Paleomagnetism of Mafic Dikes in the Northern Pilbara Craton, Western Australia

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Abstract

Two well preserved Archean cratons, Kaapvaal and Pilbara, have remarkably similar geological successions during the Archean and Paleoproterozoic. This has led some to propose that the two may have been connected during that interval, thus experiencing similar tectonic events. We sampled Archean and Proterozoic rocks from the Pilbara craton in order to test the Vaalbara hypothesis, especially the reconstruction of de Kock et. al (2009). Unfortunately, many of the samples did not yield interpretable results. We did identify the primary magnetization direction of two dikes from the Round Hummock swarm. The ages of these dikes are poorly constrained and they are in need of a geochronological study. However, by investigating some plausible ages due to our limited constraints, we can identify two possible interpretations. If we assume that the dikes are correlative with the similarly-striking Tom Price swarm to the south (dated at 2008 $\pm$ 16 Ma. by Müller et. al. (2005)), then we can test the Vaalbara hypothesis at ca. 2.0 Ga. With the VGPs given by the Round Hummock dikes we are not able to rule out Vaalbara at 2.0 Ga. Alternatively, we can compare the VGPs with existing Proterozoic paleomagnetic poles for Australia. We find that they plot very near to the 1067 Ma Bagemall Basin Sills pole raising the possibility that the Round Hummock swarm might instead be correlated with the Bangemall Basin Sills.

1 Introduction

Archean cratons are scattered across the globe, providing clues about Archean and Paleoproterozoic geodynamics. Two of the most pristinely preserved Archean cratons are the Kaapvaal craton in southern Africa and the Pilbara craton in Western Australia. Both of these cratons consist of Archean granite-greenstone basement rock with extensive Neoarchean and Paleoproterozoic cover sequences recording their tectonic evolution. The stratigraphic similarities between these two cratons between 3.6-1.7 Ga are extensive, which prompted Cheney et. al. (1988) to suggest that the two were joined as a single continent, dubbed Vaalbara, during that time period.

The histories of the Kaapvaal and Pilbara cratons and any supercontinents that they may have constituted are important for understanding Neoarchean and Paleoproterozoic tectonics, and may aid in understanding the generation of valuable ore deposits. Additionally, many of the earliest traces of life are found on both cratons during the proposed Vaalbara interval. Understanding the evolution of the two cratons, shared or not, may be important for determining the paleoenvironments of Earth during the evolution of early life.

2 Previous Work

Cheney (1996) analyzed the sequence stratigraphy of the Pilbara and Kaapvaal cratons and concluded that they were correlatable. Zegers et. al. (1998) used geological and paleomagnetic constraints to propose a reconstruction of Vaalbara at 2.87 Ga with Pilbara to the east of Kaapvaal, in the Kaapvaal reference frame. Wingate (1998) compared paleomagnetic

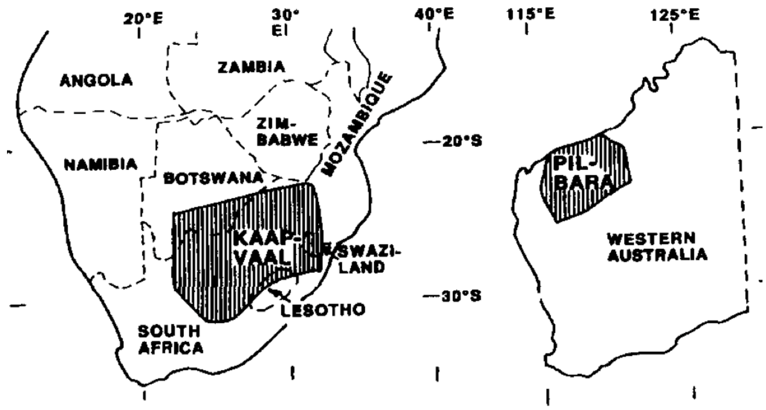

Figure 1: Locations of the Kaapvaal and Pilbara Cratons (From Cheney (1996))

poles from the Kaapvaal and Pilbara cratons at 2.78 Ga and found that they did not allow a reasonable connection between the two. However, Strik et. al. (2003) found with updated paleomagnetic data that the Vaalbara hypothesis could not in fact be rejected during this time.

de Kock et. al. (2009) have proposed a Vaalbara reconstruction using a more detailed APW path for the Kaapvaal craton. They have placed Pilbara to the northwest of Kaapvaal in the Kaapvaal reference frame. With this placement the APW paths of the two cratons match reasonably well during 2.8-2.7 Ga. In addition, the geology of the two cratons, including magmatic events, passive margin sedimentation, and orogenies, match well with this reconstruction.

In this study we sampled Archean and Proterozoic rocks from the Pilbara Craton in an effort to test the proposed reconstruction and to provide further constraints on the relative positions of Kaapvaal and Pilbara.

3 Study Area and Sampling

We performed four weeks of paleomagnetic sampling in the Pilbara during June/July 2008. Most of our samples came from Archean and Paleoproterozoic dolerite dikes and basalt flows. We collected 314 drill cores using a diamond-tipped drill bit with a 2.5 cm diameter. We oriented the cores with both a Brunton compass and a sun compass; in most areas the magnetic declination was less than 5°. Figure 2 shows the major sampling areas. Samples from the Tom Price dike swarm and the Cape Preston dikes yielded either low-quality or uninterpretable results: as such we only describe them cursorily.

