# USING AMS AND PALAEOMAGNETIC DATA TO ASSESS TECTONIC ROTATION: A CASE STUDY FROM SAVANNAH NICKEL MINE, WA

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**SUMMARY**

Recent research has shown that Ni-PGE mineralisation is typically associated with specific intrusion types, e.g., chonoliths, bladed-dykes and funnels that acted as high-throughput magma conduits within much larger magmatic provinces. The initial architecture of these systems is very different, but additional structural modification during orogenesis can render such intrusions very difficult to understand structurally, and hence make it very difficult to target the fertile zones within the system. In structural geology it is common to evoke shortening directions, which are assumed to apply to all rocks regardless of their rheology. This is not realistic. Furthermore, resolving the partitioning of strain is not straightforward for intrusive rocks, which tend not to develop visible tectonic fabrics, but act as rigid blocks that rotate to accommodate strain, rather than compress or shear, during deformation. Unfortunately there are few structural techniques that can be used to quantify such rotation.

Intrusions near the Savannah Nickel Mine, East Kimberley, WA were observed to have different deformation histories, despite being temporally equivalent. In this study we measured anisotropy of magnetic susceptibility (AMS) and remanent magnetisation in two adjacent, temporally equivalent, intrusions. The observed K3 AMS vectors are typically normal to the magmatic layering in layered intrusions. Where K3 vectors sit along a great circle, the pole to that great circle indicates the rotation axis. Original palaeomagnetic vectors would be expected to be consistently oriented with respect to magmatic layering, and can be used similarly to test the consistency of the inferred rotation analysis. The rotations inferred for the intrusions tested were consistent between the two techniques. Savannah and Savannah North, were subjected to N-S, NE-SW and NW-SE shortening, consistent with the Halls Creek Orogeny. However, N-S shortening was dominant at Savannah and NE-SW dominant at Savannah North. Therefore, despite their equivalent emplacement ages and implied tectonic history, each intrusion has undergone very different deformation.

**Key words:** Anisotropy of Magnetic Susceptibility (AMS), Palaeomagnetic Vectors, Nickel-PGE mineralisation, Layered Intrusive Complex, Tectonic History.

## INTRODUCTION

Magmatic Ni-Cu-PGE sulphide deposits are a major global resource that includes some of the world's most valuable deposits and camps. Some of the larger deposits, e.g., Noril'sk (Siberia) and Sudbury (Canada), contain many hundreds of billions of dollars' worth of metals. They are extremely attractive but notoriously difficult exploration targets. Within Australia there are several examples, e.g., Nebo-Babel, Nova and the Savannah deposit (formerly Sally Malay) in the East Kimberley which is the subject of this study.

In the past, exploration for magmatic Ni-PGE mineralisation has largely been focussed on layered mafic to ultramafic intrusions (e.g., the Bushveld Complex in South Africa or the Skaergaard Intrusion in Greenland). Many exploration programs in Australia have intersected mafic to ultramafic intrusions, particularly within the Musgrave (e.g., Austin et al., 2016) and the Arunta (e.g., Austin and Crawford, in press) but finding intrusions is only part of the battle. We have to find the right types of intrusions, and furthermore know where to target within those intrusions. Recent advances by Barnes et al. (2015), Lightfoot and Evans-Lamswood (2015) and Saumur et al. (2015) have shown that Ni-PGE mineralisation is typically associated with specific intrusion types, e.g., chonoliths, bladed-dykes and funnels, that acted as high-throughput magma conduits within much larger magmatic provinces (Le Vaillant et al., 2017). Obviously the initial architecture of these systems is very different, but additional structural modification during orogenic episodes can render such intrusions very difficult to resolve structurally, and hence make it very difficult to target the fertile zones within the system.

There are several mafic-ultramafic intrusions in the Savannah area (Fig 1a), all of which intruded at approximately the same time, e.g., Savannah North intrusion at 1833.66 ± 0.66 Ma, Savannah intrusion at 1835.64 ± 0.53 Ma (Le Vaillant et al., 2017). Although they appear to have intruded within 2 Ma of each other, the intrusions have different architecture (e.g., Savannah North appears to be a layered intrusion, Savannah appears to be a bladed-dyke. Furthermore the intrusions appear to preserve contrasting deformation histories (e.g., rotated/folded, and/or shortened/sheared in different directions). Both these factors (i.e., initial architecture and subsequent tectonic deformation) have important implications for the origin and expected current geometry of orebodies and hence affect targeting strategies within the system.

This study introduces a technique which combines insights from palaeomagnetic and AMS (anisotropy of magnetic susceptibility) studies to deduce the direction and magnitude of shortening, plus information on the style of deformation within mafic-ultramafic intrusions, in order to better understand the original geometry, and provide clues to best target fertile parts of the system. The two techniques are used in parallel because they each have different strengths and weaknesses. The palaeomagnetic data can provide information on how palaeomagnetic vectors were rotated during subsequent deformation. However, there are many potential causes of resetting of palaeomagnetic signatures and furthermore the likely variability in the coercivity of the palaeomagnetic grains within the different intrusions can make it difficult to isolate different tectono-metamorphic episodes. For this reason we have also utilised AMS data, which is particularly useful for measuring and differentiating fabrics (e.g., magmatic layering, folding and shear/strain fabrics) in order to gain additional insights into the deformation recorded within the various intrusions. In this paper we integrate the insights from both datasets in order to understand the unique geologic histories of two contemporaneous intrusions.

