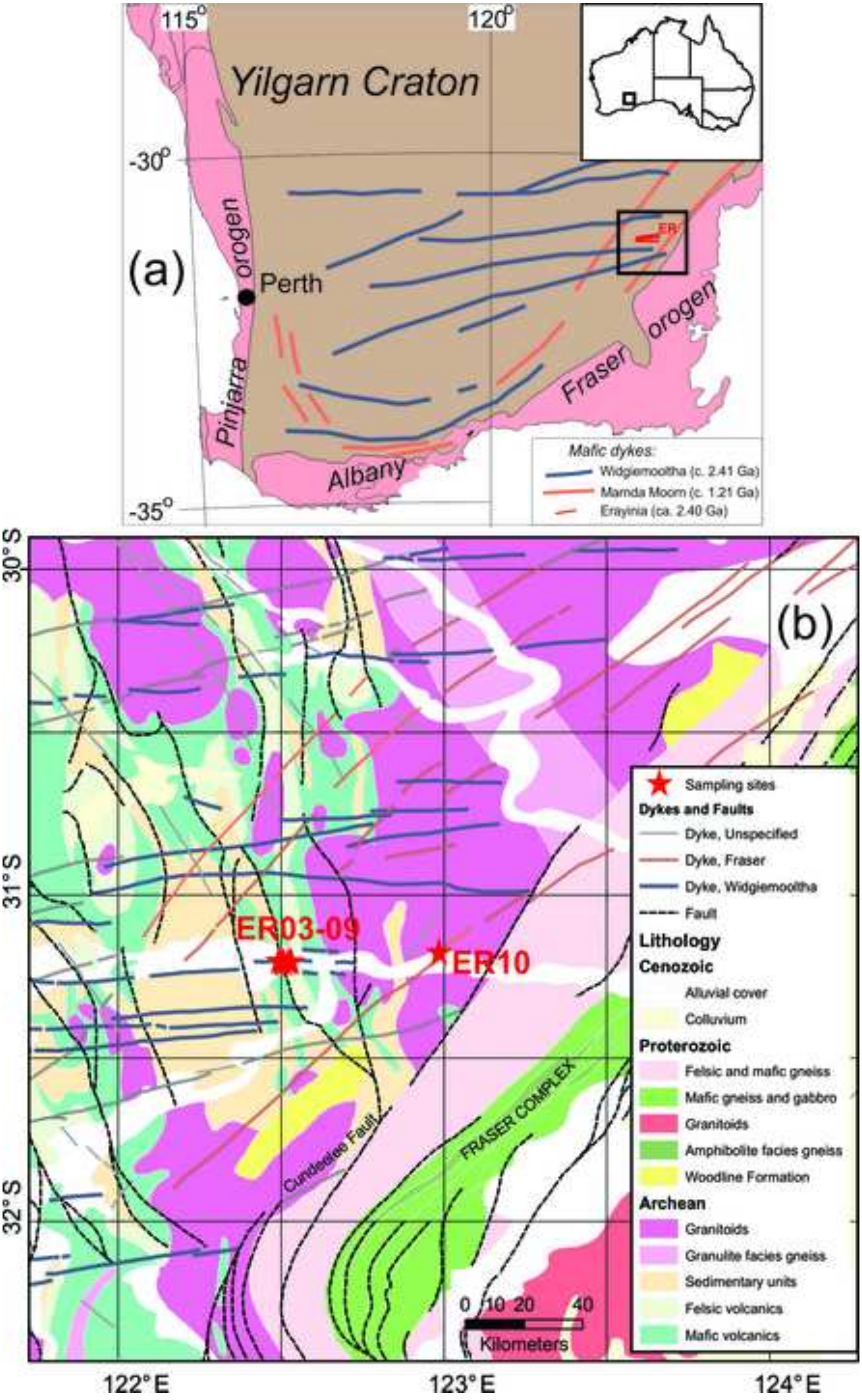
Table 3. Paleomagnetic poles for c. 2410 - 2400 Ma.

#	Pole name	Age (Ma)	Plat (°N)	Plong (°E)	A_{95} (°)	Reference
						Yilgarn
1	Widgiemooltha dykes	c. 2410	-10.2	159.2	7.5	Smirnov et al., 2013; Evans, 1968
2	Erayinia dykes	2401±1	22.7	150.5	1.4	This study
						Kola-Karelia
3	Karelian dykes	c. 2400	-16.7	250.5	8.9	Calculated from Mertanen et al., 2006 and Salminen et al., 2014
						Zimbabwe
4	Sebanga dyke	c. 2410	17.0	6.1	8.0	Smirnov et al., 2013; Jones et al., 1975; Mushayandebvu et al., 1995

A_{95} = semi-angle of the 95% circle of confidence about the mean paleopole.