3.1 Tom Price Dikes

A swarm of northwest-striking dolerite dikes intrudes much of the southern Pilbara, especially in the region near Tom Price. Müller et. al. (2005) report a date of 2008 $\pm$ 16 Ma for the

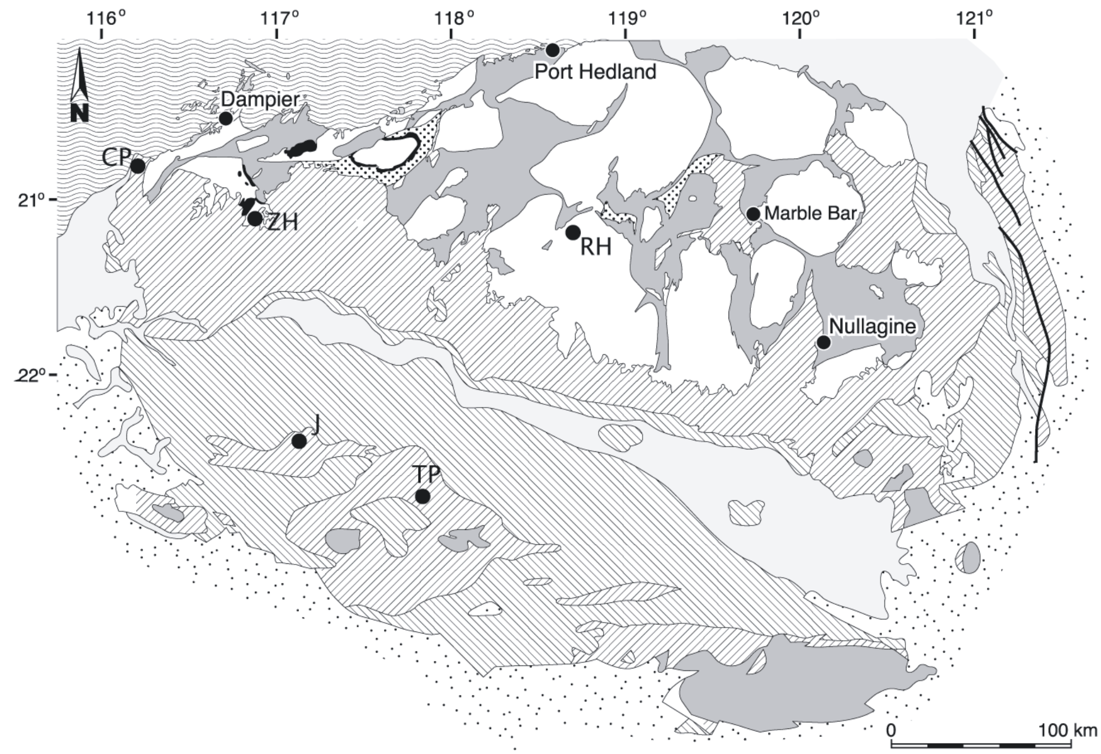

Figure 2: Simplified map of the Pilbara Craton. Shown are the major towns and the sampling regions from this study. J = Jeerinah Dome Dikes, RH = Round Hummock Dike, CP = Cape Preston Dikes, TP = Tom Price Dikes, and ZH = Zebra Hill Area. (Figure modified from Zegers et. al. 1998)

swarm using Pb/Pb SHRIMP dating of baddeleyite. The Tom Price (TP) Dikes are quite common in the area and easily identifiable in satellite and aeromagnetic images, but it proved difficult to find outcrop suitable for sampling. Near Tom Price we sampled four dikes with two baked contact tests into the Bunjinah Formation of the Fortescue Group. We also sampled two TP dikes with one baked contact test into the Bunjinah in the Jeerinah Dome (J on the Figure 2)area.

All of the sampled TP dikes intruded the country rock vertically or subvertically, giving them linear traces in map view. If they had been appreciably tilted since their intrusion, they would have arcuate traces. We therefore applied no tilt correction for the TP dikes.

3.2 Cape Preston Dikes

A set of four north-striking dolerite dikes intrude the country rock at Cape Preston in the northern Pilbara. The dikes have been dated at ca. 1815 Ma (MTD Wingate, pers. comm.

2008). We sampled all four dikes and performed two baked contact tests into the country rock.

3.3 Round Hummock Dikes

The Round Hummock (RH) Dikes are a swarm of northwest-striking dolerite dikes that intrude a large region of the northern Pilbara. They are largely unstudied, though they have been described as correlative with the Tom Price Dikes in the southern Pilbara (GSWA Memoir), largely due to their similar strikes. We sampled two Round Hummock dikes: one near the Munni-Munni layered mafic intrusion, and one that intersects the Great Northern Highway to Port Hedland. We collected seven samples from the latter dike (site RH1).

We drilled an extensive baked contact test on the RH dike near Munni-Munni. The dike cuts a thicker dike known as Zebra Hill, which stands in positive relief to the surrounding granite country rock (all the samples from this area are given the prefix ZH, though they come from several different dikes). We collected cores from two locations in the RH dike center (sites ZH5 and ZH6), and from two unbaked locations in the Zebra Hill dike (ZH3 and ZH4). ZH7 contains cores from the chilled margin of the RH dike as well as cores from the baked zone of Zebra Hill dike.

Several other dikes cut Zebra Hill, particularly a pair of ENE-striking dikes which may be part of the Mundine Well (MW) swarm. The MW dike swarm intruded the Pilbara at 755 Ma and is possibly associated with the breakup of the supercontinent Rodinia (Wingate and Giddings, 2000). The MW swarm represents one of the last major tectonic events in the Pilbara, and has a well established paleomagnetic direction (Wingate and Giddings, 2000). This is particularly relevant because one of them intersects Zebra Hill near to ZH7, potentially partially or completely remagnetizing those samples. We therefore sampled one of the ENE dikes so that we might identify any potential overprints on the ZH7 samples. Unfortunately, we could not find a suitable outcrop of the dike near ZH7, so we sampled the other ENE dike (site ZH8).