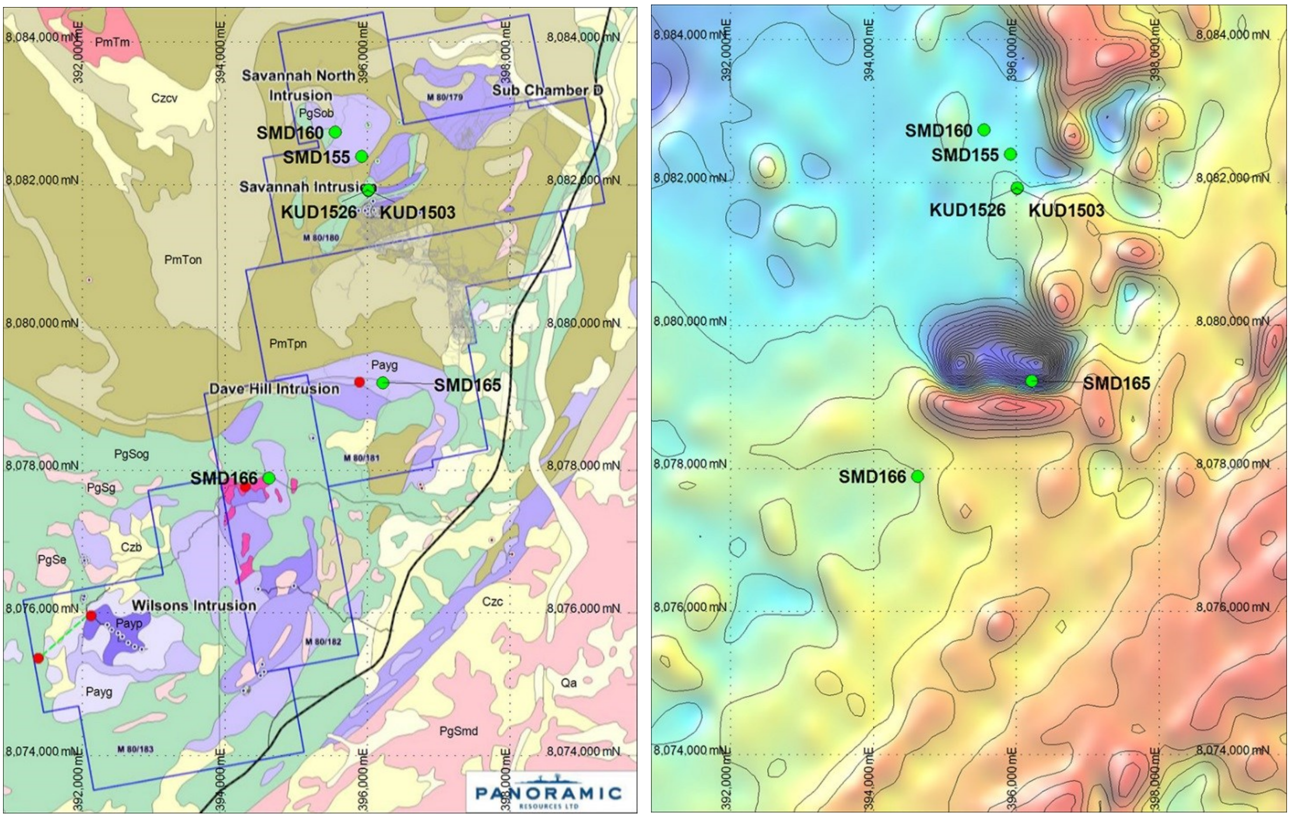


**Figure 1: Left. Geological map from Panoramic Resources that has been rectified in MapInfo. Sampled drill holes are marked in green, and the studied intrusive centres are labelled. Purple units are mapped as Sally Malay intrusions (softer colours are felsic, darker colours ultramafic. Dark blue-green colours are Sally Downs Supersuite including biotite-norite and olivine-gabbronorite (PgSob/Sog). Brown colours are Tickalara Metamorphics including mafic granulite (PmTon) and migmatitic pelitic gneinss (PmTpn). Pink colours are felsic intrusive rocks, e.g., the Mabel Downs Tonalite located in the SE corner of the map. Units are based on Tyler et al. (1998b); Right. Total magnetic intensity grid, with 50nT contouring. Note the strong negative magnetic anomaly associated with the Dave Hill Intrusion.**

## METHODS

Sampling was completed in February 2016 onsite at the Savannah mine, and produced 42 samples from 4 drillholes (as shown on Fig 1). 19 samples were obtained from Savannah North (drillholes from SMD 155 & 160) at an average sample spacing of 22.6 m. 23 samples were obtained from Savannah (drillholes KUD1503 & 1506) at an average sample spacing of 15.8 metres. Samples obtained were a mix of ¼ and ½ HQ and NQ core. The samples were re-drilled and cut into 3 specimens (2.5 × 2.2 cm cores; the optimum cylindrical approximation of a sphere), all of which were measured for magnetic susceptibility, density and NRM.

Anisotropy of magnetic susceptibility (AMS) analysis was carried out on the all specimens using an Agico MFK1-A Kappabridge magnetometer. The results are comprised of three orthogonal susceptibility vectors that together define an ellipsoid with a long-axis (K1), an intermediate-axis (K2) and a short axis (K3), which is geographically corrected using the drill-hole plunge and visualised using a stereonet. The clustering of the resultant data can be used to assess the orientations of fabric(s) within the lithologies studied. Three main parameters calculated from the results can be used to differentiate the style of fabrics present. P. $P=K1/K3$ and represents the anisotropy factor. The higher the P value, the more anisotropic the rock is, or conversely, if $P \approx 1$ the rock is isotropic. $L=K1/K3$ and defines the extent to which a rock has a lineation (i.e., if $K1>K2 \approx K3$ the ellipsoid is prolate and the rock has lineation). $F=K2/K3$ and defines the extent to which a rock is foliated (i.e., if $K1 \approx K2>K3$ the ellipsoid is oblate and the rock has a foliation).

