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Vaalbara Palaeomagnetism

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Abstract

Vaalbara is the name given to a proposed configuration of continental blocks—the Kaapvaal craton (southern Africa) and the Pilbara craton (north-western Australia)—thought to be the Earth's oldest supercraton assemblage. Its temporal history is poorly defined, but it has been suggested that it was stable for at least 400 million years, between 3.1 and 2.7 Ga. Here, we present an updated analysis which shows that the existence of a single supercraton between ~2.9 and ~2.7 Ga is inconsistent with the available palaeomagnetic data.

keywords: Vaalbara, palaeomagnetism, Wilson cycle, precambrian

Preamble by Ted Evans: Memories of David Strangway

One of the projects I worked on for my doctoral thesis involved the palaeomagnetism of a Precambrian dyke swarm in Western Australia. I obtained a good palaeopole (9°S, 157°E, A_{95}=8°), but was worried by Dave Strangway's paper claiming that dykes are not reliable recorders (Strangway, 1961). He argued that their two-dimensional geometry caused a systematic deflection of the remanence vector towards the plane of the dyke. Coming from an established researcher of high repute, this was a serious issue for a lowly graduate student. However, I was eventually able to show that all the relevant data gave no support to any deflection mechanism. Shortly after my paper appeared (Evans, 1968), I moved from the Australian National University to the University of Alberta, and was told that Professor Strangway would be passing through Edmonton in the near future. I waited in the lab like some hapless victim of an imminent *auto-da-fé*. But, of course, all was well. He breezed in, congratulated me on my paper, and I never looked back. I will always be grateful for the way he immediately treated me as an equal, and encouraged me to stay active in research. Many years later, the pole position I had reported was confirmed by a more extensive study (Smirnov et al., 2013). The updated palaeomagnetic pole for the Widgiemooltha Dyke Swarm (10.2°S, 159.2°E, A_{95}=7.5°, Q=7) now comprises data obtained in three separate laboratories (Canberra, Yale, Michigan Technical University), using instruments ranging from old-fashioned astatic magnetometers to state-of-the art cryogenic magnetometers, and employing a variety of demagnetization procedures. Smirnov and his co-authors use it to help work out the tectonic evolution of the proposed Archaean supercraton Vaalbara, the very topic of the present paper.

Introduction

Palaeomagnetism and radiometric dating are two of the more important techniques for probing the early evolution of planet Earth. A sustained effort will be required to establish an adequate amount of reliable data, but some significant first steps have been taken (Biggin et al., 2008; Tarduno, 2009; Smirnov et al., 2013). One important goal is the investigation of earlier continental configurations that may have existed prior to the establishment of Wegener's Pangaea: Rodinia, Nuna, Kenorland, and the earliest so far suggested—Vaalbara, the topic we address here. In the older literature, investigations of the Modipe Gabbro (an Archaean intrusion in southern Africa) helped initiate the task. Evans and McElhinny (1966) determined a palaeopole which the corresponding radiometric age (McElhinny, 1966) established as the oldest then known. Subsequently, McElhinny and Evans (1968) investigated the contemporary geomagnetic field strength. The continuing importance of evidence from such geologically ancient formations, coupled with instrumental and methodological improvements, have prompted renewed efforts to check results obtained half a century ago. Muxworthy et al. (2013) used an Orion three-axis low-field vibrating sample magnetometer to carry out Thellier-Thellier-Coe palaeointensity experiments. Their results supersede those of McElhinny and Evans (1968) who used a non-Thellier method based on alternating-field demagnetization because of the limitations of their thermal demagnetizer. A similar situation holds for the radiometric ages. McElhinny's (1966) rather imprecise Rb-Sr whole-rock age of 2630±470 Ma is now replaced by the robust U-Pb ID-TIMS baddeleyite age of 2784.0±1.0 Ma reported by Denyszyn et al. (2013). These latter authors also obtained palaeomagnetic directions from the Modipe Gabbro, but, in this case, the recent investigation does not replace the original work. The two results are in excellent agreement, so Denyszyn and co-authors calculate a Modipe Gabbro grand mean direction of D=164.6°, I=86.1°, α_{95}=5.0°. They then go on to compare this combined result with palaeomagnetic data from basalt flows in the nearby Derdepoort belt (Wingate, 1998), and rotate the Modipe result to account for supposed tectonic tilt using the attitude of the lava flows as a guide. Here, we put forward an alternative interpretation and discuss how it affects the Vaalbara debate.

