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Structural Interpretations from High Resolution Aeromagnetic Data, Northwest Botswana

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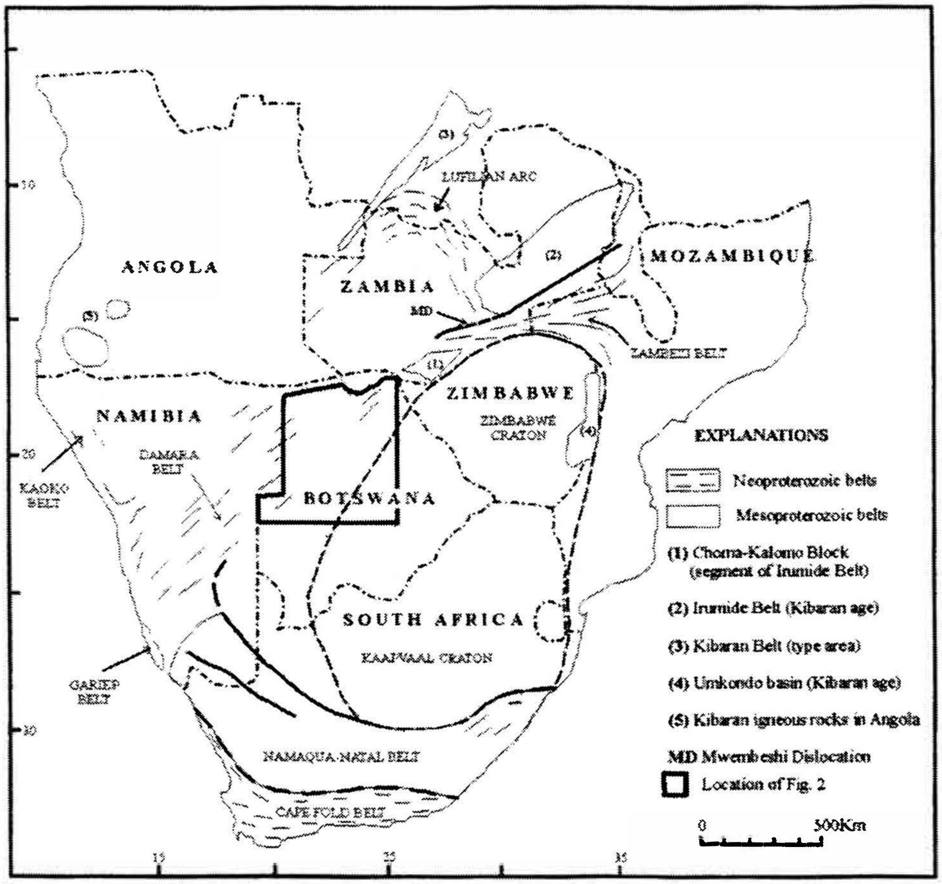
Abstract

High resolution aeromagnetic data collected over northwest Botswana has provided new insights into previously hidden geologic structures. Major antiformal and synformal structures have been recognized within the Kinabaran age Kgwebe meta-volcanics and other basement rocks. These structural features trend northeast-southwest agreeing with previously collected geologic field data and observed surface features. Further interpretation of the geophysical data has yielded relative dips of the fold limbs and indication of the direction of plunge. Folding extends both north and south of the Okavango Rift Zone for at least 100 – 200 kilometers. Further studies are being conducted to determine if these pre-existing geologic features exert structural control on neotectonic activity.

Introduction

There are two main purposes to this research. Primarily it is to interpret geologic structures based on geophysical data and determine what information can be obtained from such data. Secondly this research will be integrated with other studies to determine the role of existing geologic basement structures on neotectonic activity. Normally, geologic information is gathered through careful and intensive fieldwork. A geologist goes into the field with rock hammer, Brunton compass, and other tools to observe patterns and take samples and structural measurements from rock outcrops. Through traveling and various maps these small pieces are all combined to paint a larger, more complete geologic picture. However, circumstances are not always so kind. The northwestern regions of Botswana are one such place. It is a large area with very limited outcrops and many features are buried by more recent sedimentation. Borehole data in the area is also quite limited giving geologists only a very generalized picture of the area. So we turn to geophysical methods to do further investigations. Potential field methods such as gravity and magnetics allow us to look at the buried geology. These methods have already been used in the area (Kampunzu 1998, 2000) to delineate crustal blocks and regional features. Advances in technology have given us better tools to increase the quality of our data. The high resolution aeromagnetic data (250 meter line spacing) collected by the Geologic Survey of Botswana can be used to better delineate geologic boundaries as well as interpret structures.

The Ghanzi-Chobe belt of northwest Botswana (figure 1) extends from the Goha and Shinamba hills in the northeast to Mamuno in the southwest (Kampunzu 1998).


ANGOLA
ZAMBIA
MOZAMBIQUE
ZIMBABWE
NAMIBIA
BOTSWANA
SOUTH AFRICA
LUFILIAN ARC
MD
ZAMBEZI BELT
ZIMBABWE CRATON
KAOKO BELT
DAMARA BELT
GARIEP BELT
KAAPVAAL CRATON
NAMAQUA-NATAL BELT
CAPE FOLD BELT
EXPLANATIONS
Neoproterozoic belts
Mesoproterozoic belts
(1) Choma-Kalomo Block (segment of Irumide Belt)
(2) Irumide Belt (Kibaran age)
(3) Kibaran Belt (type area)
(4) Umkondo basin (Kibaran age)
(5) Kibaran igneous rocks in Angola
MD Mwembeshi Dislocation
Location of Fig. 2
0
500Km