In general, for an in situ undeformed layered intrusion we would expect the K3 (short axis of the AMS ellipsoid) to be vertical, reflecting the shortening vector during crystallisation i.e., the gravitational field of the Earth. The K1 (long) and K2 (intermediate) axes should form a girdle normal to K3, i.e., horizontal, and parallel to the compositional layering of the intrusion. Assuming there was no far-field stress applied to the intrusion as it cooled, K1 and K2 would be expected to be poorly clustered. If the intrusion was crystallised in the presence of an external stress field, clustering would be expected. However, the K1 and K2 would still be expected to form a horizontal girdle. Any deformation subsequent to crystallisation would likely cause folding and or shearing of the AMS fabric. So deformation may be reflected in AMS data as tilting of the (previously horizontal) layering, in which the clustering of the results is consistent with an in situ layered intrusion but with inclined layering. Fine-scale folding of the layering would result in a girdle of K3 orientations. If there were more than one deformation event there could be two or more overprinting folds, and the more overprinting events present, the more likely the results are to be poorly clustered (i.e., uninterpretable). AMS fabrics may also be acquired through pure strain (i.e., similar to a cleavage) or shear. In the case of shearing it is probable that any primary layering related to crystallisation would be entirely overprinted, however, we would expect better clustered K1 and K2 data than for a magmatic (layered) fabric. These principals are applied to the interpretation of the AMS data.

Both alternating field demagnetisation (AFD) and thermal demagnetisation techniques were used to resolve the various components of magnetisation. Low temperature demagnetisation (using Liquid Nitrogen) was undertaken to remove any viscous/low coercivity components. One specimen per sample was progressively demagnetised using an alternating field of increasing intensity to incrementally remove the ‘softest’ component of remanent magnetisation prior to each re-measurement. AFD was carried out using the 2G Enterprises 755R three-axis cryogenic magnetometer with in-line 2G 600 Series AF demagnetisers. AFD utilises two sets of perpendicular coils (aligned along the x- and z-axes of the sample) with a rapidly alternating current which produce a precisely controlled magnetic field. The field acts to randomise the magnetic moments of the rock in the x-, y-, and z-axes by rotating the sample through 90° during degaussing. Measurements of the remanent magnetisation are taken after subjecting the sample to increasing magnetic field strengths. Typically, samples were measured for NRM and LN2 (post-liquid nitrogen cleaning) then subjected to AF fields of increasing strength, typically: 2, 5, 7, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100 mT. Samples that retained stable magnetisation after 100 mT underwent further AFD up to 140 mT. One specimen per sample was also progressively demagnetised using increasing temperatures to incrementally remove thermal ‘soft’ components magnetisation prior to re-measurement. The typical steps used for thermal demagnetisation included: NRM, LN2, 150, 250, 300, 310, 320, 330, 340, 350, 400, 450, 500, 540, 550, 560, 570, 580 and 590°C.

The results of each analysis (magnetisation vectors) were plotted on stereonets and Zijderveld diagrams, which were used to assess the migration of the magnetisation vectors with successive stepwise demagnetisation. Analysis of the magnetisation components was performed using an interactive version of Linefind (Kent et al., 1983), in which linear segments are fitted to data points weighted according to the inverse of their measured variances (as for Schmidt and Williams, 2011), otherwise known as a principal component analysis (PCA). The PCA analyses were plotted in stereonets and used to interpret rotation of the rock fabric, inferred by fitting palaeomagnetic results from the intrusions to a great circle, and then comparing the inferred rotations with the AMS results.

## RESULTS

### Savannah North AMS

Savannah North displays a fabric typical of a sill or layered intrusion, with a sub-vertical mean K3 (short axis, shortening direction) and K1 and K2 sitting within a sub-horizontal girdle on the stereonet (Fig 2). In this case we use the K3 as a pole to the layering fabric (pink circles), which is related to the shortening direction during crystallisation (i.e., gravity). The close clustering at Savannah North (Fig 2a) indicates that the original layering appears to be a mostly undeformed AMS fabric. However, there is some local variability of the K3 observed, and some evidence to suggest some minor N-S, NE-SW and ESE-WNW oriented deformation may have taken place, based on a number of sub-horizontal K3 directions present.

