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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 supercontinent. 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 supercontinental unit between ~2.87 and ~2.71 Ga is inconsistent with the available palaeomagnetic data. In particular, a significant palaeolatitude misfit at ~2.78 Ga implies an ocean some 2700 km wide. We interpret the sequence of palaeopoles for the two cratons as the signature of the opening and closing of an ocean basin in a classic Wison cycle.

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), 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 Archean supercontinent 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 to build up an adequate database will be required, 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 reported by 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. 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. The new results confirm the polarities previously reported, the relevant site means being 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. Including these two site means yields 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. It has a reliability index (Q) (van der Voo, 1990) of 6 or 7, depending on how one treats the possibility of tectonic correction, as discussed below.

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. We sampled an additional site near Wingate's site LVZI. Alternating-field demagnetization was straightforward (Fig. 1) 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 Archean 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 Ushushwana 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. The poles in question are from the Mount Roe Basalts (Schmidt and Embleton, 1985—this is the one used by Wingate), the Black Range and Cajuput Dykes (Embleton, 1978), and the P1 pole of Strik et al. (2003). We also include the P2 pole of Strik et al. (2003) because it differs little in age and its 95% confidence circle significantly overlaps that of the P1 pole. Giving unit weight to each pole yields a mean virtual geomagnetic pole (VGP) at 44.0°S, 157.4°E (A_{95}=8.7°). The corresponding palaeolatitude is 51.2°S (with 95% limits 43.7°S to 59.8°S). We refer to this Pilbara group of poles as PG. It consists of 5 VGPs obtained from a total of 54 site means. We include it in the list of palaeopoles that can potentially be used to reconstruct part of the drift history of Pilbara, the others being from the Millindinna Complex (MC) and Mount Jope Volcanics (JV) (Schmidt and Embleton, 1985), and from Packages 4-7 (P4-7) and Packages 8-10 (P8-10) (Strik et al., 2003).

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 (MD) lies at 37.7°S, 18.6°E, A_{95}=9.1°, corresponding to a mean palaeolatitude of 75.4°S (95% limits 66.8°S to 84.6°S). Three other relevant Kaapvaal palaeopoles are those for the Ushushwana Complex (UC) (Layer et al., 1988), the Westonaria Basalt (WE) (Strik et al, 2007), and the Allanridge Basalt (AR) (de Kock et al., 2009). To investigate the possible history of the proposed supercontinent Vaalbara, we focus on six palaeopoles that form three approximately contemporaneous pairs UC/MC, MD/PG, and AR/P8-10. We do not consider the Mount Jope and Package 4-7 data from Pilbara because they have no counterpart in the Kaaapvaal craton. They are dated between 2752 and 2725 Ma (Strik et al., 2003) and thus fall squarely in the gap between the younger age limit for MD (2778 Ma) and the older limit for AR (2712 Ma). We also exclude the Kaapvaal Westonaria Basalt data because it is based on only four sites that yield an imprecise VGP with a large 95% error circle (18.8°).

The six results we consider are illustrated in terms of palaeolatitude plotted as a function of time (Fig. 2), and as a map (Fig. 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 (UC and MC). But thereafter, the two cratons drifted apart such that by MD/PG times they were separated by 24°±13°. In plate tectonic terms this implies an ocean some 2700 km wide created at an average full-spreading rate of ~3 cm/yr. Thus, the pendulum has swung back in favour of Wingate (1998)—there was no unified Vaalbara at this time. Between MD/PG and AR/P8-10 both cratons moved towards the equator, but Kaapvaal drifted faster than Pilbara and a new supercontintent may have been established. However, this remains no more than a possibility because absolute palaeolongitude cannot be determined palaeomagnetically. A partial way around this difficulty is attempted by de Kock et al. (2009) who point out that relative palaeolongitude can, in principle, be established if pairs of VGPs from the two cratons can be matched up. 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 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 Derdepoort-Modipe palaeopole (MD) because the 95% confidence limits are halved (from 18° to 9°). We conclude that the palaeomagnetic evidence does not support the existence of a unified Vaalbara supercontinent between ~2.87 Ga and ~2.71 Ga. On the contrary, this interval seems to have been one during which an ocean basin opened and then closed, yielding the classic palaeomagnetic signal of a Wilson cycle.