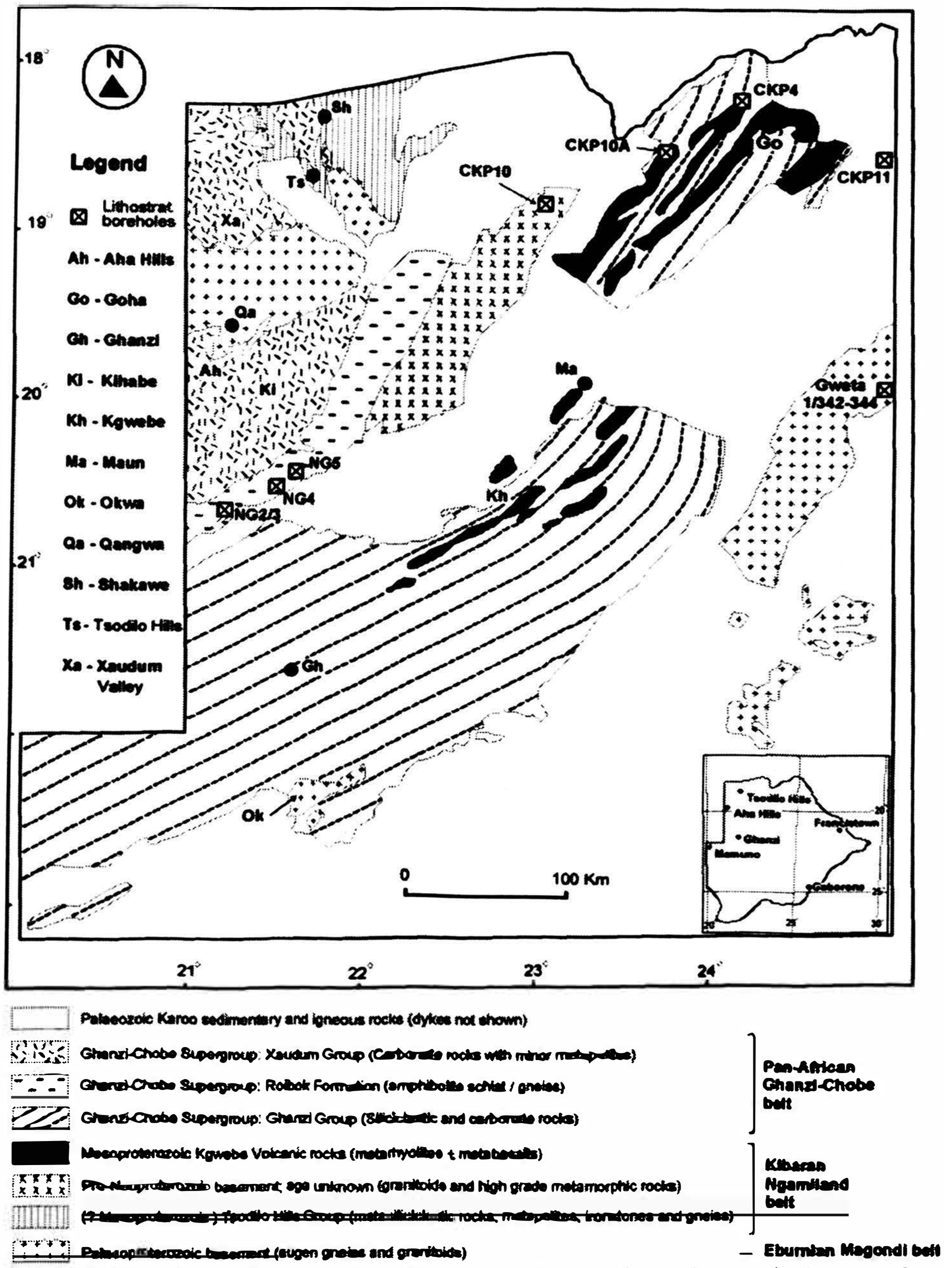


Figure 1: Top picture shows southern Botswana. Lower picture is a geologic map of northwest Botswana (after Kampunzu 2000).

It is part of the Neoproterozoic Pan-African belt system in southern and central Africa. Despite the fact that it is mostly covered by Phanerozoic strata, its boundaries have been well delineated with aeromagnetic data. The Okwa Group, a thick series of sedimentary deposits, namely sandstone, unconformably overlies the Kgwebe meta-volcanic rocks. The Kgwebe meta-volcanics make up part of the basement rock, the focus of this study. The Kgwebe meta-volcanics are primarily composed of meta-mafic and meta-rhyolite rocks. Clasts of the rocks are round in the overlying conglomerate and the rocks themselves have been correlated with meta-volcanics in Namibia which predate rifting thus making them part of the basement. The Kgwebe meta-volcanic rocks form a series of hills trending northeast-southwest in the Ghanzi ridge and U-Pb zircon dating puts their age at 1106 +/- 2 million years. These meta-volcanic rocks were part of late Kinabaran magmatism so they are orogenic igneous rocks created by an extensional event that melted lower crustal rocks.

Methodology

In order to interpret structural features of the Ghanzi-Chobe belt in northwest Botswana high resolution (250 meter line spacing) aeromagnetic data was obtained from the Geologic Survey of Botswana. In this case, aeromagnetic data proved particularly useful because of the composition of the basement rock. The basement rock, which includes the Kgwebe meta-volcanics, is typically mafic in composition. These kinds of volcanic rocks generally contain magnetite and thus tend to have higher percentages of iron than other kinds of rocks. As volcanic rocks cool and crystallize the magnetic minerals they contain take on the characteristics of the earth's magnetic field. Once the rock cools below the Curie temperature it becomes magnetized based on those characteristics. This is called thermal remnant magnetization (Telford 1990). The sediment on top of the basement rock has very little in the way of magnetic minerals because they are weathered out. So using a magnetic data set allows us to strip away that top layer and view the geology beneath. The high resolution of this data set gives better detail making it uniquely qualified for viewing and interpreting buried structures.

Once the data is collected, a variety of computer software packages are available for processing. Processing for this project was done with Oasis Montaj Geosoft v6.01. There are numerous mathematical filters that can be applied to magnetic data in order to enhance certain features, observe different measurements, or get a different view. Several of these are important to this project, one being the first vertical derivative. This filter applies the first derivative to the magnetic anomaly in the vertical (z) direction providing the rate of change of the magnetic anomalies. It also serves to enhance the shallow anomalies (Geosoft Help File 2005). Filters are applied in the Fourier Domain. The first part of pre-processing is to remove the nth-order trend or mean from the gridded data. Next, the grid is expanded to prepare for the Fourier transform which uses either the Cooley-Tukey algorithm or the Winograd algorithm. The grid is then filled with dummies using maximum entropy to fill the new expanded dimensions such that the grid becomes smoothly periodic. The expanded and filled grid is converted from the time domain to the frequency domain by taking the integral of the series of gridded data values and multiplying them by e raised to the power of (iwt) and multiplying again by dt (where w is the wavenumber). Filters previously selected by the user are then applied to the Fourier transformed grid. The gridded data is put back into terms of wavelength (distance) by transforming it from the frequency domain back to the time domain. This is done by taking the integral of the filtered series of gridded data values and multiplying them by e raised to the power of (iwt) and multiplying again by dw. Dummy areas from the original grid are masked back onto the final filtered grid and the grid size is reduced to its original size. If a trend surface was removed during pre-processing, and if no high-pass filters was applied to the data, then the trend is added back to the output grid. Post-processing uses Boolean operations to deflate the filtered grid back to its original input size and then add the trend back into the grid.

