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MADAGASCAR

AIRBORNE MAGNETIC SURVEY

MAJUNGA BASIN AREA

OFFICE MILITAIRE NATIONAL POUR LES INDUSTRIES STRATIGIQUES

REPOBLIKA DEMOKRATIKA MALAGASY

AIRBORNE MAGNETIC SURVEY

MAJUNGA BASIN AREA

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August 1977

ABSTRACT

An aeromagnetic survey was undertaken for the Office Militaire National pour les Industries Strategiques over an area of the Majunga Basin consisting of a thick sequence of continental and marine sediments deepening from the SW and containing a major stratigraphic break represented mainly by Cretaceous volcanics.

The survey has been successful in confirming the expected NE - SW structural direction, the NE deepening of basement towards Majunga and has clearly defined a large sedimentary basin to the immediate SW of Majunga. Although the thickness of volcanics and that of underlying sediments within Sheet 1 have not in the main been reliably estimated due to the strong variability of the volcanics' magnetic field, the depth and horizontal extent of the expected volcanic region has been satisfactorily determined. Approaching the eastern half of the survey area, Sheet 2, basement depths are more readily obtained due to relative absence of shallow anomalies.

A map of basement depth contours has been produced, using the best available information, together with depths to volcanics and interpreted structural features. This should, in spite of interpretation difficulties, provide valuable information throughout much of the area for determining areas of oil potential and also for clarifying seismic data ambiguities.

This magnetic interpretation is of course subject to modification as new geological information becomes available. It should be mentioned that at the time of interpretation, the only geological map available to Hunting Geology and Geophysics Limited was the 1:5,000,000 ASGA-UNESCO map of 1963.