Palaeomagnetic data and tectonic tilting

During the field work associated with our palaeointensity study (Muxworthy et al., 2013), we collected drill-cores at two additional sites in order to check the polarities determined more than fifty years ago (Evans and McElhinny, 1966). The sites in question are located near Modipe Hill (site MNE: 24.63°S, 26.17°E) where inclinations are expected to be steeply up, and near Wildebeest Kop (site WK: 24.68°S, 26.18°E) where inclinations are expected to be steeply down (Fig. 1) . The rock at both sites—like all previously studied sites—consists almost entirely of plagioclase and pyroxene. Alteration is minimal, particularly in the northern half of the outcrop, where sites MNE and WK are situated. Remanent magnetizations were measured with an Agico JR5A spinner magnetometer. Step-wise alternating-field and thermal demagnetization experiments were carried out with a static DTECH alternating field (AF) demagnetizer and an ASC TD48 palaeomagnetic oven, respectively. During demagnetization, all samples behaved in a straightforward, coherent manner (Fig. 2), and yielded well-defined site means: MNE, D=340.0°, I=-81.0°, α_{95}=3.9°, N=6, and WK, D=207.8°, I=74.9°, α_{95}=2.5°, N=4. These new results are in excellent agreement with those previously published, and lead to an updated grand mean direction of D=173.3°, I=85.2°, α_{95}=4.6°, k=83, N=13. The angular separation between this result and that of Denyszyn et al. (2013) is negligible (~1°), but the robustness of the overall result is enhanced by having input from three independent studies. We regard it as the best available palaeomagnetic result for the Modipe Gabbro. In terms of the reliability index Q (van der Voo, 1990), it has robust radiometric control, a sufficient number of samples, adequate demagnetization, and reversals. The primary nature of the characteristic remanence is supported by a baked-contact test (Evans and McElhinny, 1966), by the anti-podality of the two polarity groups, and by the lack of evidence for later magnetic re-setting (see discussion by Denyszyn et al. (2013) for both these topics). Thus the resulting palaeopole has a reliability index Q = 6. The only criterion not satisfied is that concerning structural control, to which we now turn.

Wingate (1998) reports palaeomagnetic directions for eight Derdepoort lava flows collected along the Marico River some 20 km east of the Modipe Gabbro outcrops. The mean *in situ* direction he obtains is D=9.3°, I=76.1°, α_{95}=8.3°, k=46. As an independent check, we sampled an additional site (MR, Fig. 1) near Wingate's site LVZI. Alternating-field demagnetization was straightforward (Fig. 2) and yielded an *in situ* mean of D=5.8°, I=69.4°, α_{95}=3.9°, k=388, N=5, in excellent agreement with Wingate's data. Wingate determined the attitude of the flows by measurements on laminations in silica-filled amygdales near flow tops, but a search at our site failed to locate sufficiently large amygdales. Wingate obtains a dip-corrected mean of D=222.7°, I=76.6°, α_{95}=10.4°, k=29, but the fold test is inconclusive as far as judging whether the increased scatter indicates pre- or post-tilting remanence acquisition.

There is no evidence for any tectonic tilting of the Modipe Gabbro, but Denyszyn and co-authors argue that it has been tilted around the same axis as the Derdepoort lavas on the grounds that the line of hills formed by the gabbro is parallel to the strike of the lavas (they give bearings of 126° and 125°, respectively). Closer inspection shows that the two trends are measurably different. The mean of the Derdepoort bedding poles implies a strike of 116°, and the overall strike revealed by satellite imagery is 112°. The 1:50,000 Botswana topographic map (Sheet 2426C1) indicates that the general trend of the Modipe inselbergs is ~140°, so the two trends differ by some 25°. Furthermore, Tyler (1979) demonstrates that the Derdepoort belt has been subjected to two periods of folding and at least one major episode of faulting. It is comprised of a northern asymmetrical syncline and a southern tightly-folded anticline with axes trending 115°, all preserved in a graben. The geological structure is much more complex than that implied by the simple tilt model of Denyszyn and co-authors. A more serious objection arises in connection with the amount of tectonic tilt they assume. Wingate's field measurements imply a mean tilt for the lavas of 26°, but Denyszyn and co-authors rotate the Modipe direction by only 11°. They do this arbitrarily in order to force the Modipe Gabbro and the Derdepoort basalts to lie on the same palaeolatitude. This *ad hoc* procedure is very questionable. We prefer the following alternative. The angular separation between the tilt-corrected Derdepoort direction and the unrotated Modipe direction is 11°, but their 95% confidence circles overlap ($\Sigma\alpha_{95}$=15°). Given the closely similar ages of the two units (Modipe 2784±1 Ma, Derdepoort 2782±5 Ma), we combine the magnetic data to obtain D=204.5°, I=82.6°, k=42, α_{95}=4.7°, N=21.