Derivatives can also be applied in the x and y directions which becomes very important when doing Euler deconvolutions. The apparent depth to the magnetic source is derived from Euler's homogeneity equation (Euler deconvolution). This process relates the magnetic field and its gradient components to the location of the source of an anomaly (Geosoft Help File 2005).

The degree of homogeneity is expressed as a structural index which is a measure of the fall-off rate of the field with distance from the source. Euler's homogeneity relationship for magnetic data can be written in the form: $(x - x_o)\, dF/dx + (y - y_o)\, dF/dy + (z - z_o)\, dF/dz = N(B - F)$, where (x_o, y_o, z_o) is the source location whose magnetic field F is measured *at* (x, y, z); B is the regional value of the total field; and N is Euler's structural index. N is a measure of the rate of field change with distance. At each solution the Euler deconvolution process is applied. The user defines the structural index telling the program which shapes to look for. A least-squares inversion is employed to solve the equation for an optimum x_o, y_o, z_o and B. The program creates a database of information on all the anomalies that meet the criteria. The analytic signal filter also uses the derivatives, but to identify the edges of the magnetic source bodies on the map. This filter is the square root of the sum of the squares of the derivatives in the x, y, and z directions: analytic signal = sqrt (dx*dx + dy*dy + dz*dz). It is particularly helpful when remanence and/or low magnetic latitude complicates interpretation.

Besides filters, there are a few other tricks to processing data. Ternary diagrams present the user with one map that shows the information of three different maps simultaneously making shared features pronounced and contrasting different ones. Changing the color scheme of the maps also helps to better accentuate certain features and make contrasts more visible. Similar results can be obtained by changing the degree and direction of illumination.

Results & Discussion

Looking at a magnetic map (figure 2) is much like at satellite imagery, except that the colors indicate the strength of the magnetic source.

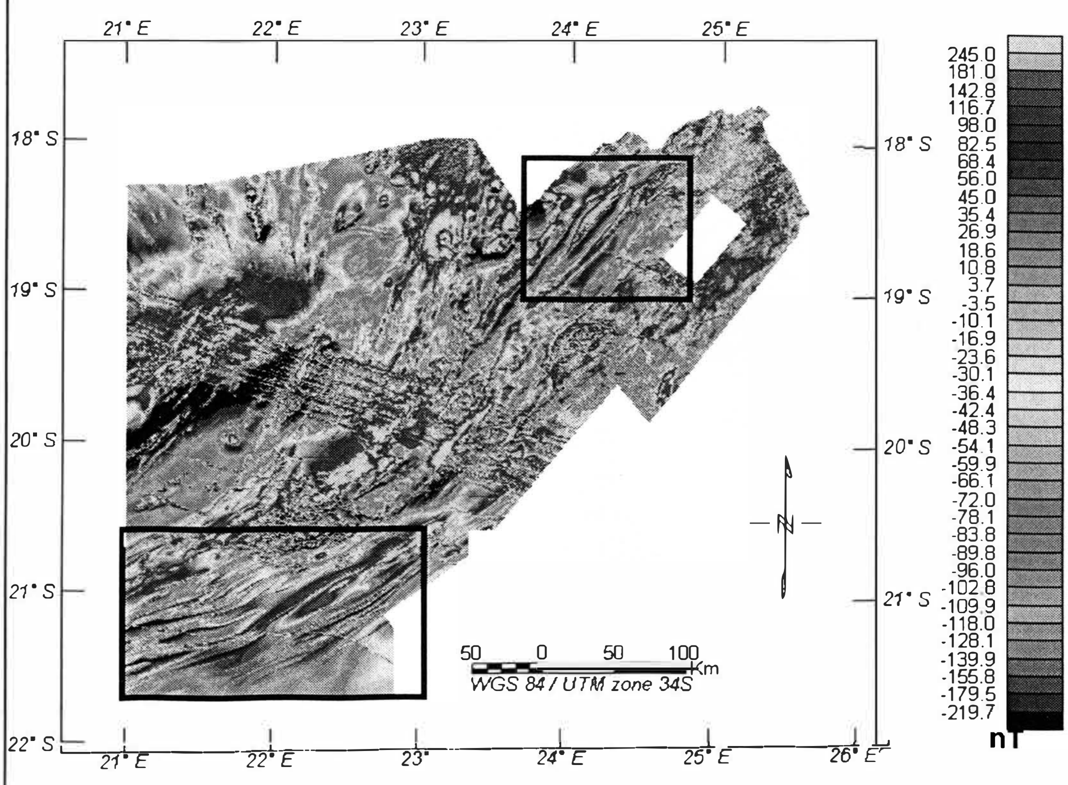


Figure 2: Magnetic map of northwest Botswana. Inserts indicate areas of research. The southern insert is shown in figures 4 and 7.