Acknowledgements

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Figure captions

Fig. 1. Alternating-field demagnetization of a typical Deredepoort Basalt sample. After removal of a modern overprint, a primary component is revealed with declination=12.3°, inclination=69.2° (MAD=1.3°). Closed (open) symbols are on the horizontal (vertical) plane. Units on axes are $10^{-2}Am^{-1}$. NRM=$2.98x10^{-2}Am^{-1}$. Labels give demagnetization fields in mT.

Fig. 2. Palaeolatitudes for Kaapvaal and Pilbara cratons. The plotted data refer to the centre of each craton.

UC: Usushwana Complex (Layer et al., 1988).

MD: Modipe Gabbro (this paper) and Derdepoort Basalts (Wingate, 1998).

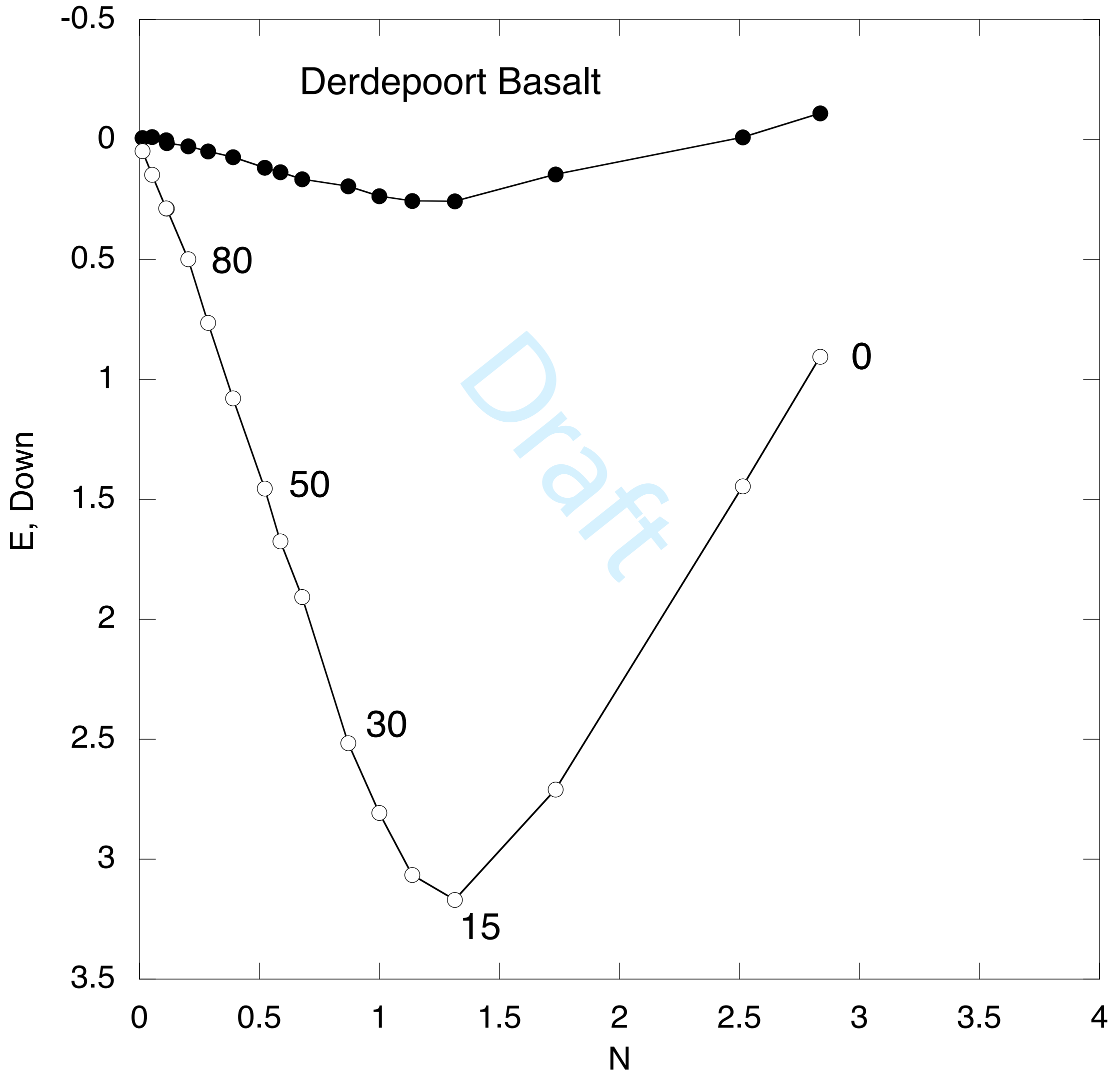
AR: Allanridge Basalt (de Kock et al., 2009).