The Round Hummock and ENE dikes cut the flat-lying Hardey Sandstone Formation, indicating that none of them have been tilted since intrusion, so no tilt-correction is necessary.

4 Methods

4.1 Demagnetization Scheme

We cut specimens 1 cm in height from the drill cores and performed our measurements in a magnetically shielded room with a 2G SQuID magnetometer and Kirschvink-style automatic sample changer (Kisrchvink et. al. 2008). We began the demagnetization process by cooling the specimens in liquid nitrogen through the Verwey transition to preferentially remove the less stable remanence of multi-domain magnetite. We then performed stepwise alternating-field (AF) demagnetization up to 100 Gauss on the specimens to remove the components of lowest coercivity (often partial remagnetizations due to lightning).

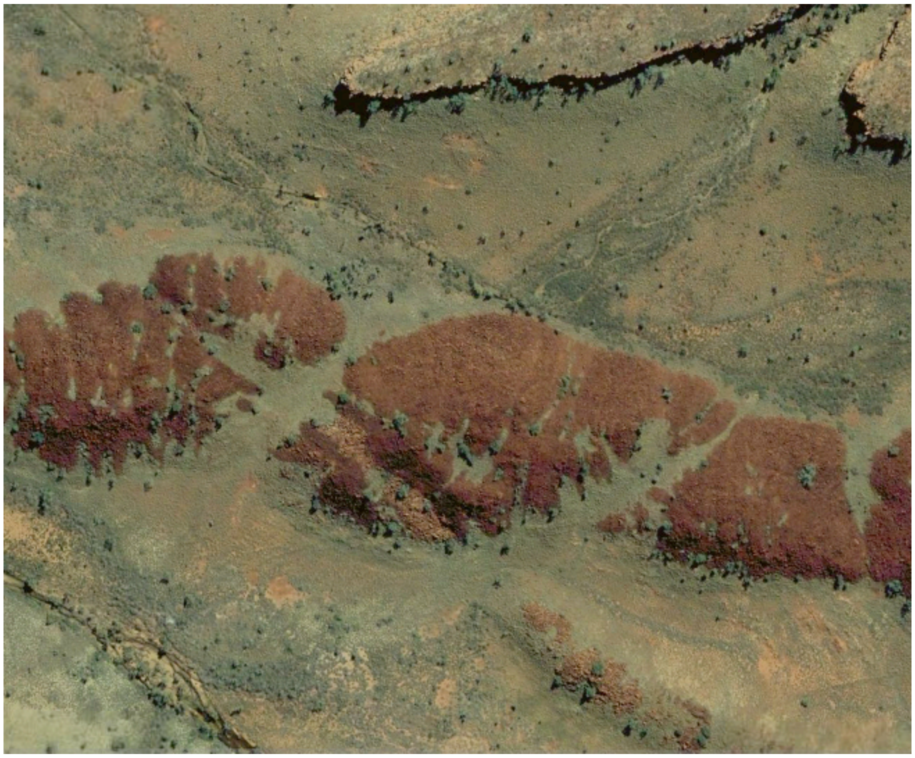

Figure 3: Satellite image of the Zebra Hill sampling area. Figure 4 shows the same area schematically

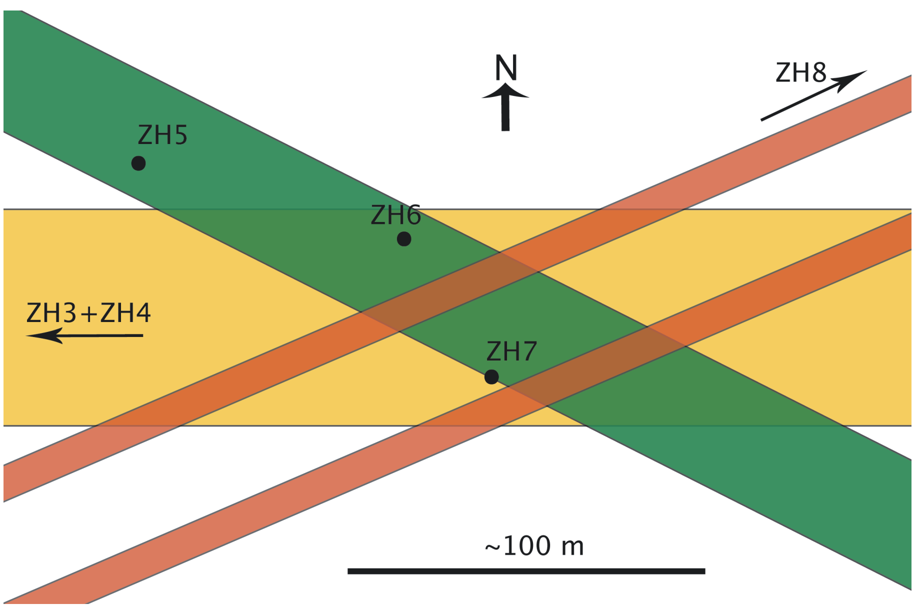

Figure 4: Schematic of the cross cutting relationships for the dikes in the Zebra Hill area. The Zebra Hill dike is in yellow, the Round Hummock dike is in green, and the two Mundine Well dikes are in red. Also shown are the sampling locations.