Discussion and Conclusions

The many geological similarities between the Kaapvaal (southern Africa) and Pilbara (western Australia) cratons prompted Cheney (1996) to propose that in the Archaean and Palaeoproterozoic they were joined together in a single continent he called Vaalbara. This suggestion has generated a great deal of discussion (Nelson et al., 1999; Eriksson et al., 2009). In what follows, we restrict attention to the role played by palaeomagnetism. Even so, a complex evolution of ideas emerges, with the pendulum swinging back and forth as far as the geological history of Vaalbara is concerned. Zegers et al. (1998) used palaeopoles from both cratons (Millindinna and Usushwana complexes for Pilbara and Kaapvaal, respectively) to demonstrate that they could have been close to one another at ~2.87 Ga. Using the same procedure with somewhat younger palaeopoles (the Pilbara Mount Roe Basalts and the Kaapvaal Derdepoort basalts), Wingate (1998) concluded that by ~2.78 Ga the two cratons were not contiguous, being latitudinally separated by 30°±19°. However, further study of the Pilbara region (Strik et al., 2003) modified its palaeolatitude, leading to the conclusion that the Vaalbara hypothesis "cannot be rejected". In fact, there are several other penecontemporaneous poles for Pilbara, and we suggest that the most objective procedure is to combine them all, with their differences being due to secular variation. The poles in question are from the Mount Roe Basalts (Schmidt and Embleton, 1985—this is the one used by Wingate), the Black Range (2772±2 Ma, Wingate (1999)) and Cajuput Dykes (Embleton, 1978), and the P1 pole (~2772 Ma) of Strik et al. (2003). We also include the P2 pole (~2766 Ma) of Strik et al. (2003) because it differs little in age and its 95% confidence circle significantly overlaps that of the P1 pole. There remains the VGP obtained from five sites the Mount Jope Volcanics (Schmidt and Embleton, 1985). It lies to the east of the other poles under discussion here, but has an age greater than 2750±5 Ma (Hall, 2005), so we have opted to include it in a group of poles that we call PG. Giving unit weight to each pole yields a mean virtual geomagnetic pole at 44.0°S, 152.7°E (A_{95}=9.3°). It consists of 6 VGPs obtained from a total of 58 site means. We include it in the list of palaeopoles that can potentially be used to reconstruct part of the drift history of Pilbara, others being from the Millindinna Complex, from Packages 4-7, and from Packages 8-10 (Strik et al., 2003). Recently, Evans et al. (2017) have reported new results from nine Black Range dykes. They find generally shallower remanence vectors than those reported by Schmidt and Embleton (1985) for the Black Range Dyke itself, and for the associated Cajuput Dyke. The new data significantly impact the older Vaalbara debate (Zegers et al. 1998; Wingate, 1998; Strik et al., 2003), but we postpone further discussion until after the relevant Kaapvaal data have been summarized.

As far as the Kaapvaal craton is concerned, Strik et al. (2003) point out that the large uncertainty associated with the Derdepoort Basalt palaeolatitude (±17.5°) indicates that "more sampling is needed". We argue that combining the Derdepoort and Modipe data implies that such sampling has, to some extent, already been done. The resulting palaeopole lies at 37.7°S, 18.6°E, A_{95}=9.1°. Three other relevant Kaapvaal palaeopoles are those for the the Usushwana Complex (Layer et al., 1988), the Westonaria Basalt (Strik et al, 2007), and the Allanridge Basalt (de Kock et al., 2009). We exclude the Westonaria Basalt result because it is based on only four sites that yield an imprecise VGP with a large 95% error circle (19°).