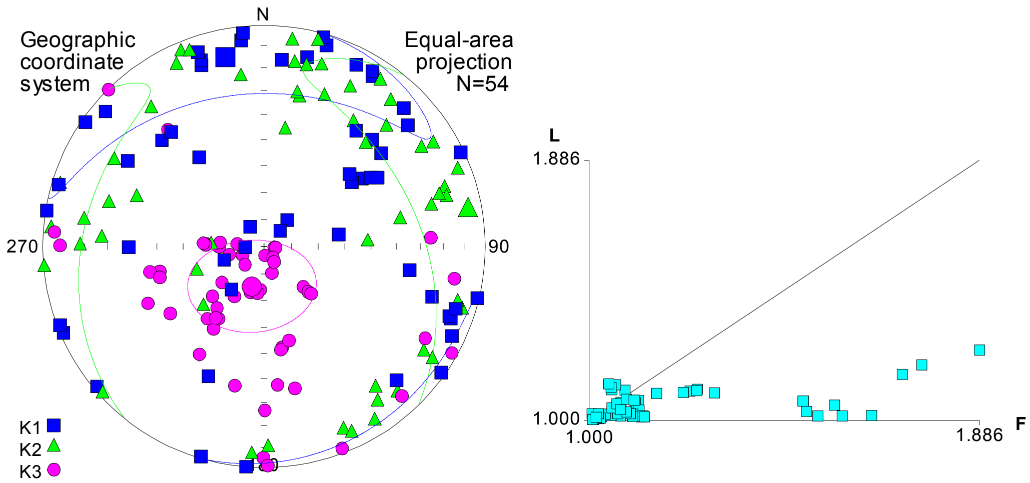


**Figure 2: AMS results for Savannah North, showing: Left. All results on a stereonet. The convention used for this and all subsequent AMS data is the blue squares=K1, green triangles=K2 and pink circle=K3; Right. Plot of L (lineation) vs F (foliation) which indicates that the fabric present is dominantly a foliation.**

There are a number of ways to further isolate different aspects of the AMS. Here we trialled several approaches, including: Clipping results to only include lineation dominant fabrics; Clipping results to only include foliation dominant fabrics; Clipping low susceptibility results and low anisotropy results which tend to have more variable/ higher error AMS orientations, these all yielded similar results. However, results may also be clipped to reflect certain K1 or K3 orientations, and these cases yield better isolated clusters, each representing a distinct variation in magnetic fabric, including those with: Sub-vertical K3 (Fig 3a); Steep SW-oriented K3 (Fig 3b); Moderate south-oriented K3 (Fig 3c), and; Sub-horizontal SE-oriented K3 (Fig 3d).

These isolated clusters of data can be used to infer distinct deformation styles. The majority of results are consistent with a sub-horizontal magmatic fabric. However, examination of the cleaned data (i.e., restricted to the main cluster of sub-vertical K3s; Figure 3 a), indicates that the main magmatic fabric has been tilted slightly toward the north and/or NE, post crystallisation. Furthermore, there is evidence in Fig 3b and c to suggest that the main magmatic fabric has been rotated more substantially (i.e., folded) in some instances resulting in moderate NE- (Fig 3b) and north-dipping (Fig 3c) fabrics being present. This implies that the main magmatic/magnetic fabric has been folded by both N-S and NE-SW directed shortening likely associated with relatively ductile conditions. There is another fabric present which appears to be sub-vertical NNE-oriented, and likely associated with WNW-directed shortening (Fig 3d). In this case the fabric appears to be related to strain or shear rather than simple tilting of the magmatic fabric, possibly related to minor reverse shearing within discreet zones of the intrusion during ductile-brittle conditions.