From there, we performed stepwise thermal demagnetization in shielded ovens with controlled N_2 atmosphere to prevent high-temperature oxidation reactions of the minerals in the specimens. We proceeded up to the Curie temperature for magnetite at 580 ° C, or until a specimen no longer held a stable magnetization.

Samples from sites ZH3 and ZH4 were analyzed at the Michican Tech Paleomagnetism Laboratory as part of a larger study in Paleoproterozoic/Archean paleointensity.

After completely demagnetizing the specimens, we performed principle component analysis on the data, fitting lines and planes to the directions (Kirschvink, 1980). After fitting lines and planes to the data we used directional statistics (Fisher, 1953) to generate site mean directions.

4.2 Effects of Lightning

Lightning strikes are a persistent problem in paleomagnetism. The strong electromagnetic fields that propagate through the ground frequently remagnetize rocks at the surface. This is particularly problematic in places like the Pilbara, where outcrops have been exposed to the weather for extremely long times. In order to conduct a good paleomagnetic study, therefore, we must be able to identify lightning struck samples and remove any resulting overprint if possible; otherwise the samples should be excluded.

Lightning struck samples can be identified by the following criteria: (1) The samples tend to be strongly magnetized, often much more so than other, non-struck samples. (2) The magnetization of the samples tends to be single component. (3) The electromagnetic fields in the rocks during a lightning strike vary rapidly in space and time, tending to produce random directions in a suite of samples at a single site.

5 Results

5.1 Demagnetization Behavior

The demagnetization behaviors of the samples from the Zebra Hill area were generally well behaved. During demagnetization the samples from the Round Hummock dike (as well as those from site RH1 to the east) lose a large low-coercivity component with the liquid nitrogen and AF pre-treatment. This may be due to some spurious lightning overprint. Thereafter the samples from sites ZH5 and ZH7 stay fairly stable until 550 ° C, at which point its magnetization decreases rapidly with increasing temperature steps, indicating that the primary remanence carrier is magnetite.

The samples from site ZH6 present some difficulties. Its direction, while broadly similar to those of ZH5 and ZH7, is some 30 ° away. Like the other samples from the area, a large low-coercivitity component is removed with liquid nitrogen and AF pretreatment. However, a very large component also comes off in the 200-300 ° C range. It is unclear what mineralogy could be responsible for this behavior. Qualitatively, the outcrop for ZH6 was considerably more weathered than those for the other sites, and it is possible that it may have been

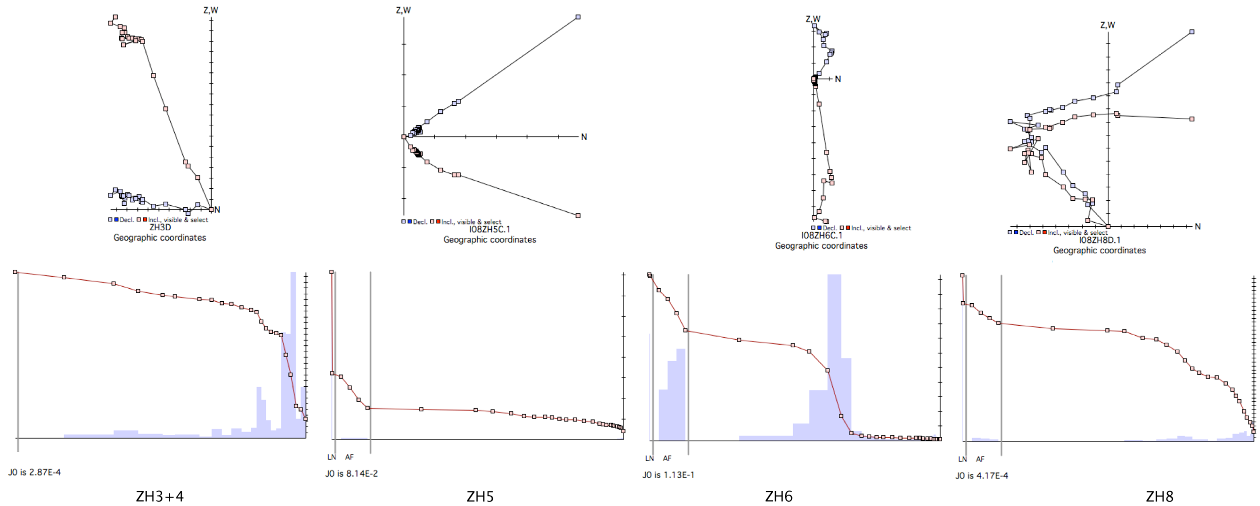

Figure 5: Typical demagnetization behavior for the sites of this study.

rotated with respect to the rest of the dike. Due to these caveats, we excluded the samples from ZH6 from our analysis.

The samples from ZH8 had demagnetization behaviors similar to those of ZH5 and ZH7. A low coercivity component was removed by pretreatment and they remained stable until 450-500 ° C. At this point they rapidly lost their magnetization until 560 °C, again indicating magnetite as the remanence carrier.

Most of the samples from the Tom Price dikes and Cape Preston dikes either showed signs of being entirely remagnetized by lightning or simply did not remain stable during the demagnetization process.

5.2 Directional Data

The samples from ZH5 have a well defined direction $D/I = 348.5°/44.3°, \alpha_{95} = 5.3°$. At ZH7 here were two distinct populations of samples roughly two meters apart, one of which was closer to the ENE dike that intruded nearby. All of the samples from the closer population were completely overprinted by a direction distinct from that of ZH5. The samples from the further population had the same overprint direction, but it was generally removed between 200 ° C and 450 ° C. At this point, the samples from the further population, both the Round Hummock ones and the baked Zebra Hill ones, gave the same direction as ZH5.