CONTENTS

Appendices

List of Text Figures

PART 1

INTERPRETATION REPORT

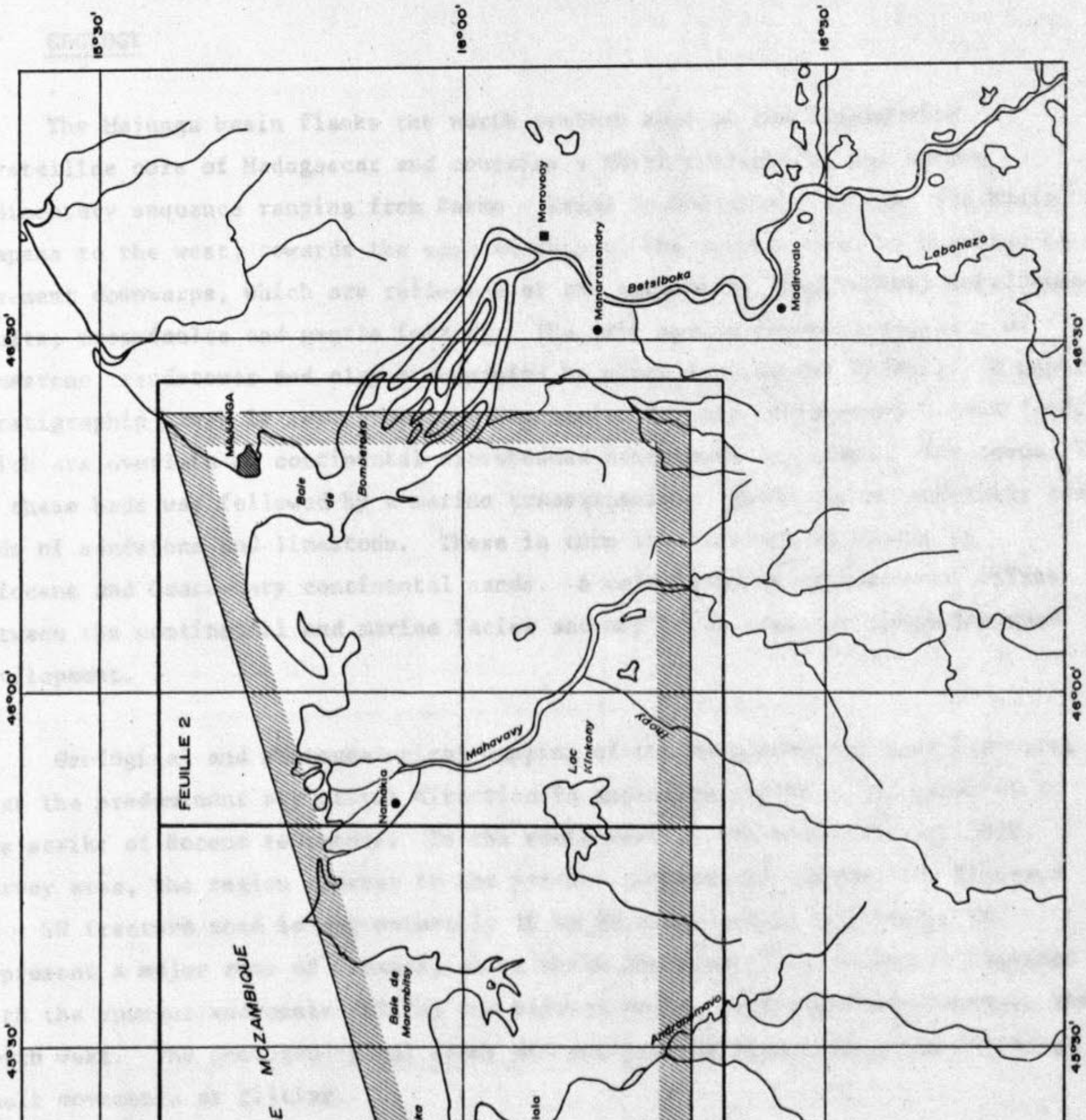
1. INTRODUCTION

This report describes the findings of an aeromagnetic survey undertaken for the Office Militaire National pour les Industries Strategiques by Hunting Geology and Geophysics Limited over an area within the Majunga Basin, to the SW of and including the town of Majunga, in NW Madagascar.

The aim of the survey was to delineate geological structures relevant to the search for oil, prior to the setting up of a more detailed program of seismic survey work:-

The flying was undertaken by our associate company Aerial Surveys Botswana (Pty) Limited using a Douglas DC-3 aircraft registration A2-ZFD between 11th - 12th April 1977 inclusive. The total distance flown was 2141 kms. Flying operations were not hampered by weather.

Hunting Geology and Geophysics Limited would like to express their appreciation for the help and assistance given by OMNIS personnel.



ETUDE MAJUNGA - CROQUIS DE SITUATION

2. GEOLOGY

The Majunga basin flanks the north western edge of the Precambrian crystalline core of Madagascar and contains a thick continental and marine sedimentary sequence ranging from Permo - Trias to Quaternary in age. The basin deepens to the west, towards the eastern edge of the survey area, by a series of basement downwarps, which are reflected at the surface by longitudinal subsidence faults, crossfaults and gentle folding. The main marine sequence consists of limestone, sandstones and clay accompanied by minor continental bedding. A major stratigraphic break is represented by Cenomanian (mainly Cretaceous) basalt flows which are overlain by continental crossbedded sandstones and clays. The deposition of these beds was followed by a marine transgression. Above the unconformity are beds of sandstone and limestone. These in turn are overlain in places by Pliocene and Quaternary continental sands. A calcareous transition zone exists between the continental and marine facies and may be an area for permeable reef development.

Geological and photogeological mapping of the Mahajamba Bay area indicates that the predominant structural direction is approximately NE - SW, parallel to the strike of Eocene sediments. In the south west of the Mahajamba Bay 1971 survey area, the region closest to the present geophysical survey, the observed NE - SW fracture zone is approximately 16 km in width and is considered to represent a major zone of flexure, along which the crystalline basement together with the younger sediments filling the Majunga Basin, were downthrown towards the north west. The photogeological study did not provide direct evidence for large fault movements or tilting.

Sediments along the western coastline of Madagascar are expected to reach depths of at least 25,000 feet in places. Drilling, which has in the past concentrated more on the Morondava Basin, has discovered a great many anticlinal and dome type structures and were found to have lacolithic, gneissic, intrusive or horst cores. There are also Cretaceous intrusions with little metamorphic effect. A drill hole in the Majunga basin found basement at approximately 9,000 feet and encountered oil shows. The area around Folakara for example, is an oil seep area. Many basement depth figures from mid 1950's drilling are between 5,000 feet and 9,000 feet. One drill hole reached a depth of 13,000 feet without reaching basement.