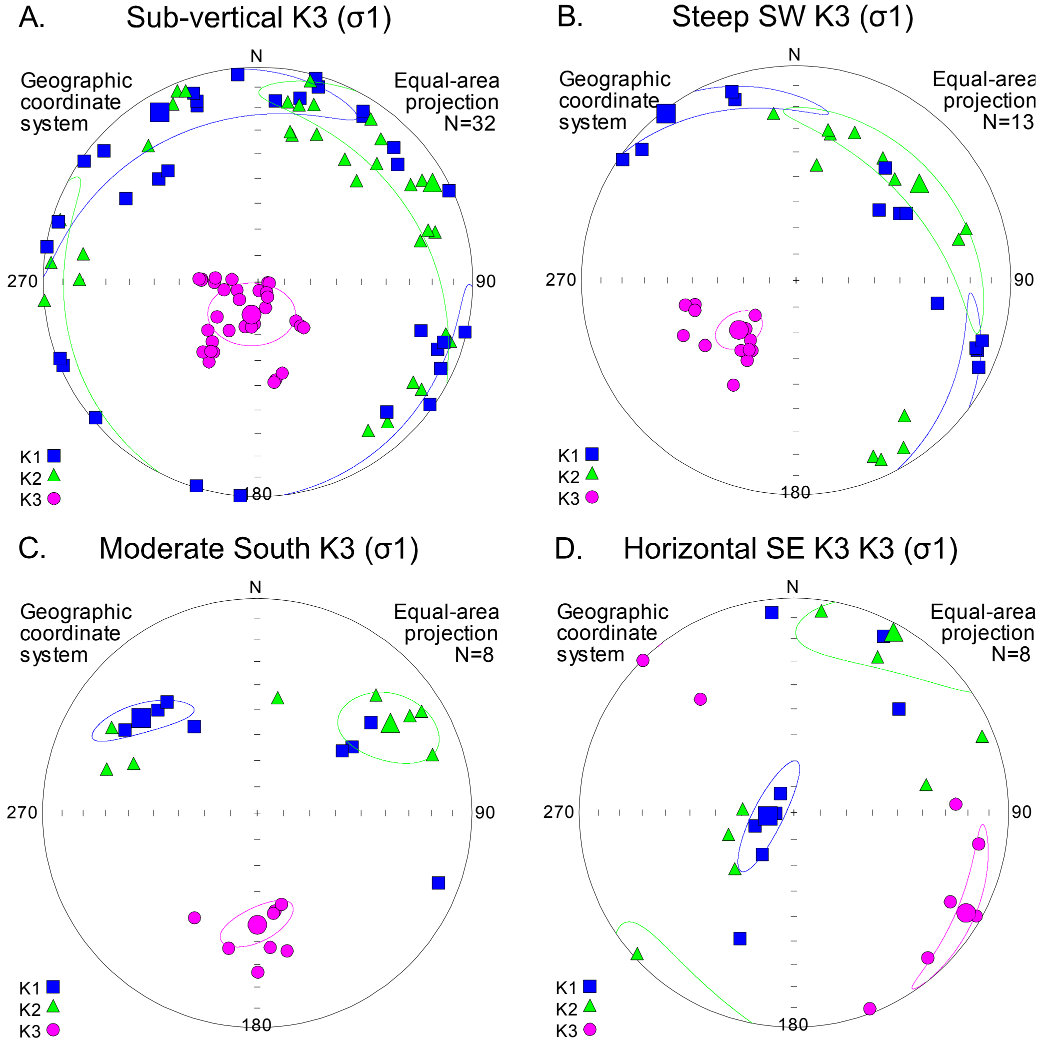


**Figure 3: AMS results for Savannah North were sub- domained to better isolated clusters each representing a different variation in magnetic fabric; A. highlights a cluster with sub- vertical K3; B. a cluster with steep SW-oriented K3; C. a cluster with moderate south-oriented K3; and D. a cluster with sub-horizontal SE-oriented K3.**

### Savannah North Palaeomagnetic Analysis

Savannah North typically has weak remanent magnetisation, and the palaeomagnetic results are very mixed and do not give much of an indication of a dominant remanence direction. There are numerous samples which contain relatively stable remanence, which can persist up to high alternating fields. In some cases there is evidence to suggest that dual polarity remanence is present, which indicates that the magnetisations are genuine. However, these samples were typically not demagnetised sufficiently for us to be certain of the directions, due to limitations in the maximum field that can be generated by the 2G instrument (140 mT). The results were sorted into magnetisations with low, moderate and high grain coercivities, and were plotted for the latter in Fig 4. The majority of the palaeomagnetic data sit in an ENE-WSW striking upright girdle (Fig 4a), which are interpreted as folding of a single palaeomagnetic direction. However, the spread of data is large (i.e., effectively 180°) which is not realistic, as it implies recumbent folding, which is not consistent with the textures observed in the intrusion.

As indicated previously, there are results in which dual polarity are noted, and the magnetisation within these samples have a wide range of declinations, so the data have been separated into data showing dual polarities and those that do not. We found that removing the results with dual polarity reduced the spread of results substantially, providing more confidence in the results. With the dual polarity results removed, a mean direction oriented steeply down to the SW can be obtained from the data (Fig 4b), albeit with very high α95 of 36.8° (low confidence). Overall we really cannot make any useful conclusions other than there appears to be a steep downward magnetisation present which appears to have been modified by folding to some extent. The folding directions inferred are not inconsistent with that interpreted from the AMS data, but they could represent much later metamorphic overprint (e.g., from the Alice Springs Orogeny.

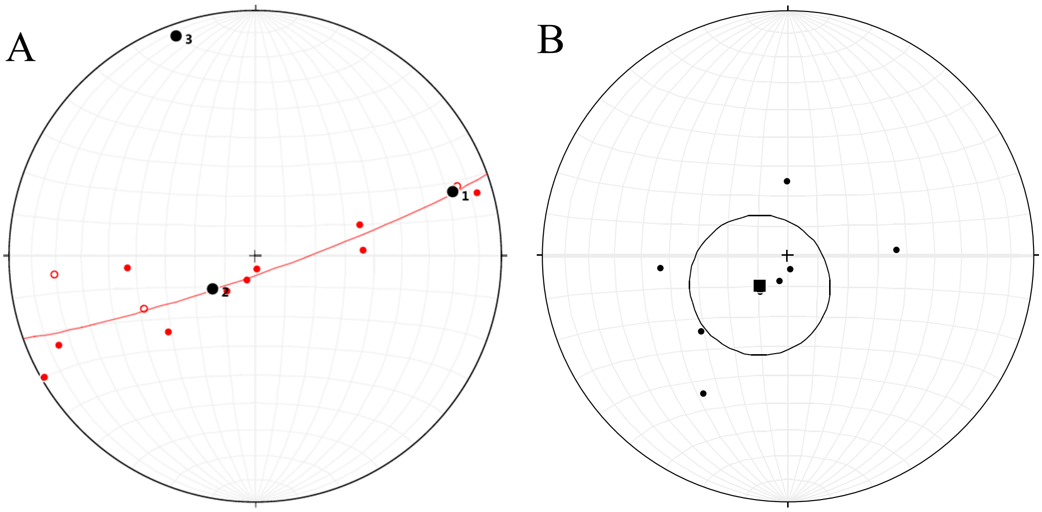


**Figure 4: A. The majority of high coercivity magnetisations within Savannah North sit within an ENE-striking girdle. B. displays results which are typically oriented steeply down to the SW.**

**Savannah AMS**

The results for Savannah are difficult to interpret, and do not show a clear pattern when viewed all together (Fig 5) or even when clipped to remove near isotropic results. This likely indicates that the intrusion has been significantly deformed, syn- to post- intrusion. The results from the different drill holes sampled are quite different. The samples from drill hole KUD1503 appear to preserve a mostly sub-horizontal fabric (as indicated by the sub-vertical K3), and in a limited number of cases also show evidence of some SE-NW oriented shortening (as indicated by the sub horizontal K3s). Within this group of sub-vertical K3 results there is a general N-S trend suggesting some modification of the magmatic fabric as will be discussed further below. The results from KUD1526 do not show evidence for a sub-horizontal foliation being the dominant fabric, as would be expected for a sill or layered intrusion, but broadly indicate a sub-vertical NW-SE oriented foliation. The AMS data for savannah were clipped to better isolated clusters each representing a different variation in magnetic fabric, including those with: Sub-vertical K3 (Fig 6a); Sub-horizontal NW-SE-oriented K3 (Fig 6b); Sub-horizontal N-S-oriented K3 (Fig 6c), and; Sub-horizontal NE-SW-oriented K3 (Fig 6d).