Though we could not sample the ENE dike that overprints ZH7, we were able to sample the other ENE dike at ZH8, which yields a similar (though not identical) direction to the ZH7 overprint. Thus, somewhat indirectly, there is a complete baked contact test for the ENE dikes, with a dike direction, baked country rock with the same direction, and unbaked

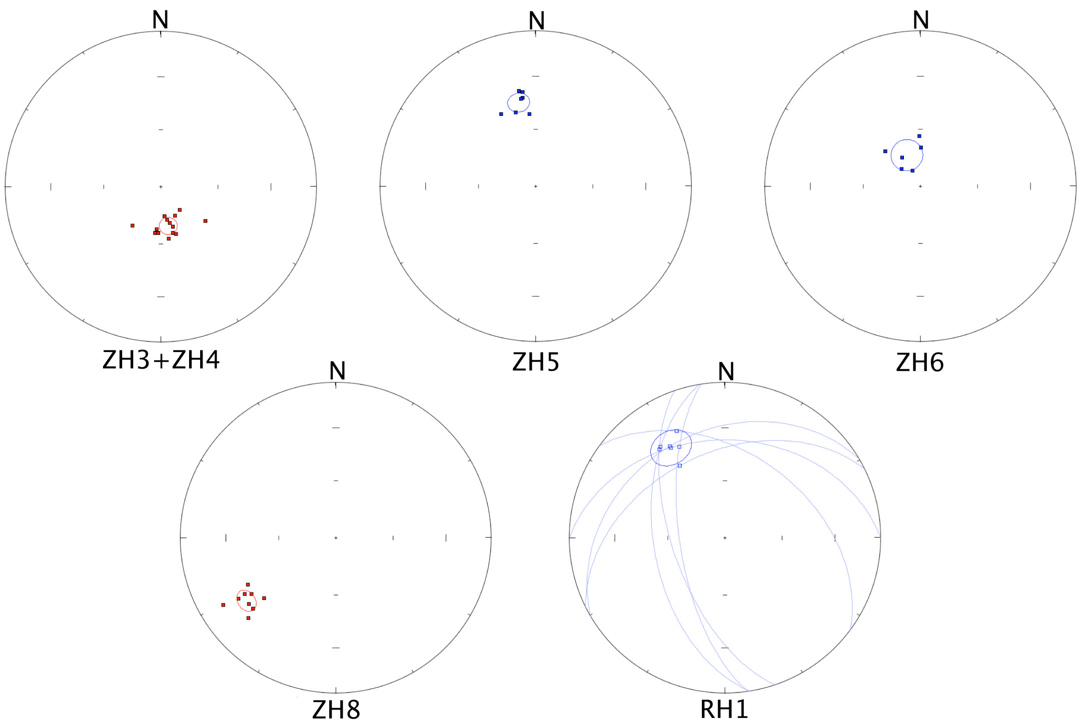

Figure 6: Fisher means for the sites of this study. Blue symbols refer to the lower hemisphere, red symbols refer to the upper hemisphere. The dots are the line fits to samples with a well defined decay to origin. The great circles are plane fits to samples for which the characteristic magnetization is not completely isolated by the demagnetization procedure. Also shown are the α_{95} s calculated according do Fisher (1953). Refer to Table 1 for the numerical values

ID	Lat (°N)	Long (°E)	D	I	α_{95}	PLat (°N)	PLong (°E)
ZH3	-21.192	116.831	175.5	-67.2	8.8	-18.8	293.7
ZH4	-21.197	116.864	162.1	-70.8	4.1	-12.2	286.4
Average Zebra Hill	-	-	169.3	-69.1	4.6	-15.7	290.1
ZH5	-21.187	116.865	348.5	44.3	5.3	41.6	102.9
ZH6	-21.187	116.867	336.6	72.2	8.2	9.2	104.2
RH at Zebra Hill	-	-	344.4	43.4	5.8	41.2	98.0
ZH7	-21.189	116.867	-	-	-	-	-
ZH8	-21.185	116.870	234.9	-30.4	5.2	-24.9	356.4
RH1	-21.398	118.708	328.4	34.4	7.4	39.3	78.9

Table 1: Results from the Round Hummock Dikes and the baked contact test at Zebra Hill

country rock further away.

The samples Zebra Hill dike, ZH3 and ZH4, complete the baked contact test for the Round Hummock dike (A. Smirnov, pers. comm. 2009). They have a well defined direction of $D/I = 169.3°/-69.1°, \alpha_{95} = 4.6°$, completely distinct from both the ZH5 direction and the ENE dike direction, indicating that the magnetization direction of the Round Hummock dike is primary.

The samples from the second Round Hummock dike that we sampled had scattered NRMs. However, demagnetization revealed that they all were scattered from a common direction, and as the procedure continued they returned moved towards it. Several of them did not reach the mean before losing their magnetization, but fitting planes to these components showed a well defined direction quite near to that of the Round Hummock dike at Zebra Hill. This direction, RH1, is $D/I = 348.5°/44.3°, \alpha_{95} = 5.3°$.

RH1 and the results from the Zebra Hill area are shown in Figure 7.