The relevant palaeopoles are summarized in Table 1, and plotted as a map in Figure 3. As pointed out above, Zegers et al. (1998) showed that it is possible to bring

Kaapvaal and Pilbara close together at ~2.87 Ga (Usushwana Complex -UC, and Millindinna Complex - MC). Subsequent radiometric dates modify the argument, but do not necessarily invalidate it. Gumsley et al. (2015) obtained a very precise baddeleyite age of 2989±1 Ma from the same area of the Usushwana Complex that Layer et al. (1988) sampled for their palaeomagnetic study. The age of the Millindinna Complex has also been updated from the poorly constrained Sm-Nd age of 2860±20 Ma used by Zegers et al. (1998). Gumsley et al. (2013) state that "more recent U-Pb dating has obtained ages of 2925 and 3015 Ma for different Millindinna intrusions", but no error bounds are given. Bearing in mind these current difficulties, we indicate on Figure 3 the two more recent ages for pole MC. If the 2925 Ma age is applicable, then the original "Zegers" reconstruction remains valid, since it is close to the 2989±1 Ma Kaapvaal UC age. If not, then there is no palaeomagnetic support for the original Vaalbara.

For later times, de Kock et al. (2009) have attempted a reconstruction using pairs of poles from the two cratons. In principle, this offers a way around the thorny problem of palaeolongitude, which cannot be determined from single palaeopoles because of the zonal nature of the field produced by a geocentric axial dipole. They use two pairs of poles: K1-P1 (~2780 Ma), and K2-P2 (~2700 Ma). For Kaapvaal, the K1 pole is the Derdepoort Basalt pole of Wingate (1998) and the K2 pole is their own Allanridge Formation pole (referred to as AR in the present paper). The P1 and P2 Pilbara poles are both from Strik et al. (2003), but care must be taken not to confuse P2 of de Kock et al. (2009) with P2 of Strik et al. (2003)—it is actually pole P8-10 of these latter authors. In their analysis, de Kock and colleagues suggest a palaeogeographic solution that brings Kaapvaal and Pilbara close together and simultaneously produces dual K1-P1 and K2-P2 overlap (see their Fig. 8d). In fact, the 95% confidence circles for K1 and P1 do not overlap, despite the large uncertainty associated with K1. The situation is made worse if K1 is replaced by the combined Modipe-Derdepoort palaeopole (MD) because the 95% confidence limits are halved (from 18° to 9°). A robust Vaalbara reconstruction remains elusive. The situation is further complicated by the new data for the Black Range Suite (BRS) (Evans et al., 2017), from which the authors infer a "rapid drift of the Pilbara craton across the Neoarchean polar circle". In Figure 3, we summarize the rather sparse dataset currently available. In our view, there are only three Kaapvaal "anchor poles": UC, MD, and AR. For Pilbara, there are five: MC, BRS, PG, P4-7, and P8-10. In present-day co-ordinates, both apparent polar wander (APW) paths indicate a generally southerly movement of several tens of degrees. Details differ, but the most serious problems arise from the chronology as it is currently understood. The "rapid drift" of Pilbara inferred by Evans et al. (2017) is severely restricted by the fact that both ends of the trajectory have the same age (2772±2 Ma). Statistical uncertainty thus allows no more than 4 million years for 47° (>5000 km) of movement, implying a plate speed in excess of 130 cm/yr. A similar conclusion is drawn by de Kock et al. (2003) for the interval between P4-7 and P8-10. On the other hand, Kaapvaal moved at a much slower pace over a longer time interval. Between MD and AR (~2780 Ma to ~2710 Ma) the average plate speed was less than 6 cm/yr. A single supercraton cannot be reconciled with two such widely differing plate speeds.

We conclude that the currently-available palaeomagnetic evidence does not support the existence of a unified Vaalbara supercraton assemblage between ~2.9 Ga and ~2.7 Ga. Although the individual drift histories of the two cratons *throughout* the ~2.9 to

~2.7 Ga interval do not favour the existence of a single supercraton, it is interesting to note that their palaeolatitudes are comparable at the start, and again at the end, of this interval. At the start of the interval, UC and MC have palaeolatitude 95% confidence limits of 28°-40° and 41°-54°, respectively. These ranges do not quite overlap, but the geographic extent of the cratons themselves certainly permit contiguity. At the end of the interval, AR and P8-10 have overlapping 95% confidence limits of 30°-42° and 26°-36°, respectively. The intriguing possibility therefore arises that an ocean opened up between Kaapvaal and Pilbara after ~2.9 Ga, and then closed again some 200 Ma later, constituting a geologically very early classic Wilson Cycle. It remains to be seen if new data—particularly from southern Africa—confirm this scenario.