Table 4. Rotation parameters for the reconstruction in Fig. 8 (absolute framework)

Craton	Pole of rotation (°N)	(°E)	Angle (°)
Kola-Karelia	-56.09	-128.58	+220.93
Superior	-49.72	168.72	+150.15
Yilgarn	19.99	-139.74	+241.72
Zimbabwe	3.85	-70.21	-296.25


115°
120°
Yilgarn Craton
-30°
-35°
(a)
Perth
Pinjarra orogen
Albany
Fraser orogen
ER
Mafic dykes:
Widgiemooltha (c. 2.41 Ga)
Marnda Moorn (c. 1.21 Ga)
Erayinia (ca. 2.40 Ga)
(b)
30°S
31°S
32°S
122°E
123°E
124°E
ER03-09
ER10
Cundeelee Fault
FRASER COMPLEX
0 10 20 40
Kilometers
Sampling sites
Dykes and Faults
Dyke, Unspecified
Dyke, Fraser
Dyke, Widgiemooltha
Fault
Lithology
Cenozoic
Alluvial cover
Colluvium
Proterozoic
Felsic and mafic gneiss
Mafic gneiss and gabbro
Granitoids
Amphibolite facies gneiss
Woodline Formation
Archean
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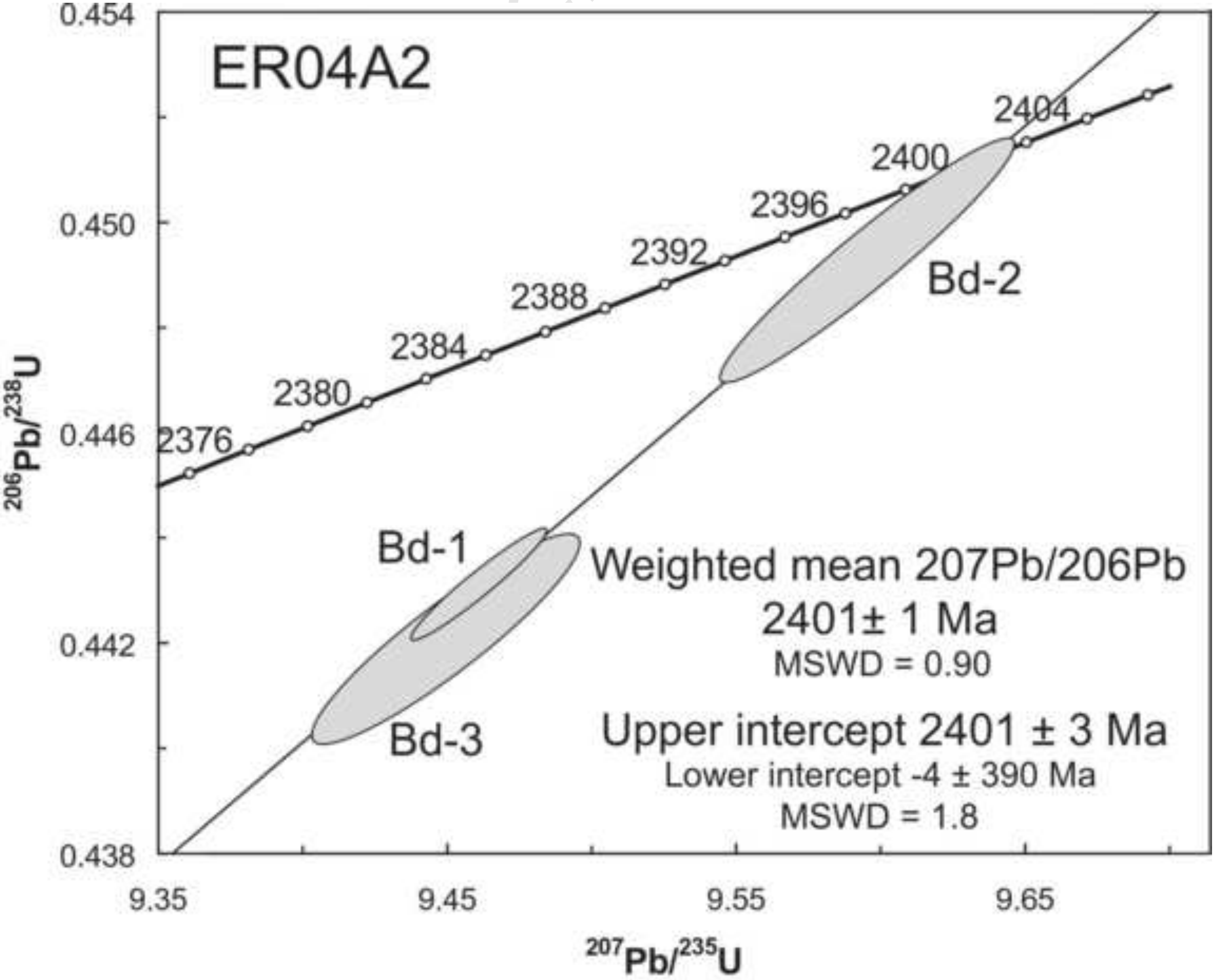