6 Discussion

Interpretations based on the results of this study are hampered by two serious shortfalls of the data set. First of all, the Round Hummock dike swarm is undated. This makes placing it within the context of other paleomagnetic studies and making tectonic reconstructions very difficult. Secondly, we only have two VGPs of the Round Hummock swarm, which does not average secular variation of Earth's magnetic field. The paleo-spin-axis could have been a non-negligible distance from the VGP locations. Therefore, any attempt to form conclusions from the Round Hummock data must involve hypotheticals.

6.1 Age of Round Hummock Dikes

The oldest possible age of the Round Hummock dikes is that of the youngest granite basement in the Pilbara, at 2.85 Ga. If we assume that the dike at Zebra Hill is correlative with the

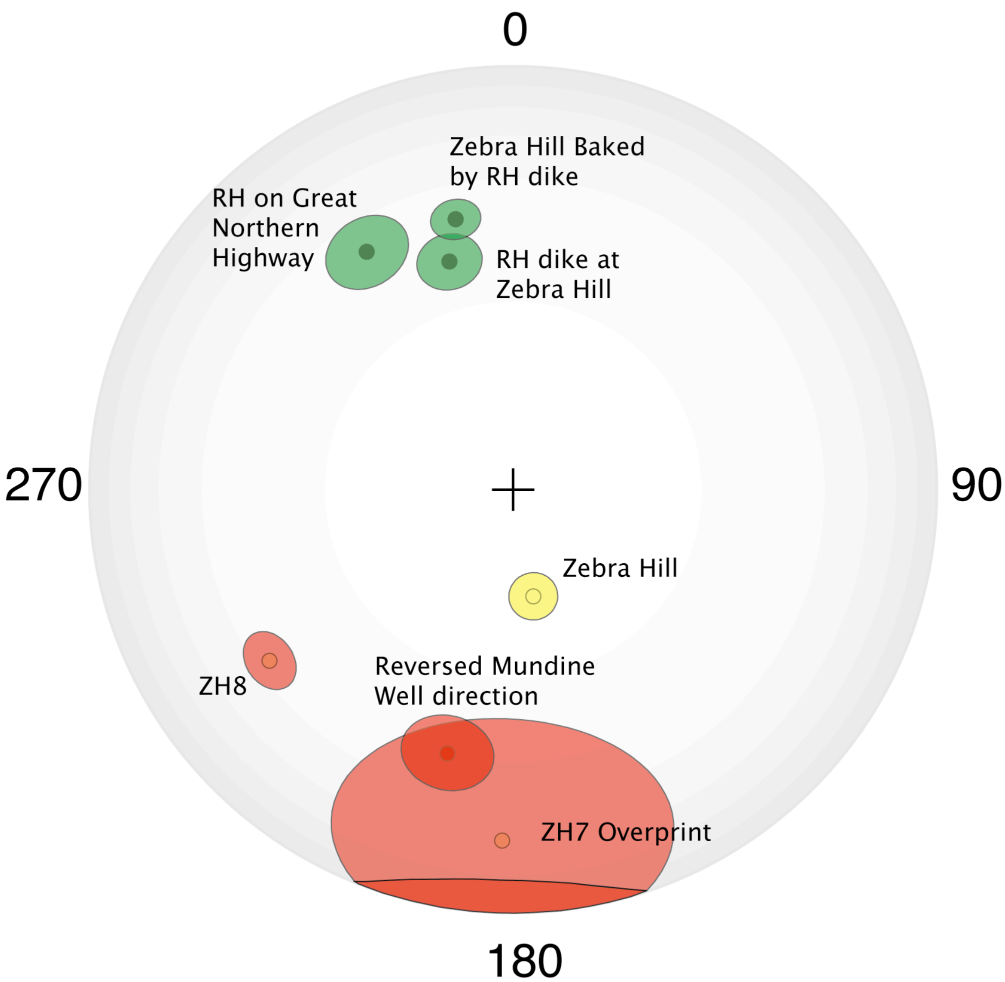

Figure 7: Results from the Round Hummock Dikes, as well as the baked contact test into Zebra Hill. Open dots indicate upper hemisphere directions, closed dots indicate lower hemisphere directions. Shown in green are the VGPs from the RH dike south of Port Hedland (RH1), the RH dike at Zebra Hill, and the Zebra Hill baked zone. Shown in yellow is the VGP for the unbaked Zebra Hill dike (A. Smirnov, pers. comm. 2009). Shown in red are the VGPs for ZH8 and the overprint on ZH7. The reverse direction of the paleomagnetic pole for the Mundine Well (Wingate and Giddings, 2000) swarm is also shown for a first-order comparison.

other Round Hummock dikes south of Port Hedland (which is reasonable, given their common strikes, outcrop characters, and paleomagnetic directions), then we can further constrain the maximum intrusion age to be younger than the Hardey Sandstone at 2750 ± 5 Ma, as the dike at Zebra Hill cuts it.

The Mundine Well dike swarm is well dated at 755 ± Ma and has a reliable paleomagnetic pole (Wingate and Giddings, 2000). The swarm outcrops over much of Western Australia, striking NS to the south of the Pilbara, and fanning out to strike ENE in the Pilbara. The ENE dikes from the Zebra Hill area have similar, but not identical, directions to the reversed Mundine Well direction (Figure 7). The previous paleomagnetic studies on the Mundine Well swarm (Wingate and Giddings, 2000; Embleton and Schmidt, 1985) have not found any reversed directions, but it is still reasonable to expect them in the Neoproterozoic. Additionally, Mundine Well dikes frequently have felsic xenoliths (Wingate and Giddings, 2000), which we found in a rock near site ZH7. If the ENE dikes at Zebra Hill are indeed from the Mundine Well swarm, then it would indicate that the Round Hummock dikes are at least older than 755 Ma, since ZH7 has a Mundine Well overprint.