2. GEOLOGY

The Majunga basin flanks the north western edge of the Precambrian crystalline core of Madagascar and contains a thick continental and marine sedimentary sequence ranging from Permo - Trias to Quaternary in age. The basin deepens to the west, towards the eastern edge of the survey area, by a series of basement downwarps, which are reflected at the surface by longitudinal subsidence faults, monoclines and gentle folding. The main marine sequence consists of limestone, sandstones and clay accompanied by minor continental bedding. A major stratigraphic break is represented by Cenomanian (mainly Cretaceous) basalt flows which are overlain by continental crossbedded sandstones and clays. The deposition of these beds was followed by a marine transgression. Above the unconformity are beds of sandstone and limestone. These in turn are overlain in places by Pliocene and Quaternary continental sands. A calcareous transition zone exists between the continental and marine facies and may be an area for permeable reef development.

Geological and photogeological mapping of the Mahajamba Bay area indicates that the predominant structural direction is approximately NE - SW, parallel to the strike of Karoo sediments. In the south east of the Mahajamba Bay 1972 survey area, the region closest to the present geophysical survey, the observed NE - SW fracture zone is approximately 15 km in width and is considered to represent a major zone of fissure, along which the crystalline basement together with the younger sediments filling the Majunga Basin, were downthrown towards the north west. The photogeological study did not provide direct evidence for large fault movements or slicing.

Sediments along the western coastline of Madagascar are expected to reach depths of at least 25,000 feet in places. Drilling, which has in the past concentrated more on the Morondava basin, has discovered a great many anticlinal and dome type structures and were found to have anticlinal, geotectic, intrusive or horst cores. There are also Cretaceous intrusions with little metamorphic effect. A drill hole in the Majunga basin found basement at approximately 9,000 feet and encountered oil shows. The area around Folakara for example, is an oil seep area. Many basement depth figures from old 1950's drilling are between 5,000 feet and 9,000 feet. One drill hole reached a depth of 13,000 feet without reaching basement.

3. MAGNETIC METHOD

3.1 Theory

The magnetic method of geophysical prospecting depends on measuring accurately variations in the total intensity of the Earth's magnetic field produced by the presence of varying amounts of magnetic minerals (mainly disseminated magnetite) which occur in different rocks. The Earth's magnetic field and rock magnetisations are vector quantities in that they possess both a direction and magnitude. In northern Madagascar the approximate parameters of the Earth's magnetic field are:-

Total intensity:	34000	nT
Inclination:	50^o	South
Declination:	9^o	West

Note: 10^5 gamma = 10^5 nT (nanotesla) = 1 gauss

The magnetisation of rocks is caused partly by induction in the Earth's field and partly by residual (remanent) magnetism. Induced magnetisation depends primarily upon the magnetic susceptibility of rocks and has the same direction as the inducing magnetic field of the Earth. Remanent magnetisation is independent of the strength and direction of the present day Earth's field and represents a permanent magnetisation of rocks acquired during an earlier geological period. Consequently the induced and remanent magnetisations are not necessarily similar in either magnitude or direction. They both combine vectorially with the Earth's field to produce a resultant magnetic field intensity, and it is this parameter which is measured during magnetic surveys by total field magnetometers.

The shape and magnitude of a magnetic anomaly caused by a magnetic body depends upon:-

(a) The inclination and intensity of the Earth's magnetic field.

(b) Shape and size, and orientation of the body in the Earth's field.

(c) The magnetic susceptibility contrast with the country rocks.

(d) The magnitude and direction of any remanent magnetisation.

(e) The distance between the body and the magnetometer. (i.e. for airborne surveys the depth of burial plus the flying height of the aircraft).

A theoretical magnetic anomaly can be computed when the shape and depth of the body is known as well as the magnetisation vector, susceptibility contrast and the inclination of the Earth's field. In this case the solution is unique. However for the inverse problem, for a given magnetic anomaly there corresponds, theoretically, an infinite number of solutions as to the size, shape and depth of burial of the body. Thus, the interpretation of magnetic anomalies depends largely on comparisons with theoretical anomalies which can be calculated for relatively simple geometrical bodies together with some prior knowledge of the geology. The latter is needed in order that the simple bodies chosen may approximate to known or possible geological structures, (See Figures 2a - 2e).

Generally ultrabasic and basic igneous rocks are more magnetic than acidic igneous rocks which in turn are more magnetic than metamorphic and sedimentary rocks. The magnetic properties of metamorphic rocks are clearly influenced by the original igneous or sedimentary rocks from which they were derived whilst some iron bearing sediments may also be strongly magnetic.