Granulite facies gneiss
Sedimentary units
Felsic volcanics
Mafic volcanics

Figure



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^{207}Pb/^{235}U
2376
2380
2384
2388
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2396
2400
2404
Bd-1
Bd-2
Bd-3
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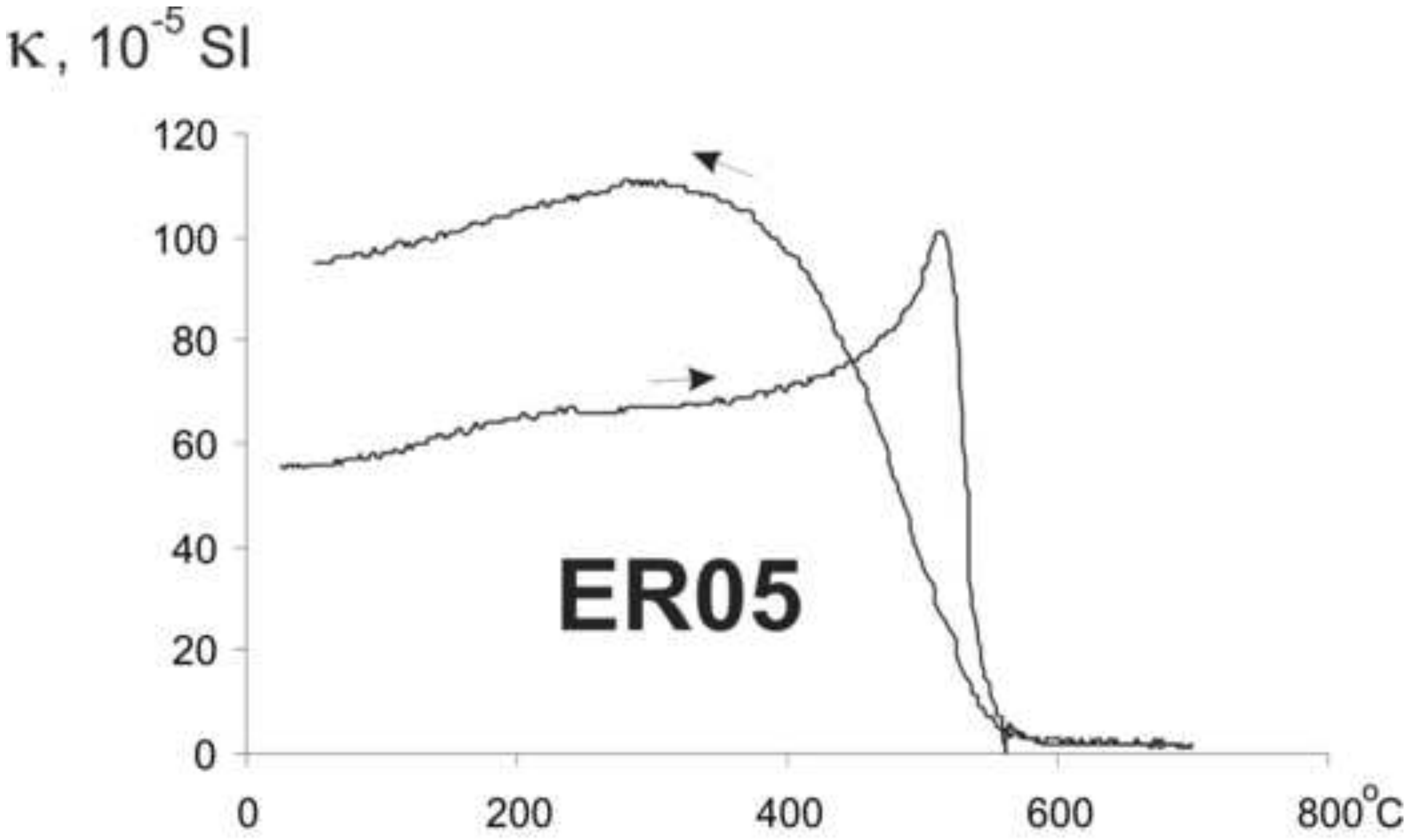
MSWD = 0.90
Upper intercept 2401 ± 3 Ma
Lower intercept -4 ± 390 Ma
MSWD = 1.8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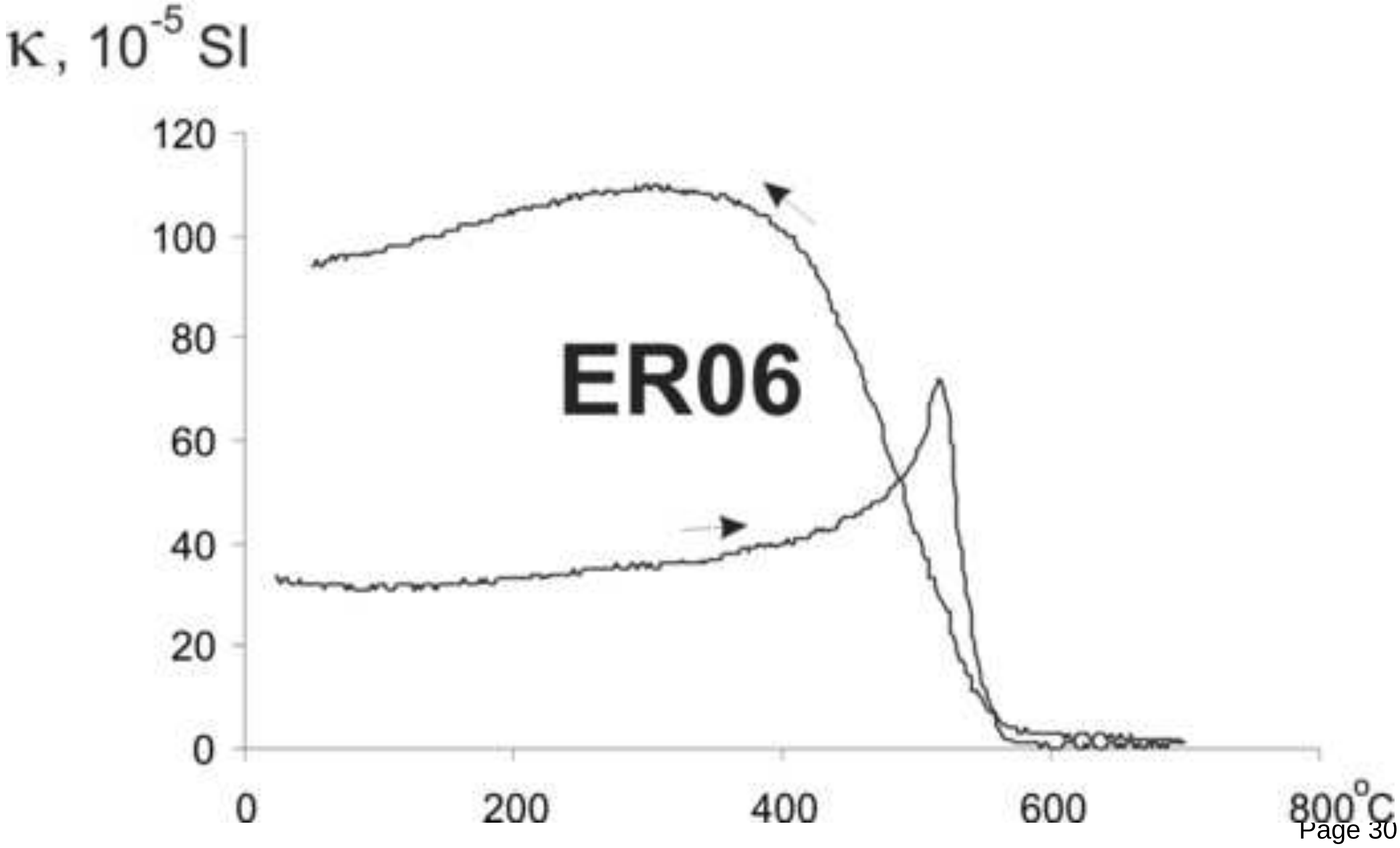