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Figure captions

Fig. 1. Map showing the locations of the Modipe Gabbro (locations MNE, WK and BO) and Derdepoort Basalt (location MR). Localities MNE, WK and MR are discussed in the text. We also plot locality BO, which was the focus of the study of Muxworthy et al. (2013). The border between Botswana and South Africa follows the Marico River to the east on the map.

Fig. 2. Normalized alternating-field demagnetization Zijderveldt plots of typical Modipe Gabbro and Derdepoort Basalt samples. The primary components revealed are: Modipe Gabbro declination=195.3°, inclination=71.3° (MAD=1.6°), Derdepoort Basalt declination=12.3°, inclination=69.2° (MAD=1.3°). Closed (open) symbols are on the horizontal (vertical) plane. Labels give demagnetization fields in mT.

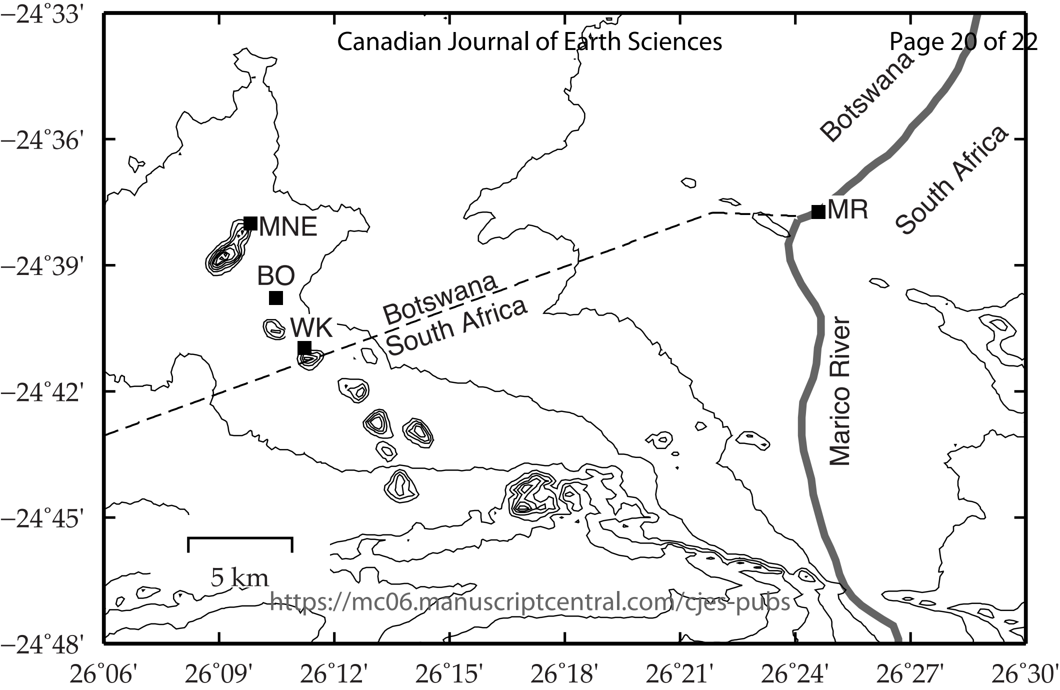
Fig. 3. Map showing the Kaapvaal and Pilbara cratons and their relevant Virtual Geomagnetic Poles (VGPs). Ages in Ma. The craton polygonal outlines were digitized from published maps. The main palaeopoles ("anchor poles") are shown in red. The individual palaeopoles that are used to obtain MD and PG are shown in grey. UC: Usushwana Complex (Layer et al., 1988). MD: Modipe Gabbro (MG, this paper) and Derdepoort Basalts (DB, Wingate, 1998). AR: Allanridge Basalt (de Kock et al., 2009). MC: Millindinna Complex (Schmidt & Embleton, 1985). BRS: Black Range Suite (Evans et al., 2017). PG: Mean of 6 poles (this paper). P1 and P2 (Strik et al., 2003), Black Range Dyke (BR) and Cajaput Dyke (CD) (Embleton, 1978), Mount Roe Basalt

(RB) and Mount Jope Volcanics (JV) (Schmidt & Embleton, 1985). P4-7: P4-7 (Strik et al., 2003). P8-10: P8-10 (Strik et al., 2003).