MC: Millindinna Complex (Schmidt & Embleton, 1985).

PG: Mean of 5 poles (this paper). P1 and P2 (Strik et al., 2003), Black Range Dyke and Cajaput Dyke (Embleton, 1978), Mount Roe Basalt (Schmidt & Embleton, 1985).

P8-10: P8-10 (Strik et al., 2003).

Fig. 3. Map showing the Kaapvaal and Pilbara cratons and their relevant Virtual Geomagnetic Poles (VGPs). Labels as in Figure 2. Ages in Ma. Azimuthal equidistant projection from the South Pole (at the centre) to 20°N. The craton polygonal outlines were digitized from published maps.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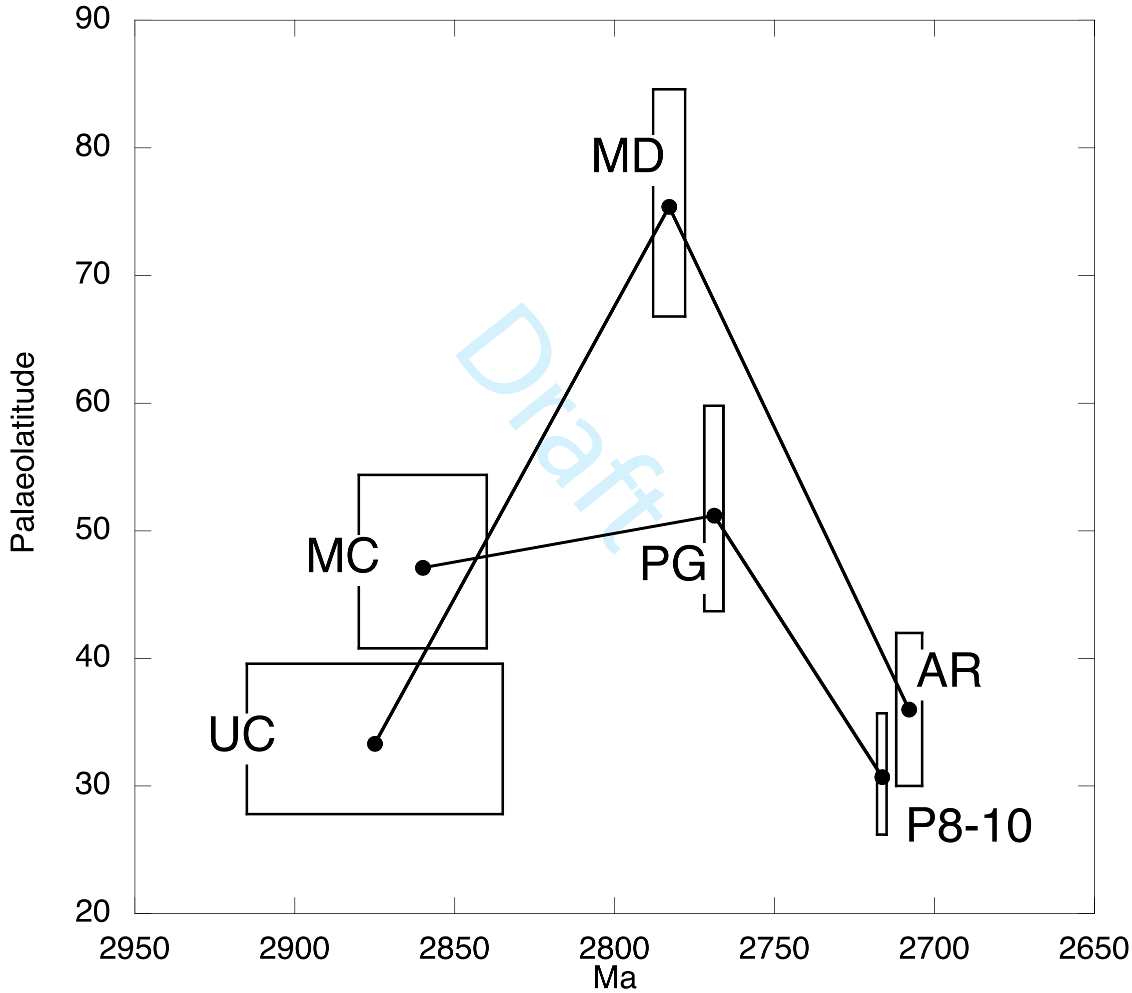
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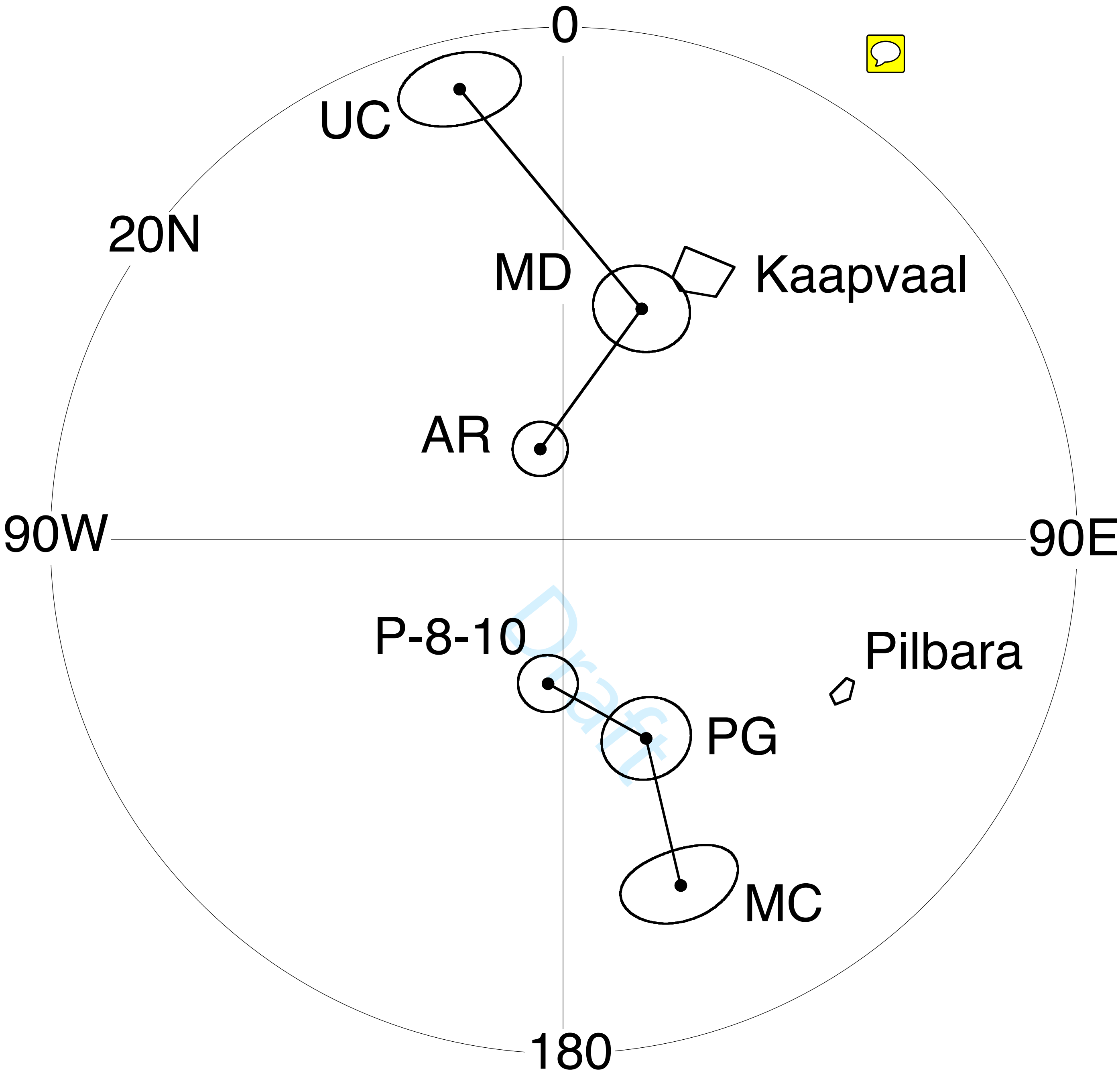
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