In order to speculate about the consequences of the Round Hummock direction, we can identify three possibilities about its age: (1) The Tom Price dike swarm in the Hamersley Basin has been correlated with the Round Hummock swarm due to their similar strikes (GSWA Memoir 3, 1990). Müller et. al. (2005) have Pb/Pb dated the Tom Price swarm at 2008 ±16 Ma. If the two swarms are indeed correlative, we can use that date for the Round Hummock direction. (2) The Round Hummock dikes are Proterozoic in age, in which case we can compare the direction to existing Proterozoic poles from Australia. (3) The Round Hummock dikes are a different age altogether. We investigate the first two possibilities.

6.2 Case 1: Round Hummock is ca. 2.0 Ga

If we assume that the Round Hummock VGPs to are ca. 2008 Ma, we can look at how well they match the APW path for the Kaapvaal craton during the Paleoproterozoic using the Vaalbara reconstruction of de Kock et. al. (2009) (Figure 8). The Pilbara Craton and its associated poles are rotated into the Kaapvaal reference frame using the C3 configuration, with Euler rotation parameters 57°N, 73°E, -92° CCW. The RH VGPs plot very near to the ca. 2.06 Ga poles from the Lower Waterberg (WUBS-I) Phalaborwa 1 (PB1), and the Bushveld (BVMU). This would suggest that we cannot rule out Vaalbara at ca. 2.0 Ga, and that the Round Hummock/Tom Price dikes might indeed be associated with the final rifting of the Pilbara and Kaapvaal cratons.

If the RH poles are indeed 2008 Ma, then the proposed Vaalbara reconstruction would actually predict that they would plot nearer to the WUBS-II pole at 1992 ± 62 Ma, somewhere on the APW path shown. However, high-precision geochronological data from the Superior Province in Canada indicates that large igneous provinces can be emplaced over tens of millions of years (Halls et. al., 2008). Even if the Round Hummock swarm were correlative with the Tom Price swarm, it could well be closer to the 2.06 Ga age of the Kaapvaal poles with which the VGPs match well.

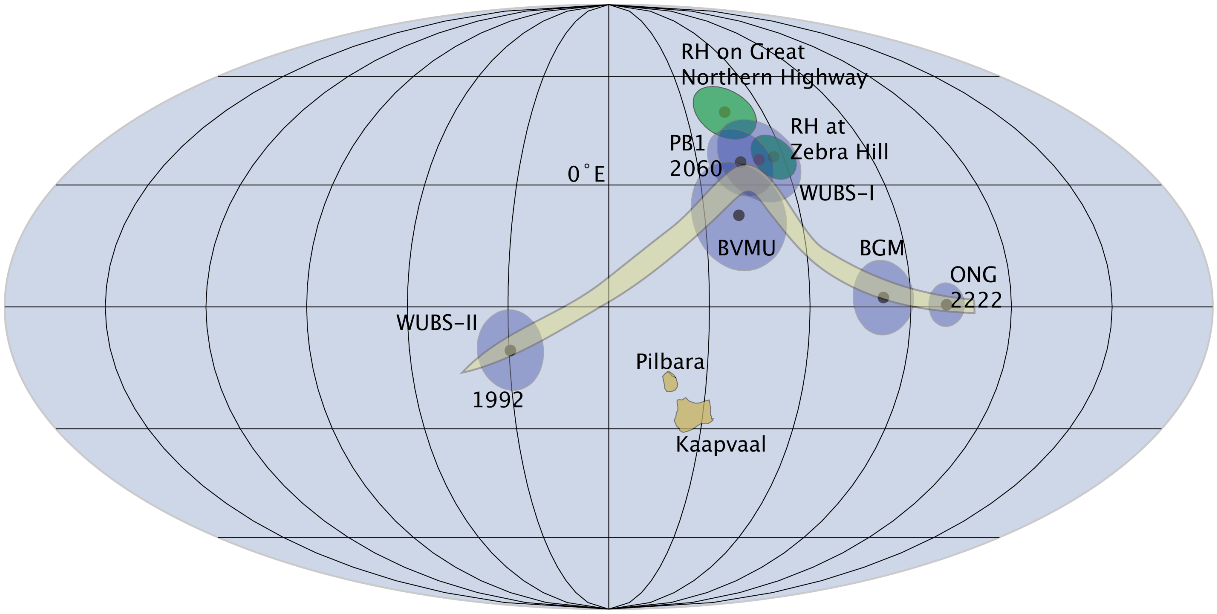

Figure 8: Round Hummock VGPs (green) rotated into the Vaalbara reconstruction of de Kock et. al. (2009). Everything is in the South African reference frame, with an Euler rotation of 57°N, 73°E, -92° CCW. The Round Hummock poles match well with the ca. 2.06 Ga poles from the Kaapvaal Craton. Also shown is a generalized APW path with selected Kaapvaal poles. ONG = Ongeluk lavas (Evans et. al. 1997); BGM = Basal Gamagara/Mapedi (Evans et. al., 2002); PB1 = Phalaborwa 1 (Morgan and Briden, 1981); BVMU = Bushveld main and upper zones (Hattingh and Pauls, 1994); WUBS-I and WUBS II = Waterberg sequences 1 and 2 (de Kock et. al. 2006) The date on the WUBS-II pole is poorly resolved at 1992 ± 62 Ma