Table 1: Summary of palaeomagnetic and radiometric data

ID	Lat	Long	α_{95}	Age(Ma)
UC	09	347	8	2989±1
MD	-38	19	9	2784±1(a) 2782±5(b)
AR	-70	346	6	2708±4
MC	-12	161	8	2925(c)
BRS	-04	130	15	2772±2
PG	-44	157	9	2772-2766
P4-7	-50	138	13	2752-2725
P8-10	-59	186	6	2718-2715

Lat, Latitude (degrees North).
Long, Longitude (degrees East).
α_{95}, 95% confidence cone (degrees).
(a) Modipe Gabbro (Denyszyn et al., 2013).
(b) Derdepoort Basalt (Wingate, 1988).
(c) See discussion in text.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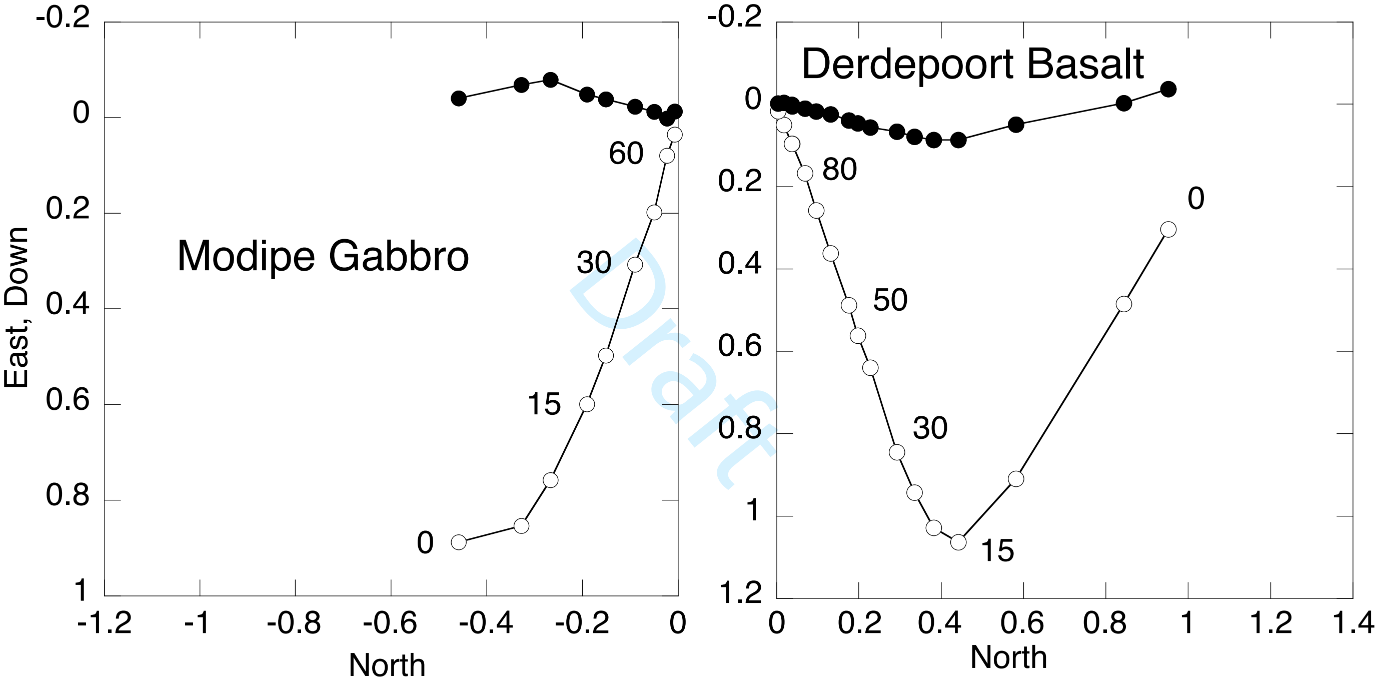