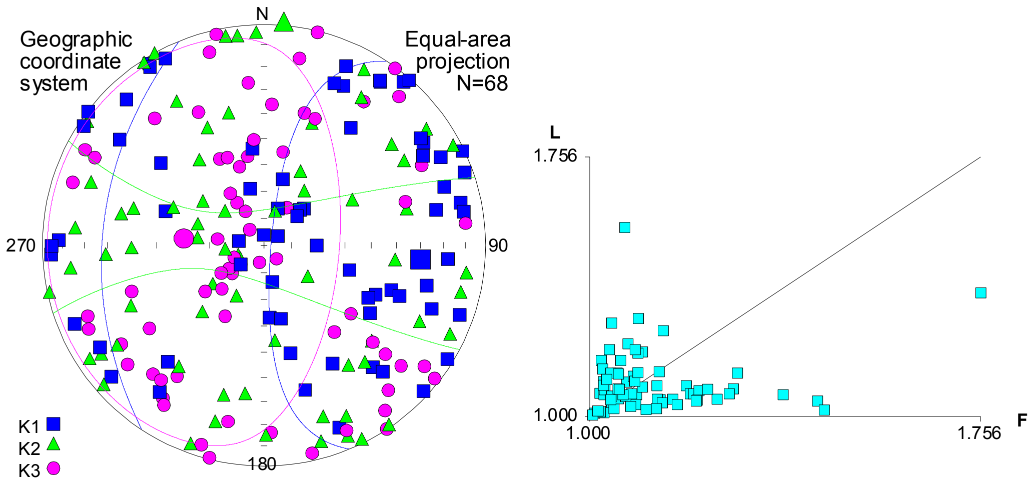


**Figure 5: Left. AMS results for Savannah, showing: A. Stereonet displaying K1, K2 and K3 for all samples, plus mean directions and confidence ellipses; Right. plot of L (lineation) vs F (foliation) which indicates that the fabric present is dominantly a foliation.**

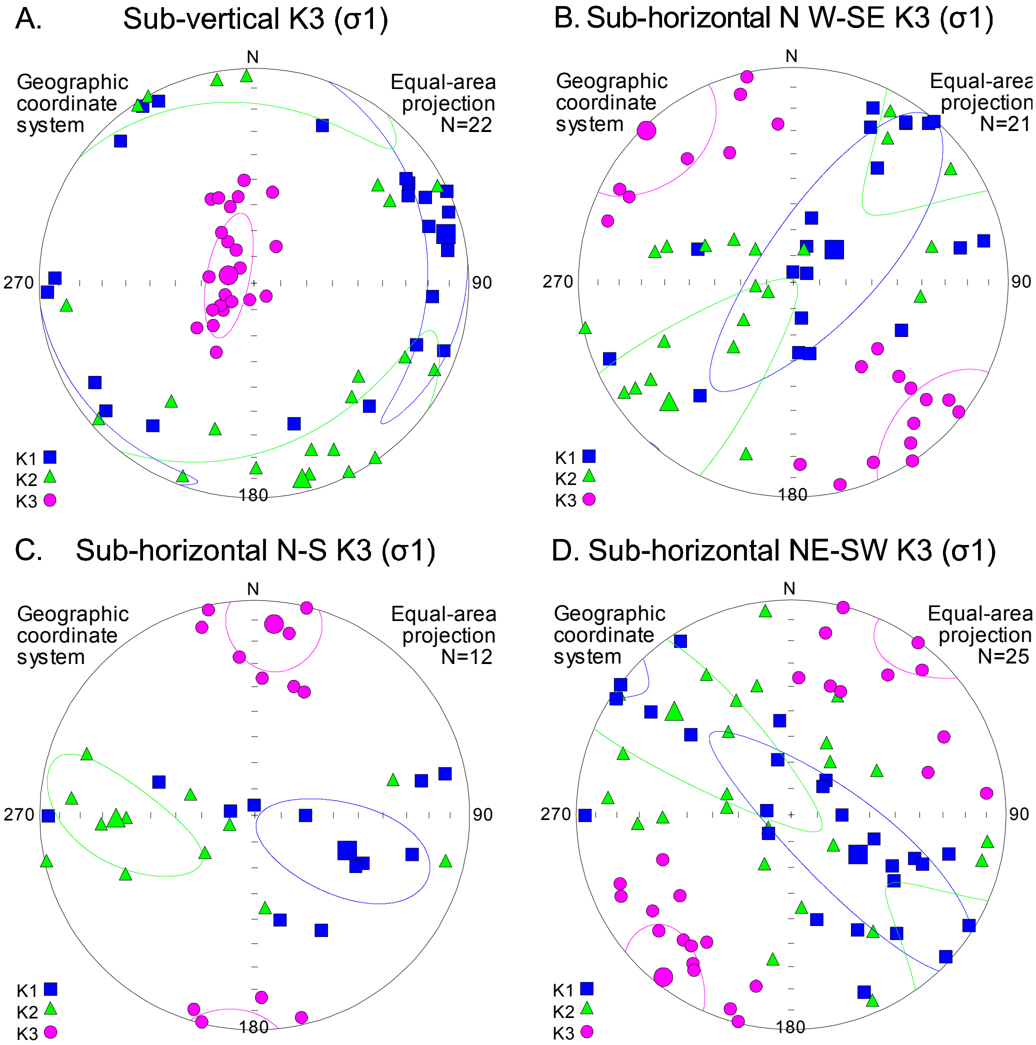


**Figure 6: AMS results for Savannah were clipped to better isolated clusters each representing a different variation in magnetic fabric; A. Sub-vertical K3; D. Sub- vertical K3; B. Sub-horizontal NW-SE-oriented K3; C. Sub-horizontal N-S-oriented; and D. Sub-horizontal NE-SW-oriented K3**