It was this similarity that first prompted the idea that the northeast-southwest trending magnetic anomalies were indeed geologic structures. It fits that if they are geologic structures that they should show up. The basement rocks, especially the Kgwebe meta-volcanic rocks, are much more magnetic than the overlying rock so any feature within should also show up. However, previous studies lacked the resolving power to differentiate these features. One may notice that the northeast-southwest trending structures, if traversed perpendicular to trend, alternate from high magnetic anomalies to low ones. This pattern was the first indication that these features were folds. This same pattern also emerged in the data after several filters were applied including the first vertical derivative and analytic signal. So, in order to view several maps at a time, the magnetic, first vertical derivative, and analytic signal grids were combined into one ternary diagram (figure 3). The same high alternating with low anomaly pattern can be observed on this map. One can also notice those areas where all three maps exhibit magnetic highs (black) or two maps exhibit highs (blue, bright green or red) seem to stand up off the map. On the other hand, areas of very low anomalies are subdued and seem depressed. Therefore, areas of magnetic highs are interpreted to be antiforms (hills in topographic expression) and areas of magnetic lows are interpreted as synforms (basins in topographic expression). These folded features can be better observed in the southern area of the map where they are prevalent as seen in figure 4. It can also be perceived at this scale that the smaller features mimic the larger ones; a very common characteristic of folding.

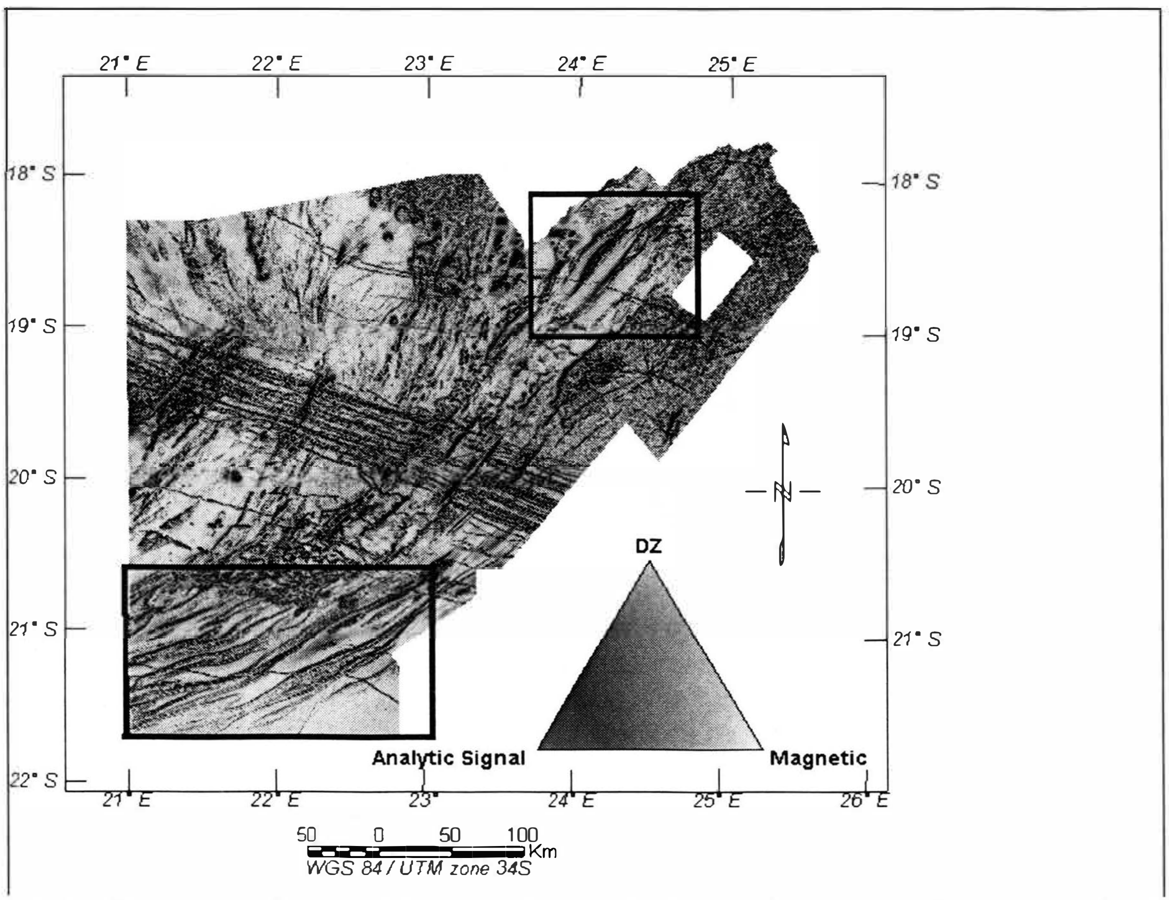


Figure 3: Ternary map of northwest Botswana. Inserts indicate areas of research. Southern insert depicts the area of figures 4 and 7.