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-0.2
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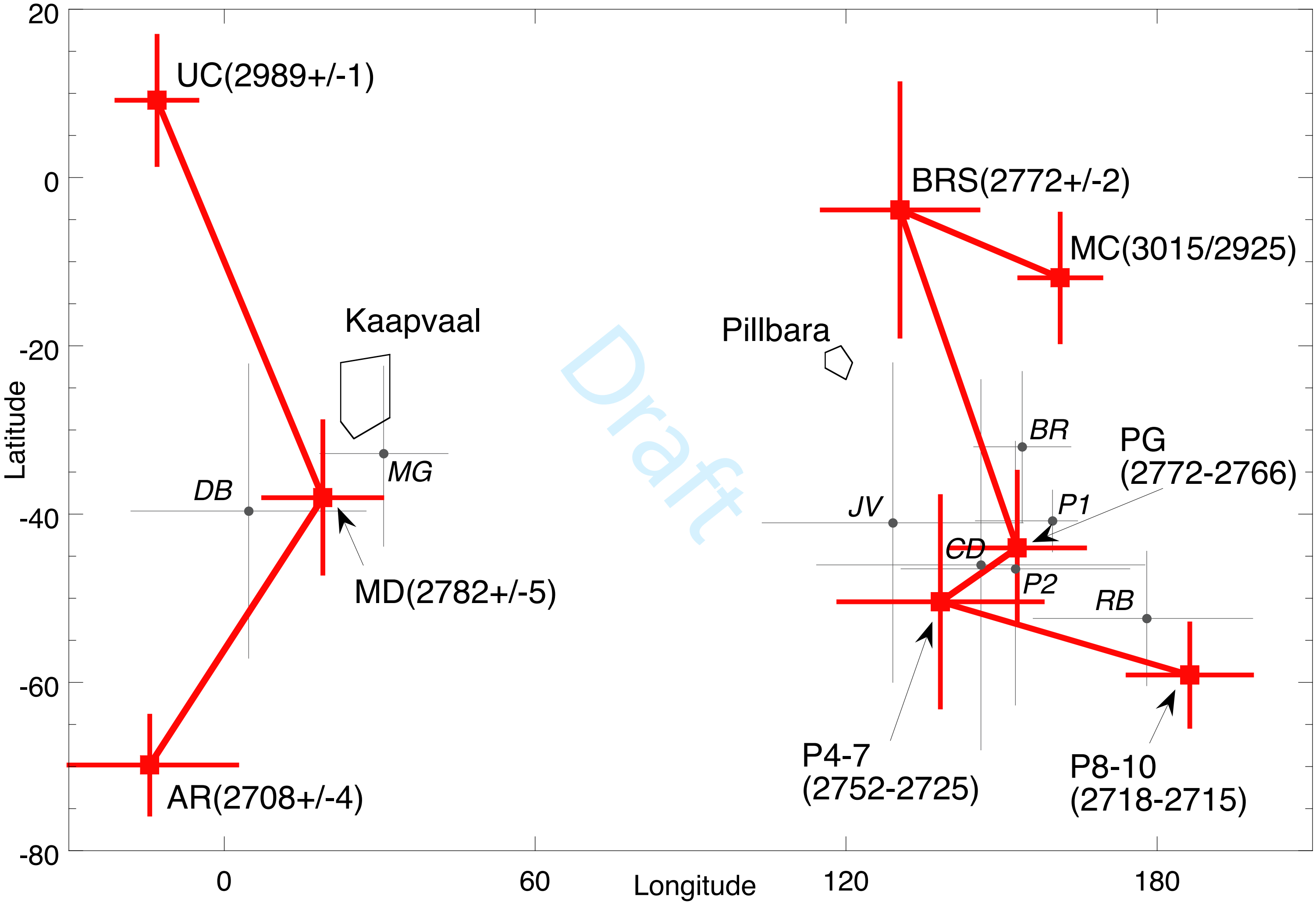
0.2
0.4
0.6
0.8
1
1.2
-1.2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
60
30
15
0
80
50
30
15
0



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0
-20
-40
-60
-80
Latitude
0
60
Longitude
120
180
UC(2989+/-1)
Kaapvaal
DB
MG
MD(2782+/-5)
AR(2708+/-4)
Pillbara
BRS(2772+/-2)
MC(3015/2925)
BR
PG
(2772-2766)
JV
P1
CD
P2
RB
P4-7
(2752-2725)
P8-10
(2718-2715)