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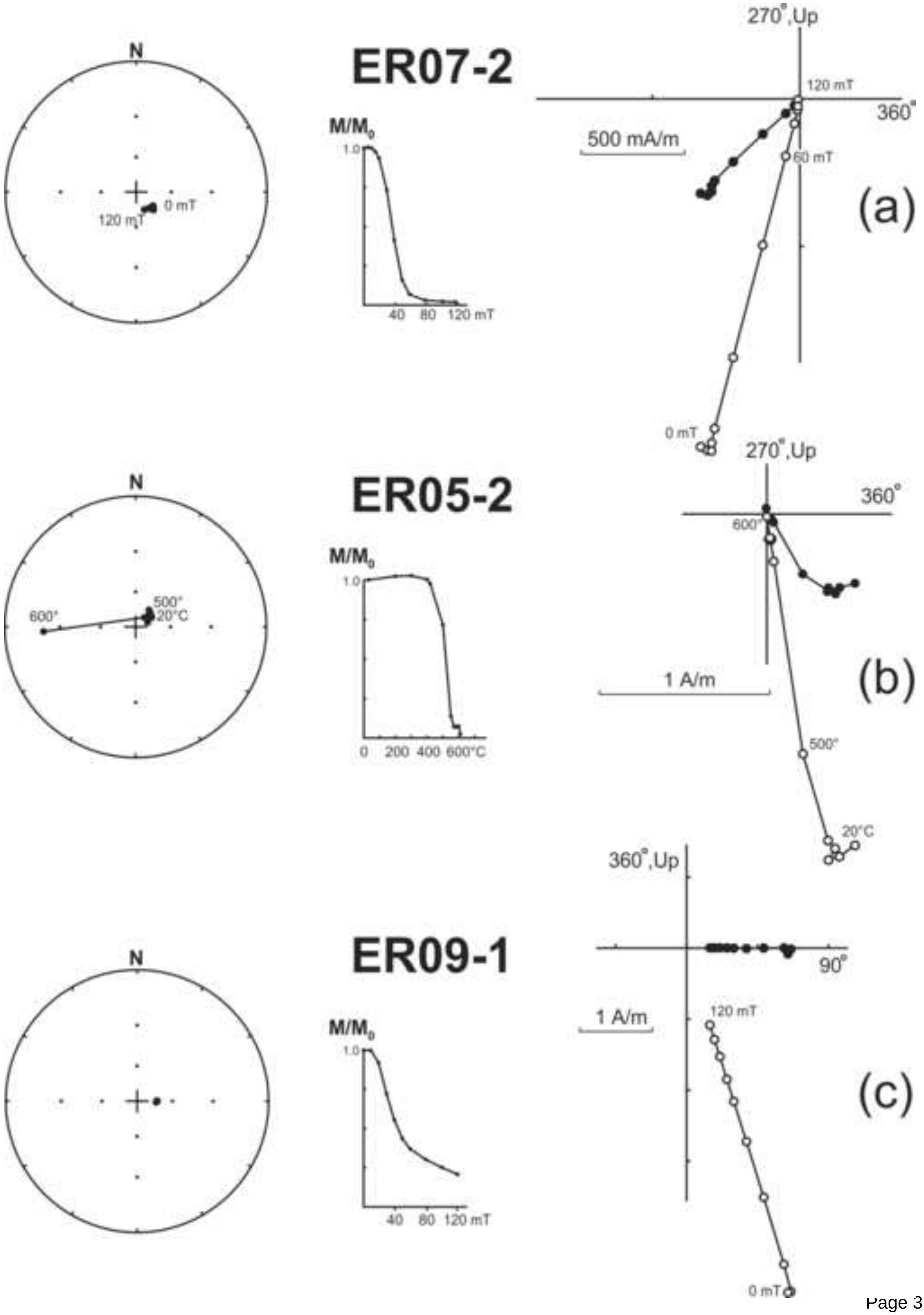
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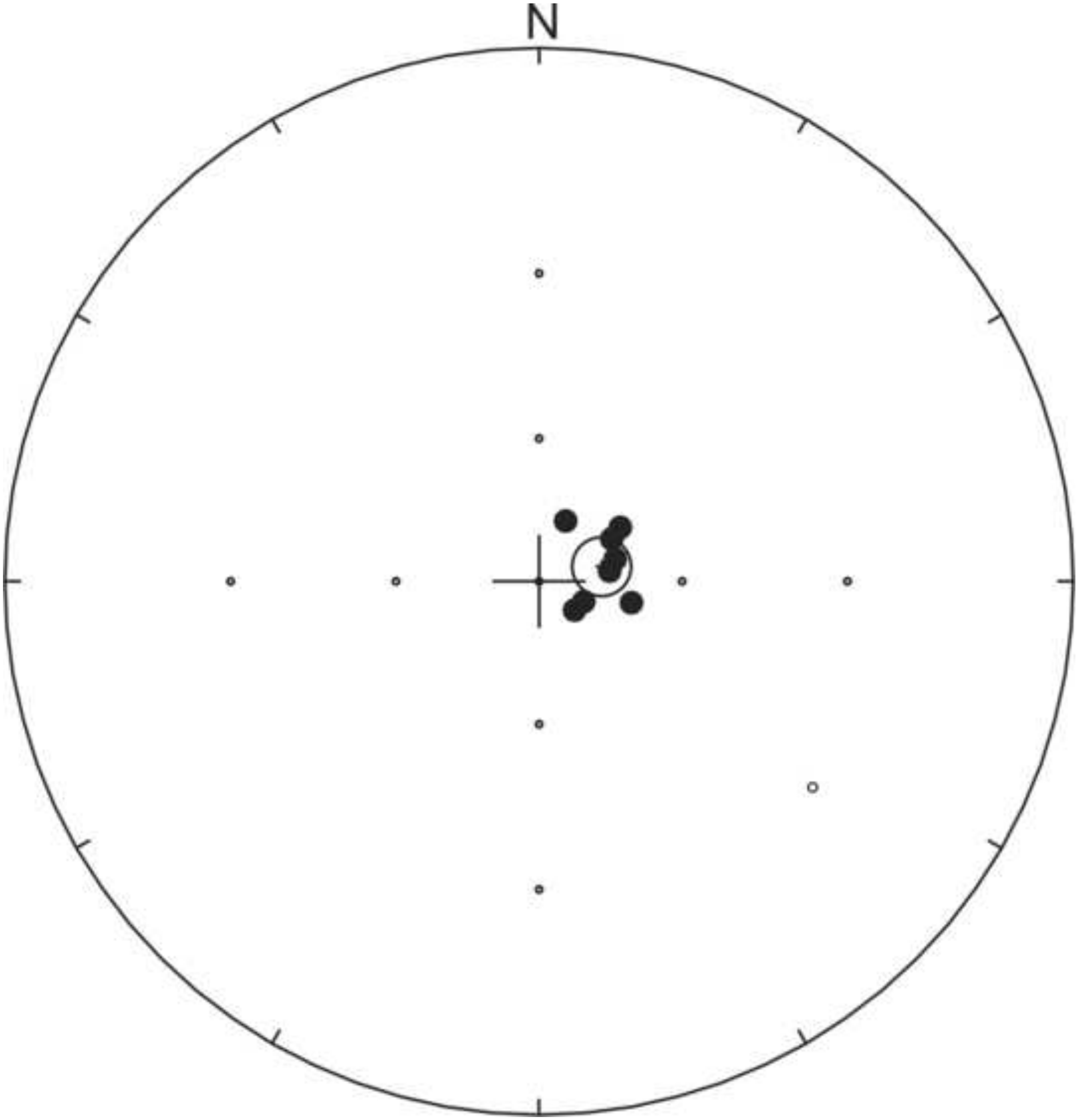
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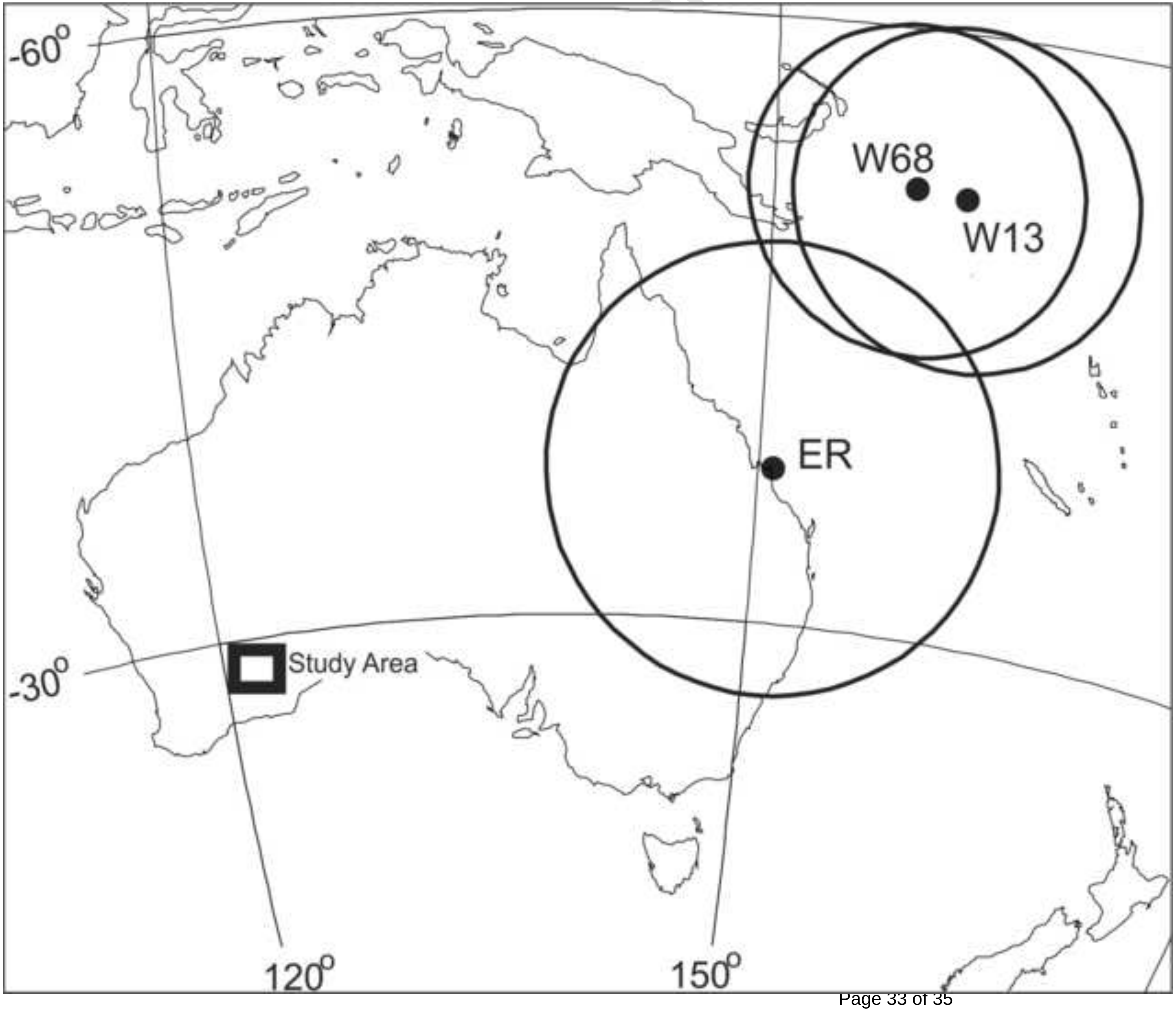