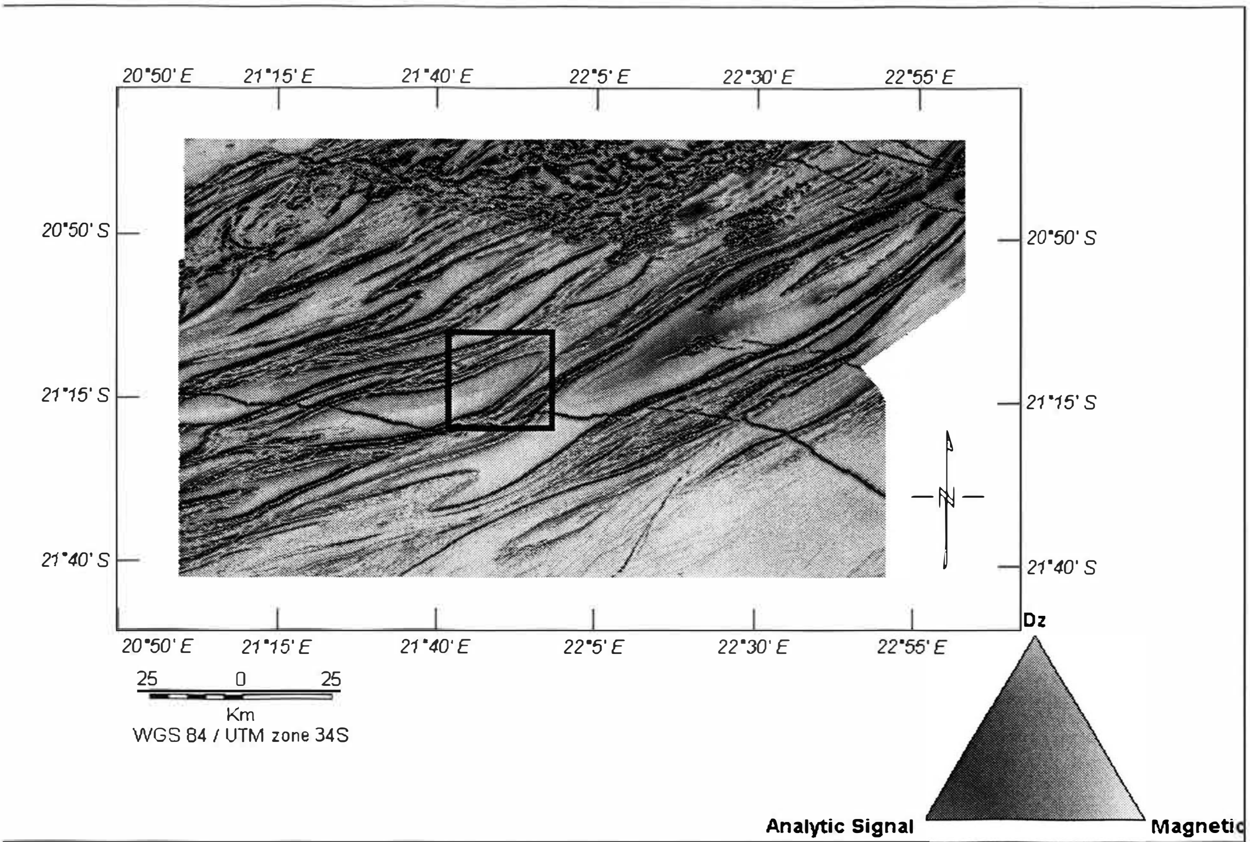


Figure 4: Ternary map of southern folds. Insert shows area of figure 5.

Figure 5A shows one area that was windowed out for Euler deconvolution. The structural index was chosen to detect cylinders, the closest approximation to a fold possessed by the program. Rocks can be folded or rolled up much like we do to magazines. One can observe that the Euler deconvolution symbols prefer to follow zones of magnetic highs contained on all three maps (figure 5B). The solution symbols also tend to form linear features. This could indicate one of several things or a combination thereof. First the solution symbols could be plotted along the limbs of the fold where the Kgwebe meta-volcanic rocks or other similar magnetic basement rock is found within the folds. Another possibility is that the solution symbols are being plotted along the peaks of the antiforms. Just as a hill changes elevation slowly at its base and more steeply as it nears its peak, if the peaks of the antiforms are more magnetic then the rate of change would increase as you neared the source until you were on the source where change would be essentially zero. This situation would very closely resemble a horizontal cylinder - which is exactly what the computer is looking for. This situation could also be produced if parts of the folds were more magnetic than others. A stronger magnetic source would produce a faster rate of change as one nears the source. This scenario, or a combination of the two, seems to be more probable given that it is highly unlikely that the bedrock should have uniform magnetic strength. The delineation of the fold limbs is shown in figure 5C.

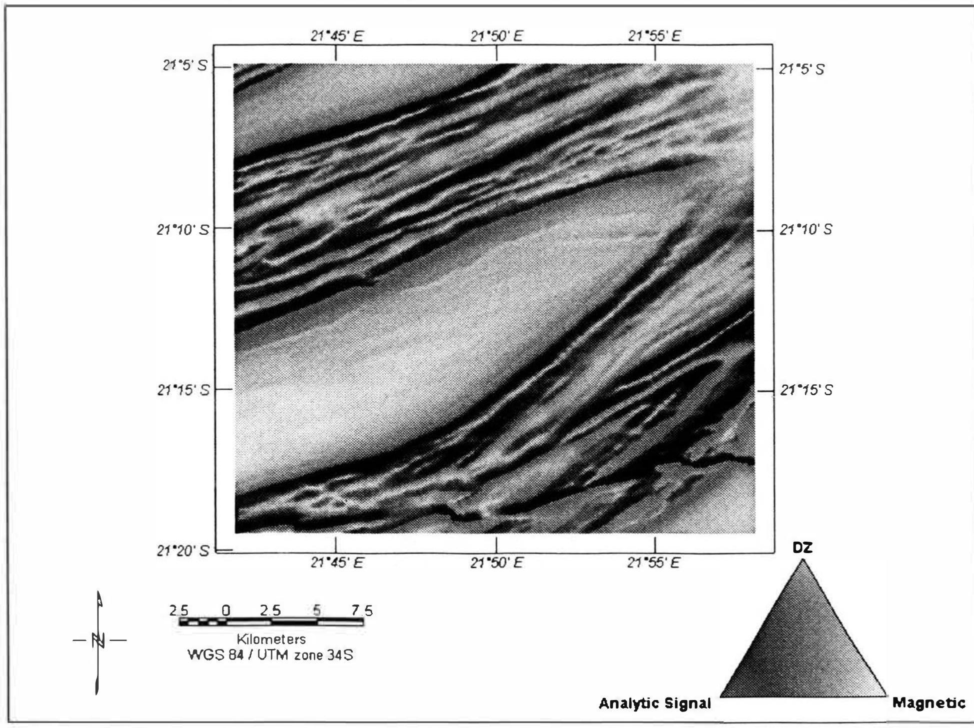


Figure 5A: Ternary map of an area of folding windowed out for Euler deconvolution.