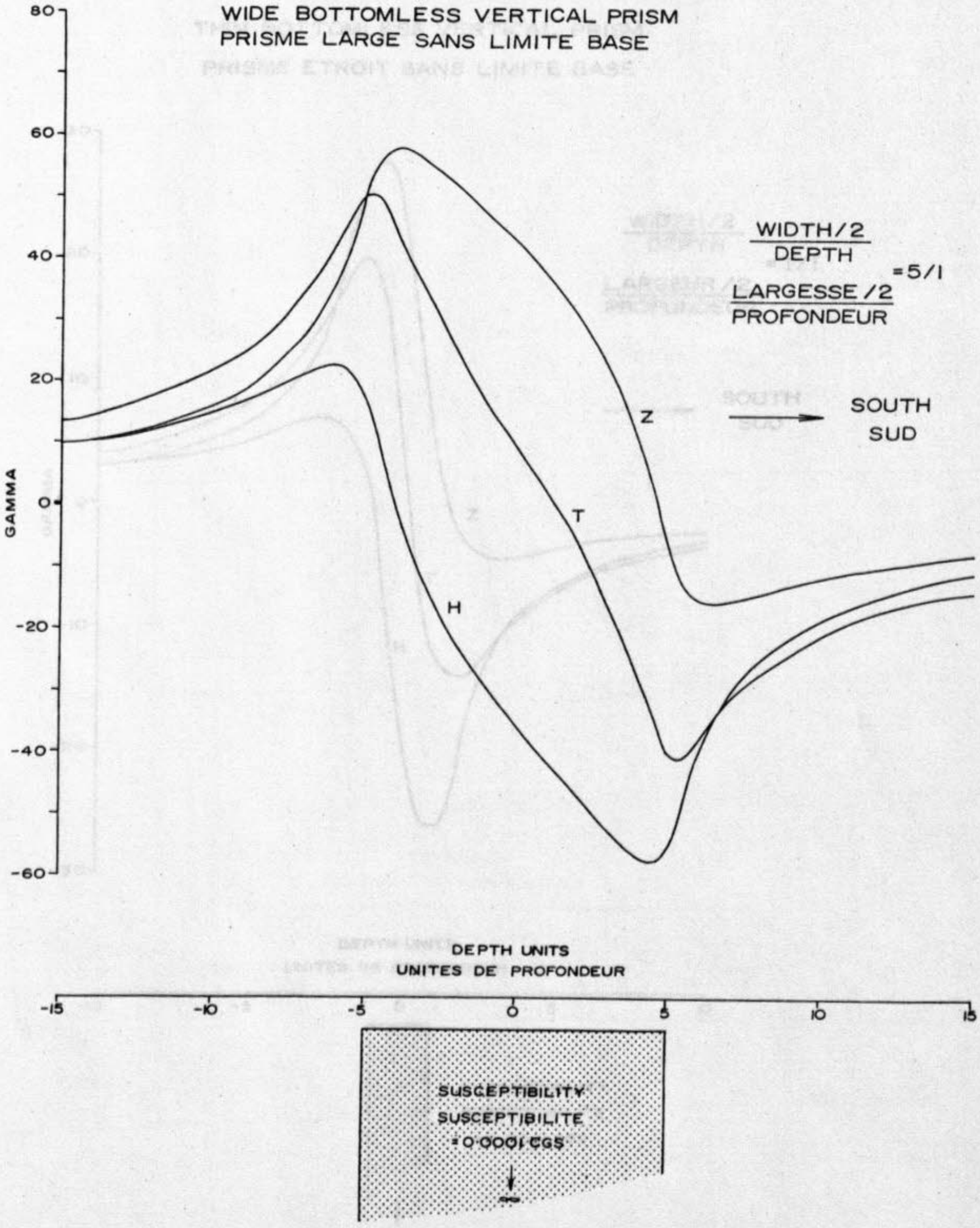
3.2 Qualitative Interpretation

The success of any qualitative magnetic interpretation is dependent upon being able to identify both geological structures and different rock types from features which are contained on a magnetic contour map. In many cases rock types can be distinguished from each other by their magnetic signature. The term signature encompasses a multitude of different magnetic properties which include, level of intensity, strike direction, anomaly amplitude, wavelength, magnetic gradient, and characteristic patterns or shapes of magnetic contours.