6.3 Case 2: Round Hummock is much younger

We can plot the Round Hummock VGPs on the Mesoproterozoic/Neoproterozoic APW path for Australia (which should have been fully amalgamated by that point (Wingate and Evans 2003)). We can see in Figure 9 that the Round Hummock direction plots almost directly on top of BBS, the 1070 Ma Bangemall Basin Sills pole (Wingate et. al., 2002). The Bangemall Basin consists of a sequence of carbonate and siliciclastic rocks deposited after 1.8 Ga following the Capricorn Orogeny when the Pilbara and Yilgarn Cratons joined. During the latest Mesoproterozoic, the quartz dolerite Bangemall Basin Sills intruded the sedimentary succession (Wingate et. al., 2002). Furthermore, the Round Hummock direction does not coincide with any other Proterozoic poles from Australia. The coincidence of the RH VGPs and the BB1 pole raises the possibility that the Round Hummock swarm and the Bangemall Basin Sills are associated with similar tectonic events, and may even be comagmatic.

Between the two options we have considered, the young age for the Round Hummock dikes may be preferable. Although the Round Hummock and Tom Price swarms have similar strikes, there are several differences: (1) The Round Hummock dikes tend to be thicker

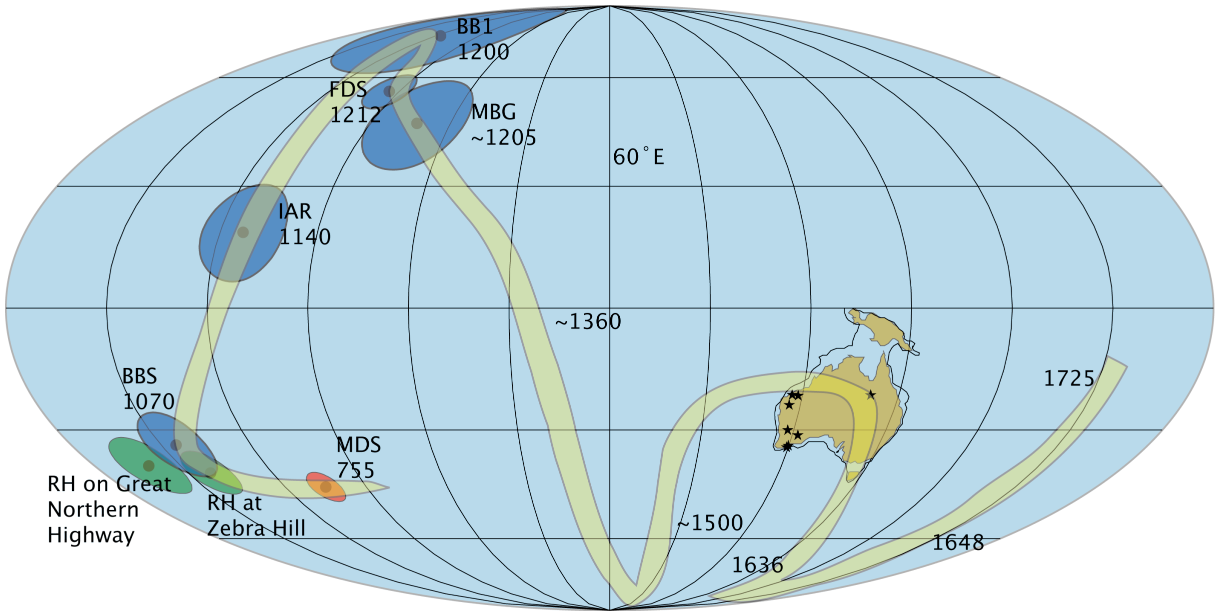

Figure 9: Proterozoic APW path for Australia. Shown in green are the two Round Hummock VGPs. MDS=Mundine Well Dikes (Wingate and Giddings, 2000); BBS = Bangemall Basin Sills (Wingate et. al., 2002); IAR=Mt. Isa Dolerite Dikes (Tanaka and Idnurm, 1994), BB1=Bremer Bay Metamorphics, FDS=Fraser Dike, MBG=Mt. Barren Metasediments (Pisarevsky et. al., 2003). The APW path is after Wingate and Evans (2003)

than the Tom Price dikes (25-30m vs. 5-15 m). (2) Based on interpretation from satellite images, the Round Hummock dikes appear to be much longer, up to hundreds of kilometers. (3) The Tom Price dikes much more densely populated than the Round Hummock dikes where they outcrop. (4) Both Round Hummock dikes were well behaved during demagnetization, whereas none of the Tom Price dikes that we sampled held a reliable and stable magnetization.

7 Summary

We have identified two VGPs for the Round Hummock dike swarm in the Pilbara. Unfortunately, the dikes are not well dated, and two VGPs do not adequately average secular variation. Therefore, the conclusions we can reach from the data are limited. However, a well resolved baked contact test indicates that the magnetization of the two dikes is primary. It is possible that the VGPs could argue for a Kaapvaal-Pilbara connection at 2.0 Ga, though it may instead be the case that the Round Hummock dikes are genetically related to the Bangemall Basin Sills to the south. In any event, the dike swarm behaves well paleomagnetically, so it should be amenable to a more extensive study. Evans and Pisarevsky (2008) found that from all published pre-800 Ma paleomagnetic poles, only about fifty have a field test, paleohorizontal control, well behaved demagnetization behavior, good statistics, and a well constrained age. This study lacks the latter two. If we combine VGPs from several more Round Hummock dikes with a geochronological study we would likely produce a robust paleomagnetic pole from which we could conclude more.

8 Acknowledgments

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