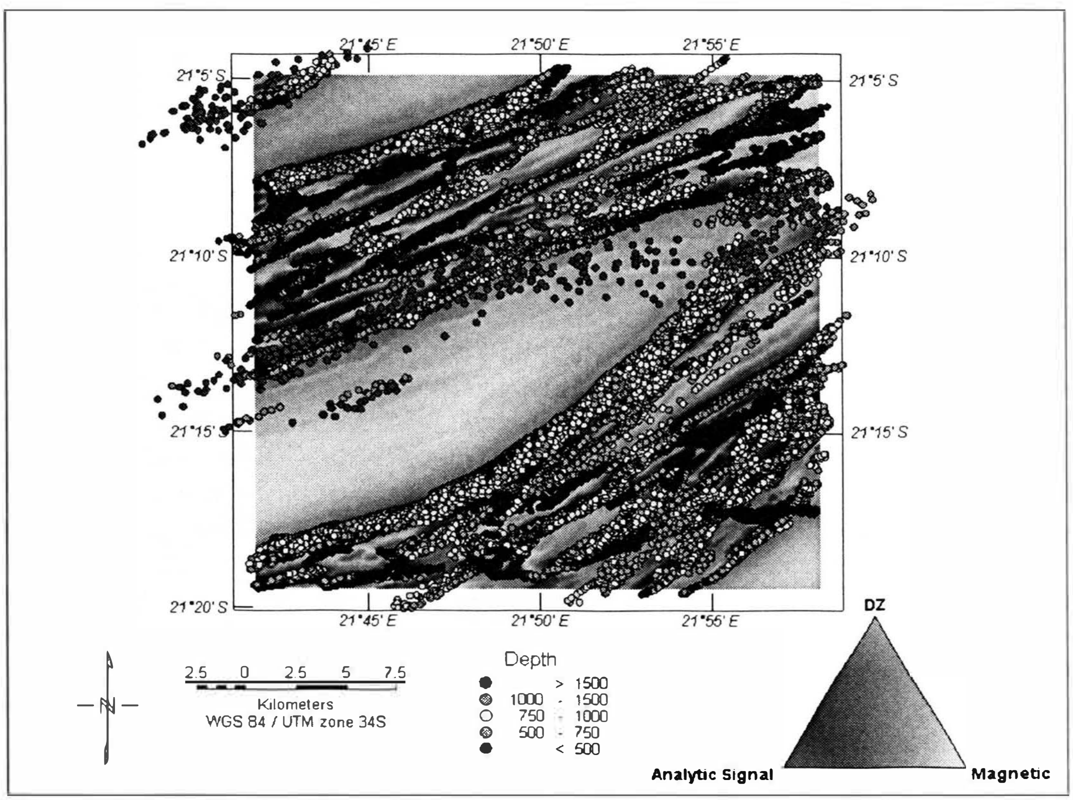


Figure 5B: Ternary map with Euler deconvolution depth to solution symbols plotted. Depths are in meters.

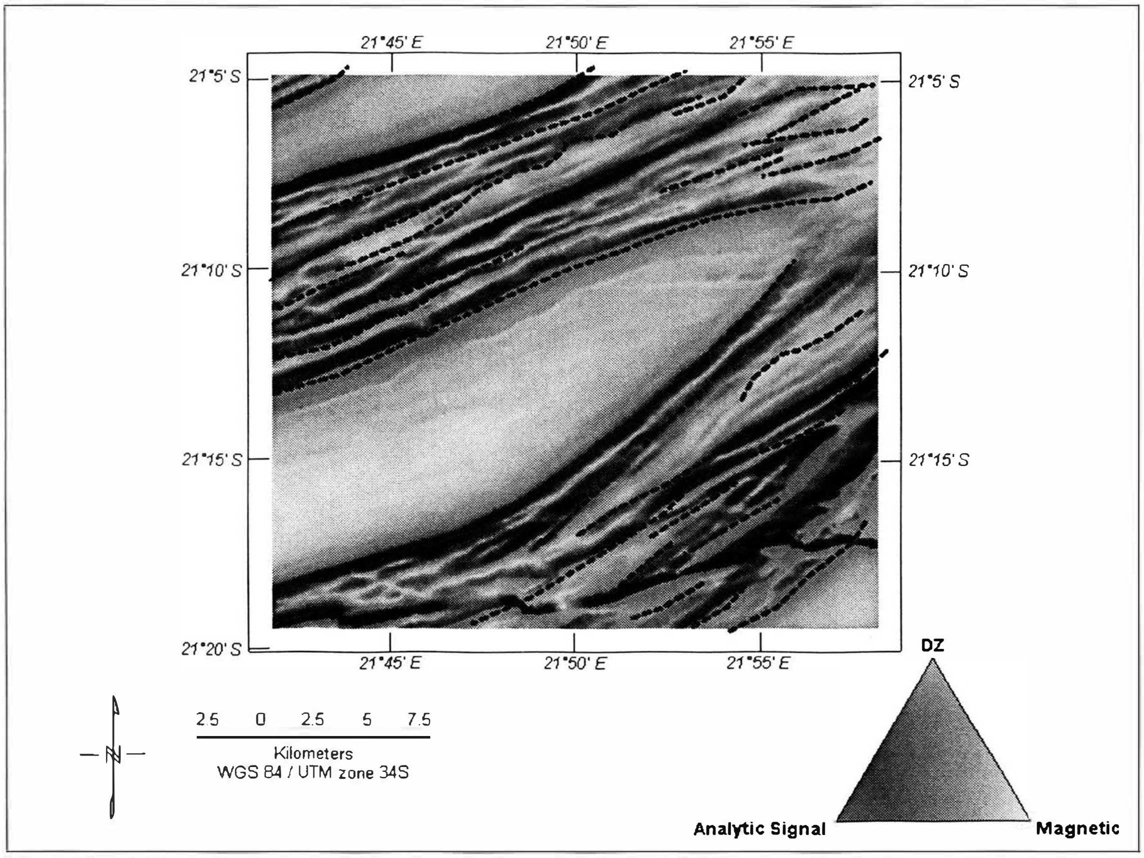


Figure 5C: Ternary map, dashed blue lines indicate interpreted fold limbs.

The Euler deconvolution supplies other important information as well. It can be seen from figure 5B that the deeper solutions follow the large center structure. To either side are more shallow solutions with deeper solutions on the other side again. The Euler deconvolutions symbols that indicate depth to source show the same pattern that the magnetic strength colors did. Not only that, but where magnetic strength was high the solutions were shallow while at low magnetic strengths solutions are deeper. Based on this, the large center feature is interpreted to be a synform. Yet the Euler deconvolution symbols can tell even more of the story. Notice how the very deep solutions are concentrated at the northeast end of the structure. This suggests that the synform plunges toward the northeast. Now, let us compare the limbs of our synform. The northern limb has solutions of 500 meters or less next to solutions of greater than 1500 meters. Meanwhile, the southern limb has solutions of less than 500 meters plotted next to solutions of 750 – 1000 meters. This would point towards the conclusion that our northern limb has a higher angle of dip than does the southern one. Also, now that the limbs of the fold have been outlined, it is possible to estimate the trend of the synform. Since this structure is interpreted as a synform, the adjacent feature should be antiforms. The adjacent features show shallower depths and stronger magnetic anomalies as expected. So, from the interpretation of one fold we may begin to interpret the features adjacent to it and so on throughout the area. With several smaller areas done, we can then backup and view the larger picture and begin to interpret the whole area, just a geologist would work his or her way up from outcrop scale to regional scale (figures 6, 7).