The first clip (Fig 6a) which isolates sub-vertical K3 results indicates a sub-horizontal fabric, which is likely to be a magmatic fabric formed via settling within the magma chamber. The results with such fabrics come mainly from drill hole KUD1503, suggesting that the fabric present in the part of the intrusion intersected by this drill hole has not been significantly overprinted by tectonic fabrics. Conversely, the results from drill hole KUD1526 do appear to be mostly overprinted, so we may infer that it has been significantly more deformed. A notable feature of the K3 data in Fig 6a is that they sit along a N-S girdle, which indicates that the primary magmatic fabric has been folded, post-crystallisation. In this case the data indicate that upright N-S oriented folding of the magmatic fabric took place and this style of deformation is consistent with N-S shortening under ductile conditions, but could also be caused by rotations associated with transpression in an adjacent shear zone.

The other fabrics interpreted appear to be ductile-brittle fabrics, or in other words tectonic fabrics that have overprinted the magmatic fabric. These fabrics are all upright (sub-vertical) and have a range of orientations from NW to NE-striking. Here we have clipped the data to three K3 clusters oriented approximately NW-SE, N-S and NE-SW (Figs 6b-d) based on an assumption of pure strain. However, it is highly likely that the fabrics formed with some component of shearing and that strain was partitioned within the different fabrics. For example in Fig 6c there is a dominant K1 orientation indicating a dominant throw within the inferred shear zone, hence implying dextral transpression. However, in Fig 6d, the spread of both K1 and K2 within the NW-SE girdle indicate more mixed kinematics, i.e., more evenly distributed strain. The more evenly distributed K1 and K2 vectors imply that the shortening direction was approximately normal to the fabric, i.e., that the shortening direction was NE-SW for the case shown in Fig 6d. Hence, it would appear that NW-SE and NE-SW shortening was likely associated with approximately normal tectonic fabrics, whereas, the E-W fabric shown in Fig 6c is more likely associated with transpression related to NE-SW shortening.

### Savannah Palaeomagnetic Analysis

Principal component analyses (PCA) revealed mixed results with samples displaying soft (unstable) to hard (very stable) remanence, often comprised of 2-4 individual components. Many samples showed only weak-moderate coercivity components, other samples essentially recorded palaeomagnetic noise, which indicates a lack of magnetic minerals, or very soft (low coercivity) magnetic grains. However, in many cases the highly stable, remanently magnetised, lithologies retained two high coercivity palaeomagnetic components which had opposite polarity. In many cases preferential removal of the minor component during demagnetization means that the highest measured remanent magnetisation intensity occurs on the last step. Hence the most stable component is incompletely resolved. In such cases we have just assumed the magnetization direction of the most stable component based on the last two degaussing stages (i.e. 130 mT and 140 mT). Unfortunately, thermal demagnetisation did not further clarify the directions. The PCA results were subdivided into weak, moderate and high coercivity components and were plotted and analysed separately. The moderate to high coercivity components, plotted in Fig 7a, all sit on a N-S oriented girdle. This is not common for palaeomagnetic data from rocks of approximately comparable coercivity within a single intrusion. The results are widely spread, from sub-vertical to sub-horizontal, which is not consistent with a folding model. However, because the data represent two polarities, they were converted so as to represent one polarity (Fig 7b).The converted results provide a more tightly clustered dataset in which the results spread from sub-horizontal south, to moderately downward inclined north–plunging magnetisations. The mean direction of these magnetisations, when al converted to the dominant polarity (i.e., downward), has declination: 176.5° and inclination: 59.1°.

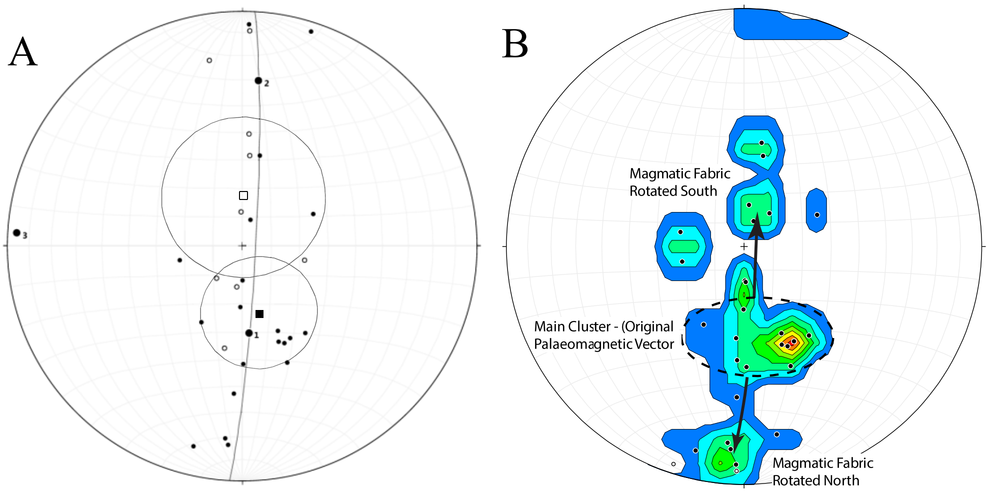


**Figure 7: Stereonets displaying: A. all medium to high coercivity magnetic components extracted from principal component analyses. B. Stereonet displaying polarity converted PCA data for higher coercivity palaeomagnetic components from Savannah, with a 1% contour underlain. The contouring highlights that there are at least three clusters present along the N-S trend. These could be interpreted as due to tilting of the primary palaeomagnetic vector (moderate south plunging) both north and south by 40-50°.**