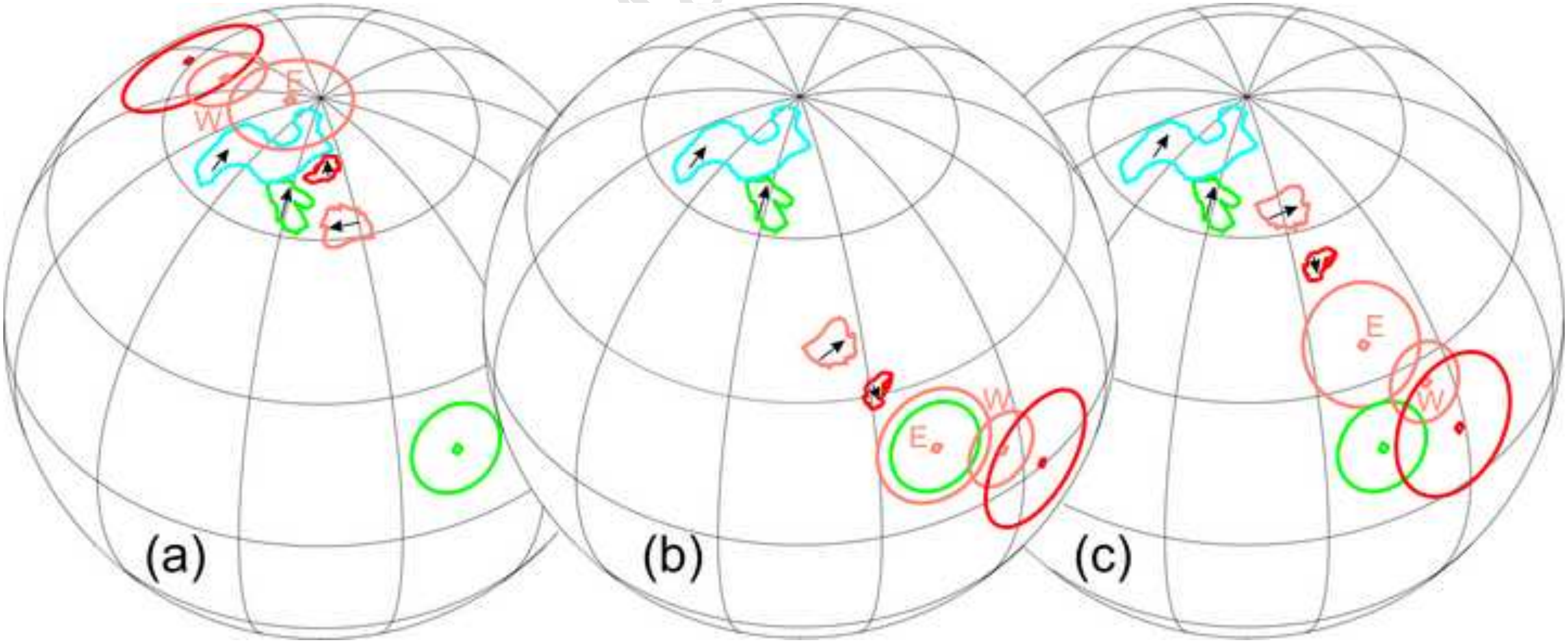
Figure

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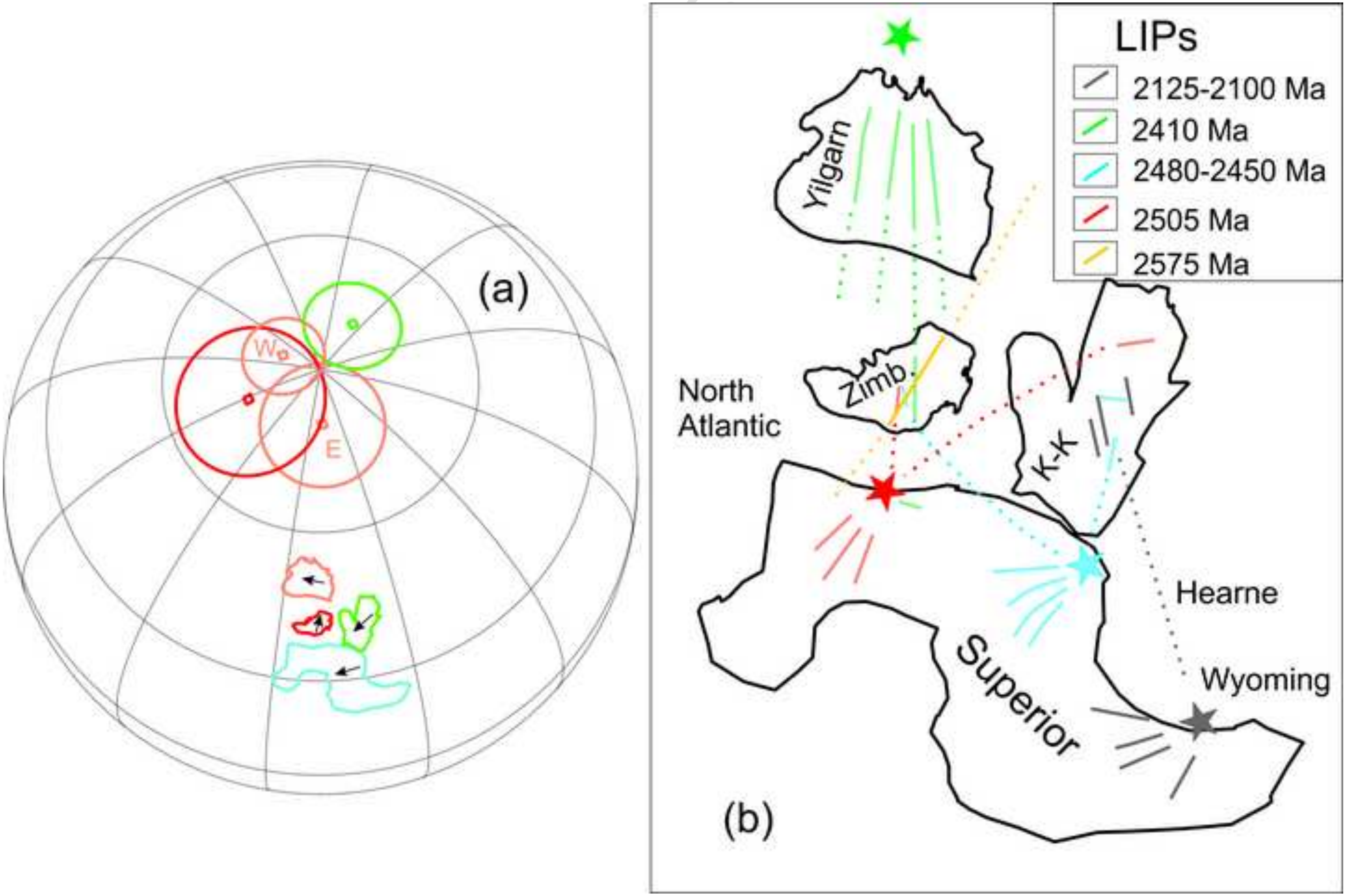
(c)

Figure


(a)
W
E
LIPs
2125-2100 Ma
2410 Ma
2480-2450 Ma
2505 Ma
2575 Ma
Yilgarn
Zimb.
North Atlantic
K-K
Hearne
Superior
Wyoming
(b)