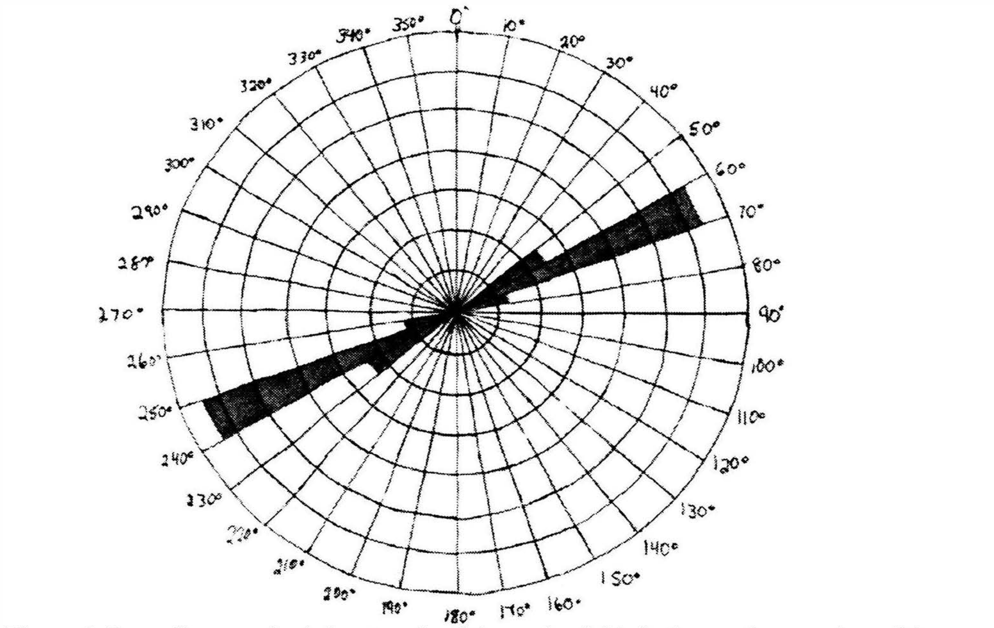


Figure 6: Rose diagram depicting trends of the major folds in the southern region of the map. Each circle is 10% of the total trends.

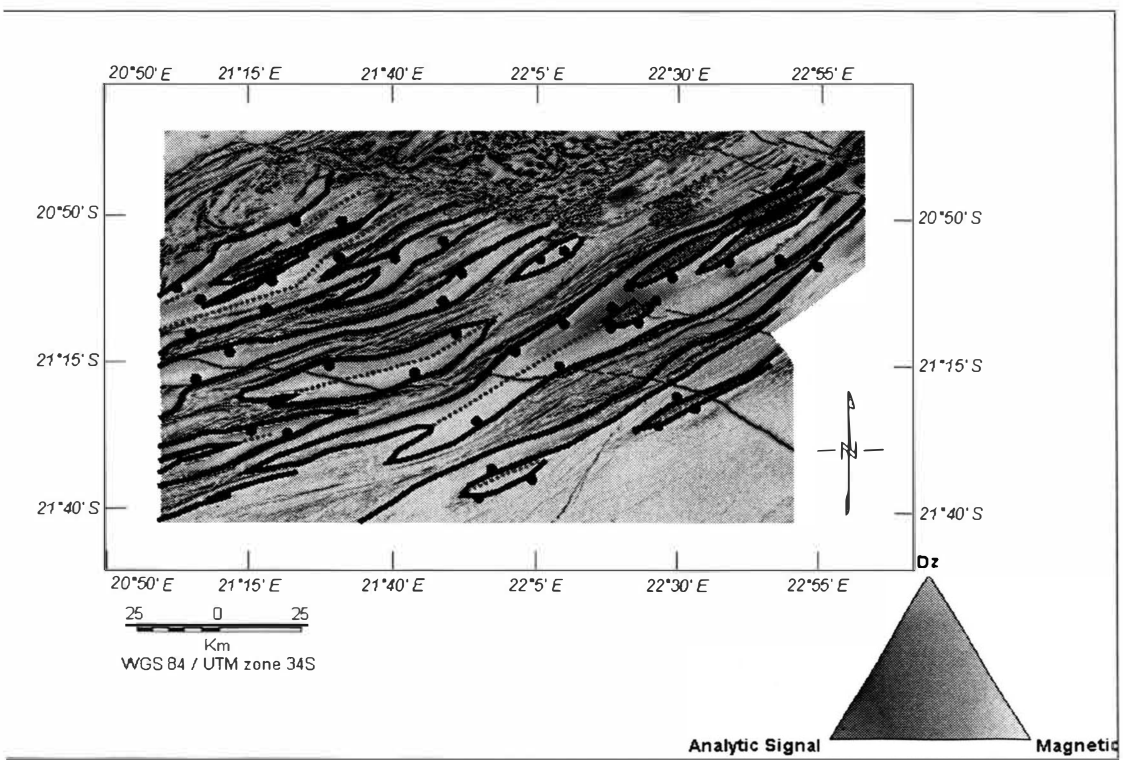


Figure 7: Ternary map of southern folds with major folds outlined in solid black lines, examples of trend in dotted red lines, and solid black circles indicate the direction of dip.