There are three main clusters, as illustrated by the 1% contour provided in Fig 7b and the spread of the palaeomagnetic vectors along a N-S girdle is consistent with the spread of AMS data for Savannah. Hence, it is reasonable to infer that N-S-oriented shortening may have rotated both the paleomagnetic vectors and the AMS fabrics. The clustering of the data, interpreted as a folding model, imply that the main palaeomagnetic vector was rotated by 40-50°, both north and south resulting in three clusters of palaeomagnetic results; the original moderate-steep south magnetisations, a shallow-sub-horizontal south magnetisation and a steep to moderate north magnetisation. However, it is possible that the rotation was ~90° to the north, if we flip the polarity on the steep north plunging cluster.

There is some evidence to suggest that the palaeomagnetic vectors could also have been rotated to the NW and SE which is not inconsistent with the deformation interpreted from the AMS, but it is less well substantiated by the paleomagnetic data. Alternatively, it could be that there are two main paleaomagnetic clusters, a moderate south plunging cluster, which is interpreted to have been folded at Savannah to form a N-S girdle of magnetisation vectors, and a second, moderately SSE-plunging cluster has not been modified. If this is the case then the SSE-plunging magnetisation must post-date the N-S folding. The SSE-cluster magnetisations are of moderate coercivity, and are typically removed in alternating fields of ~40 mT. This is consistent with the SSE-magnetisation being a secondary metamorphic overprint, rather than a magnetisation formed during cooling/exsolution. The directions are consistent with those obtained from nearby intrusions (e.g., Dave Hill, Wilsons) and probably represent a *ca* 1200 Ma overprint associated with the Yampi Orogeny.

## DISCUSSION

There is a fundamental difference between the style of deformation present at Savannah and Savannah North. Both appear to record an early N-S oriented folding event. However, the clustering of the data at Savannah North is consistent with minor tilting whereas the wide distribution of K3 within a N-S girdle at Savannah is consistent with substantial rotation of the primary magmatic layering. Savannah appears to have undergone complex deformation, e.g., the elongate shape of the intrusion suggests that a fault zone may have acted as a conduit to the intruding magma, and the juxtaposition of the intrusion relative to the fault may have caused significantly more intense deformation within the intrusion. Conversely, the AMS data for Savannah North are generally consistent with a sub-horizontal magmatic fabric, with some evidence of minor N-S and NE-SW tilting. Savannah north appears less deformed, possibly in part due to its relatively large stock-like architecture, which would be kinematically resistant to overprinting deformation. The primary (high coercivity) palaeomagnetic components at Savannah and Savannah North have been modified by deformation. In the case of Savannah North it is difficult to resolve the likely primary and secondary components. However at Savannah, it is apparent that the primary component has been rotated N-S by up to 90° during a folding event that was also inferred from the AMS results.

A review of prior work on the deformation and metamorphism in the Savannah area, summarised in Table 1, allows us to place the results of the palaeomagnetic and AMS study into a regional tectonic context. In terms of the AMS results, it seems clear that NE and

NW- striking shear fabrics observed at Savannah and Savannah North are related to high temperature strain/shearing during the Halls Creek Orogeny and possibly also the Stafford Tectonic Event. The un-sheared (i.e., original magmatic) fabrics at Savannah appear to be tilted north, which we attribute to N-S shortening during the Stafford Tectonic Event. This is also consistent with the palaeomagnetic results, since we interpret that there was an early high coercivity magnetisation that was rotated in a N-S plane. Provided peak metamorphic conditions during the Halls Creek Orogeny did reach approximately ~565° the early magnetisation probably represents a high temperature metamorphic overprint that was subsequently rotated by folded in the Stafford Tectonic Event. Later overprints are also present, and appear to be consistent with the Yampi and Alice Springs orogenies.

**Table 2: Summary of tectonic and metamorphic events in the Savannah area**

| Orogen | Timing (Ga)* | Stage $ | Shortening Direction(s)* | Folding style^ | Thermal Conditions^ |
|---|---|---|---|---|---|
| Hooper Orogeny | 1.87- 1.85 | D1-D2 | | | |
| Savannah Intrusions | ~1.845# | | | | |
| Halls Creek Orogeny | ~1.835 | D3 | NW-SE | Northeast to ENE-trending folds | Upper greenschist to amphibolite (550-650°C) |
| Mount Stafford Tectonic Event | ~1.81 | D4 | N-S to NE-SW | | |
| Yampi Orogeny | 1.4-1.0 | D5 | NE-SW | NNE (sinistral) & E-W (dextral) strike-slip | Greenschist <450°C |
| King Leopold Orogeny | ~0.56 | D6 | S-thrusting linked to sinistral strike-slip | Open NW-plunging folds | |
| Alice Spring Orogeny | <0.43 | D7 | | NNE & SSW plunging large-scale folds | |

* Based on Tyler et al. (2012) # from Lightfoot and Evans-Lamswood (2015) ^ from Orth (2002) $ Griffin et al. (1998)

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