The first clues to the interpretation of northwestern Botswana were simple visual clues made by an eye with field and satellite imagery experience. Continued experimentation with various maps produced similar results. There are several ideas that are pertinent to this interpretation. First, what does stronger versus weaker magnetic anomalies mean? Well, to start, igneous and metamorphic rocks tend to have higher percentages of magnetic minerals giving them a stronger magnetic signal. Stronger magnetic potential also gives a faster rate of change near the source. In this case, the area is known to be made up of volcanic rock with overlying sediment. Volcanic rock also tends to be more resistant, so it lasts longer. This also means that as weathering occurs, the more resistant rock is left while less stable materials are eroded away so volcanic rocks frequently are raised up when compared to their surroundings. This puts them closer to the survey so they give a stronger signal, as seen in this survey. We would then expect that magnetic potential would be weaker from lower areas. It would also follow that these lower areas weren't as resistant and therefore had a different composition. It also makes sense that now these lower areas would be filled in by the overlying sediment which is magnetically weaker. Given that there is an unconformity between the basement rock and overlying sediment an erosional event resulting in just that is a possibility. Also, if these features are folds, then the oldest rocks should be at the core of the antiforms as this interpretation predicts. Folded layers of rock are further supported by the history of the region. The Kgwebe meta-volcanics were created by an extensional collapse brought on by a collisional orogeny. Continued stress after emplacement may have resulted in the deformation of rock and fold structures observed today. Besides just interpretation there is some data as well that backs up the interpretations. Satellite imagery in figure 8 presents features of differing elevation that are surface expressions of antiforms and synforms. Field evidence also demonstrates that the Kgwebe meta-volcanic rocks form hills trending northeast-southwest (Kampunzu 1998). As mentioned earlier, antiforms are frequently expressed as hills in the topography. Also, the trend of the hills matches that of the trends measured from the major folds within the basement rock. Furthermore data collected from the limited outcrops of the region shows that the dominant foliation of the rocks also matches this same trend as seen in figure 9 (Atekwana 2005).

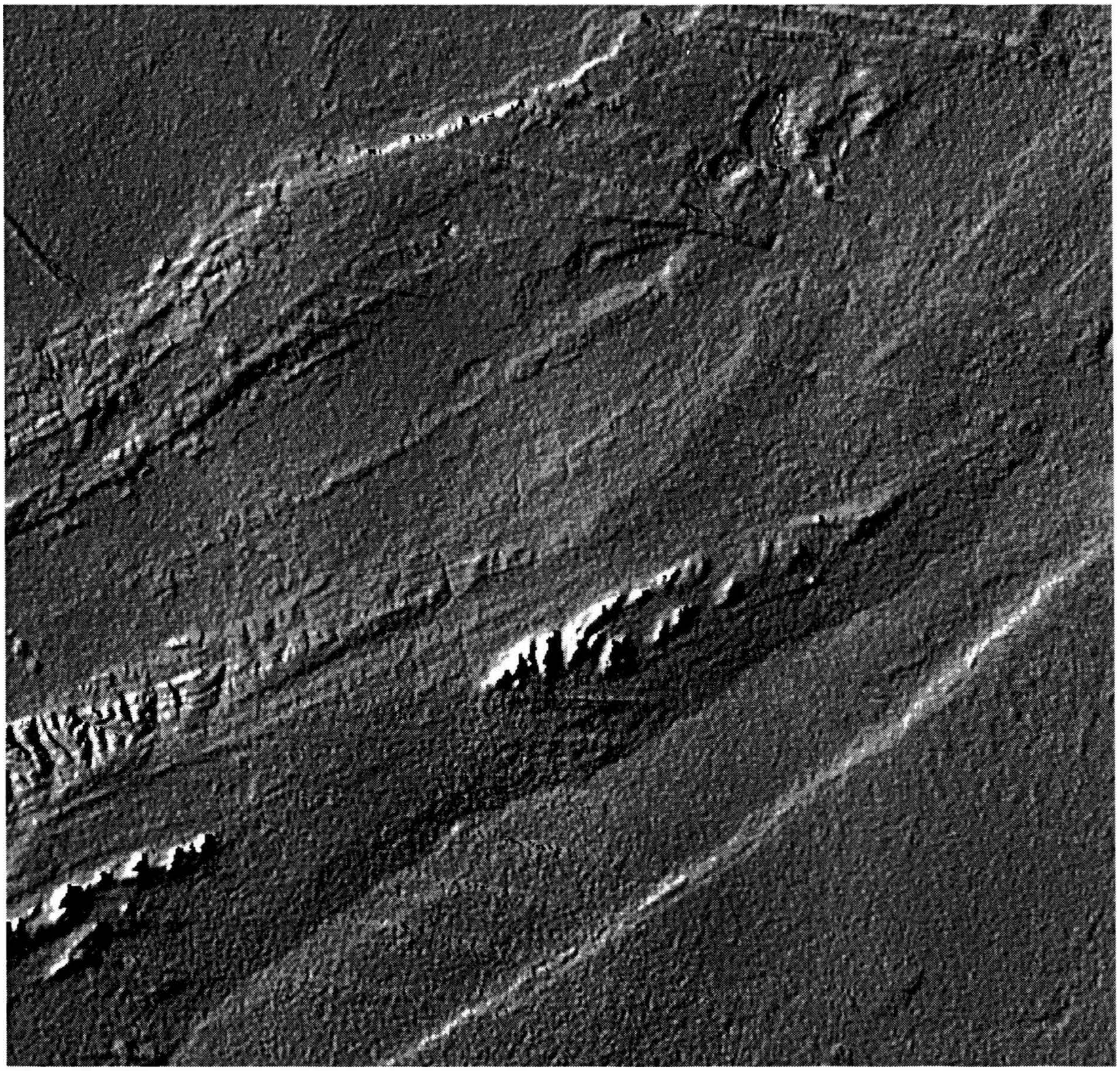


Figure 8: SRTM data from northwest Botswana showing surface expressions of antiforms and synforms.


Figure 9: Field picture from northwest Botswana showing basement foliation of 60 degrees (after Atekwana 2005).

Conclusions

High resolution aeromagnetic data collected over northwest Botswana has provided a glimpse into the geology of a barely explored region. From this new information, northeast-southwest folds have been identified within the bedrock. The antiformal and synformal features extend at least 100 – 200 kilometers to the north and south of the Okavango Rift Zone. Relative dips of the fold limbs and indications of the direction of plunge have also been gathered from the geophysical data. This new information is important in several ways. First, it helps to unravel the geologic past of an area that has received little attention. It is also part of a larger project that will help determine if pre-existing basement structures influence modern rifting and other tectonic events. Finally it shows that geophysical data from magnetic studies can help in the structural interpretation of otherwise inaccessible areas.

Acknowledgments

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