The principal structural elements identified qualitatively are faults,folds bodies, dykes and contacts between different magnetic zones. Faults may be recognised on magnetic maps either by the displacement of a magnetic marker horizon, which can be recognised on both sides of the fault or by the termination of perhaps several magnetic horizons along the line of the fault. Alternatively faults may be recognised by a change of magnetic character (e.g. strike direction) across a fault line.

Folds may be inferred by a variety of methods which include relatively smooth changes of strike of conformable magnetic horizons possibly associated with corresponding changes in dip of the beds, or by the identification of similar magnetic beds on either side of either an anticlinal or synclinal fold.

MAGNETIC MODEL ANOMALIES AT INCLINATION 50° S
ANOMALIES DES MODELES MAGNETIQUES A L'INCLINATION 50° S



MAGNETIC MODEL ANOMALIES AT INCLINATION 50°S
ANOMALIES DES MODELES MAGNETIQUES A L'INCLINATION 50°S

THIN BOTTOMLESS VERTICAL PRISM

PRISME ETROIT SANS LIMITE BASE

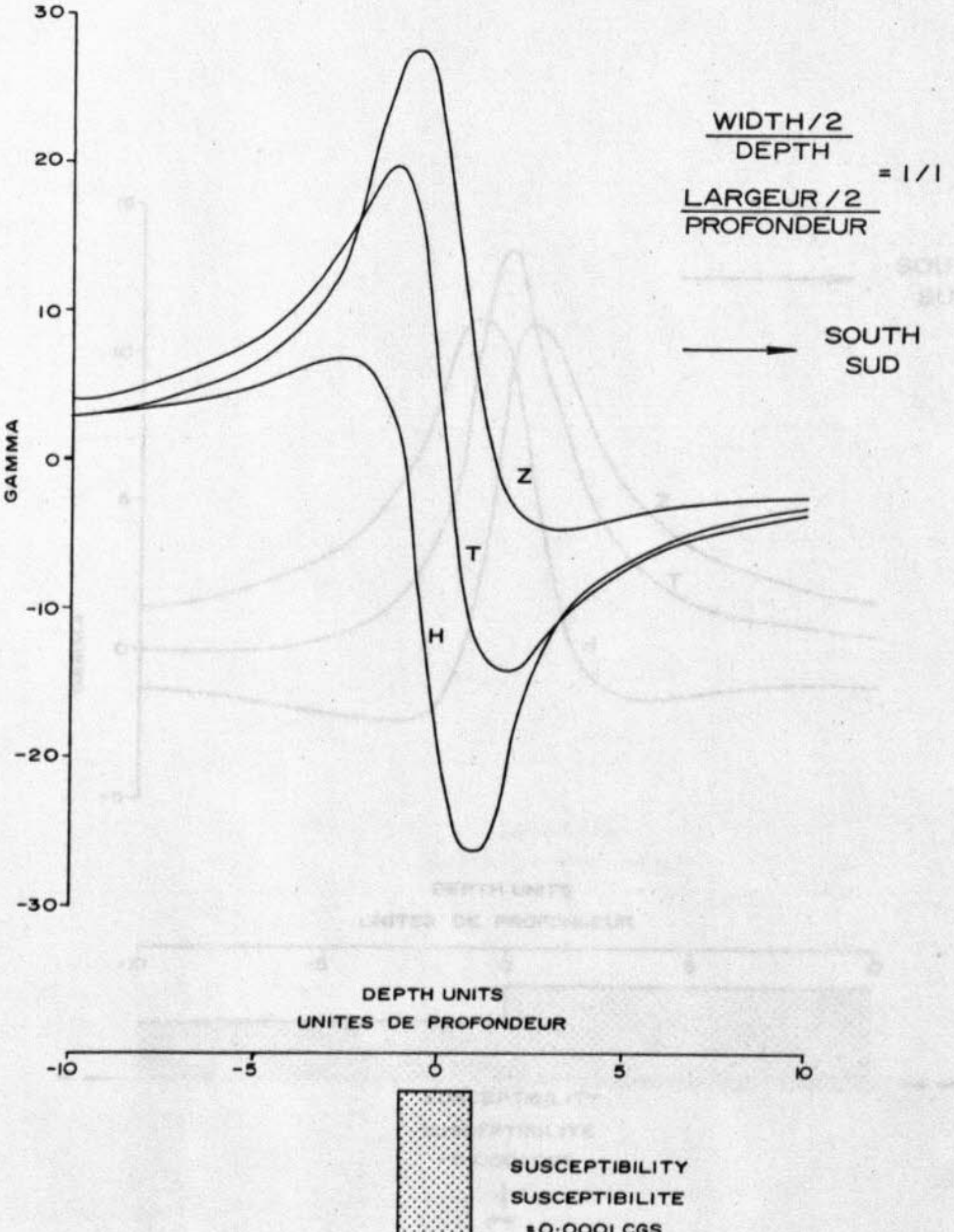


FIGURE 2c

MAGNETIC MODEL ANOMALIES AT INCLINATION 50°S
ANOMALIES DES MODELES MAGNETIQUES A L'INCLINATION 50°S

FAULT. DEPTH / THROW = 1/1

FAILLE. PROFONDEUR / REJET = 1/1

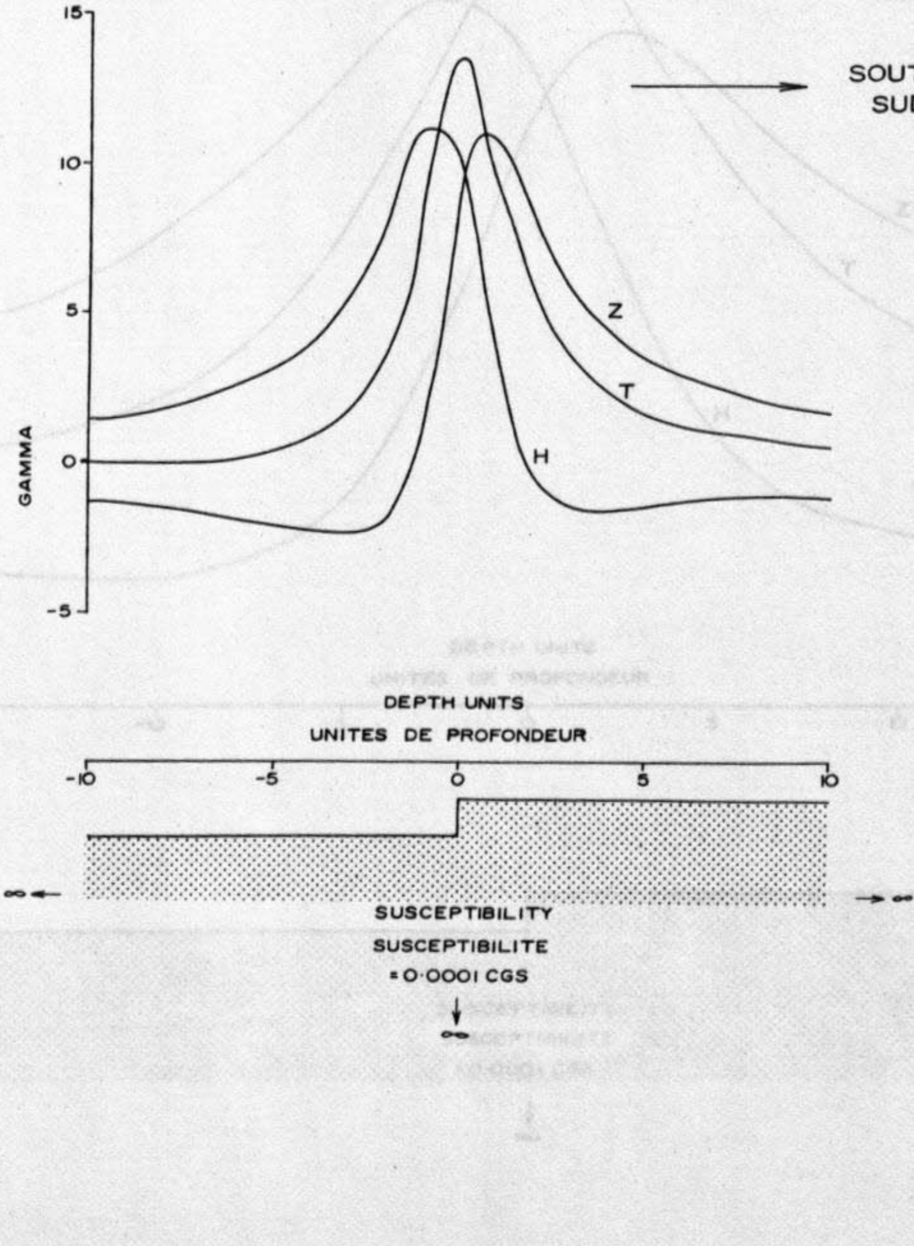


FIGURE 2d

MAGNETIC MODEL ANOMALIES AT INCLINATION 50°S
ANOMALIES DES MODELES MAGNETIQUES A L'INCLINATION 50°S

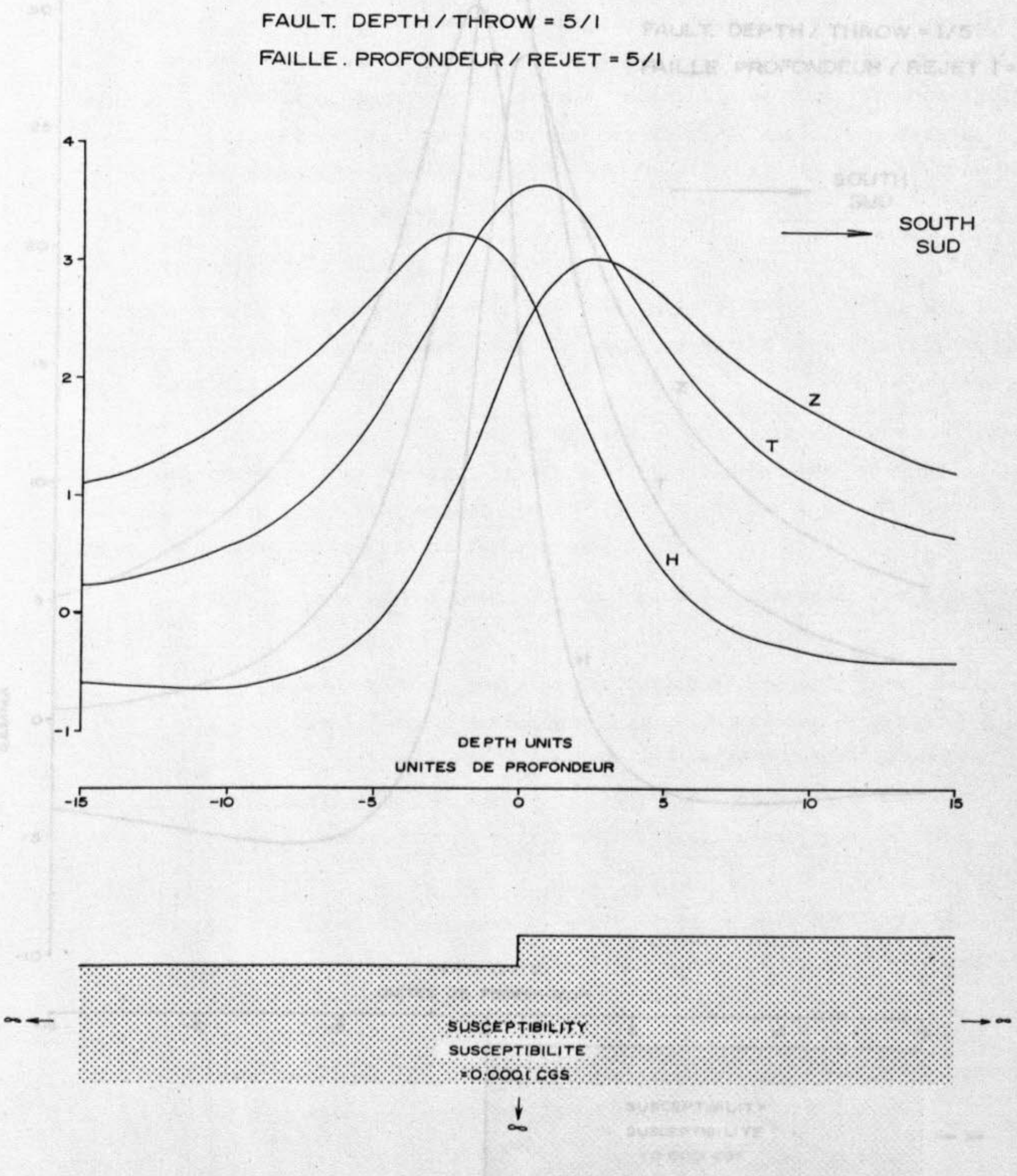
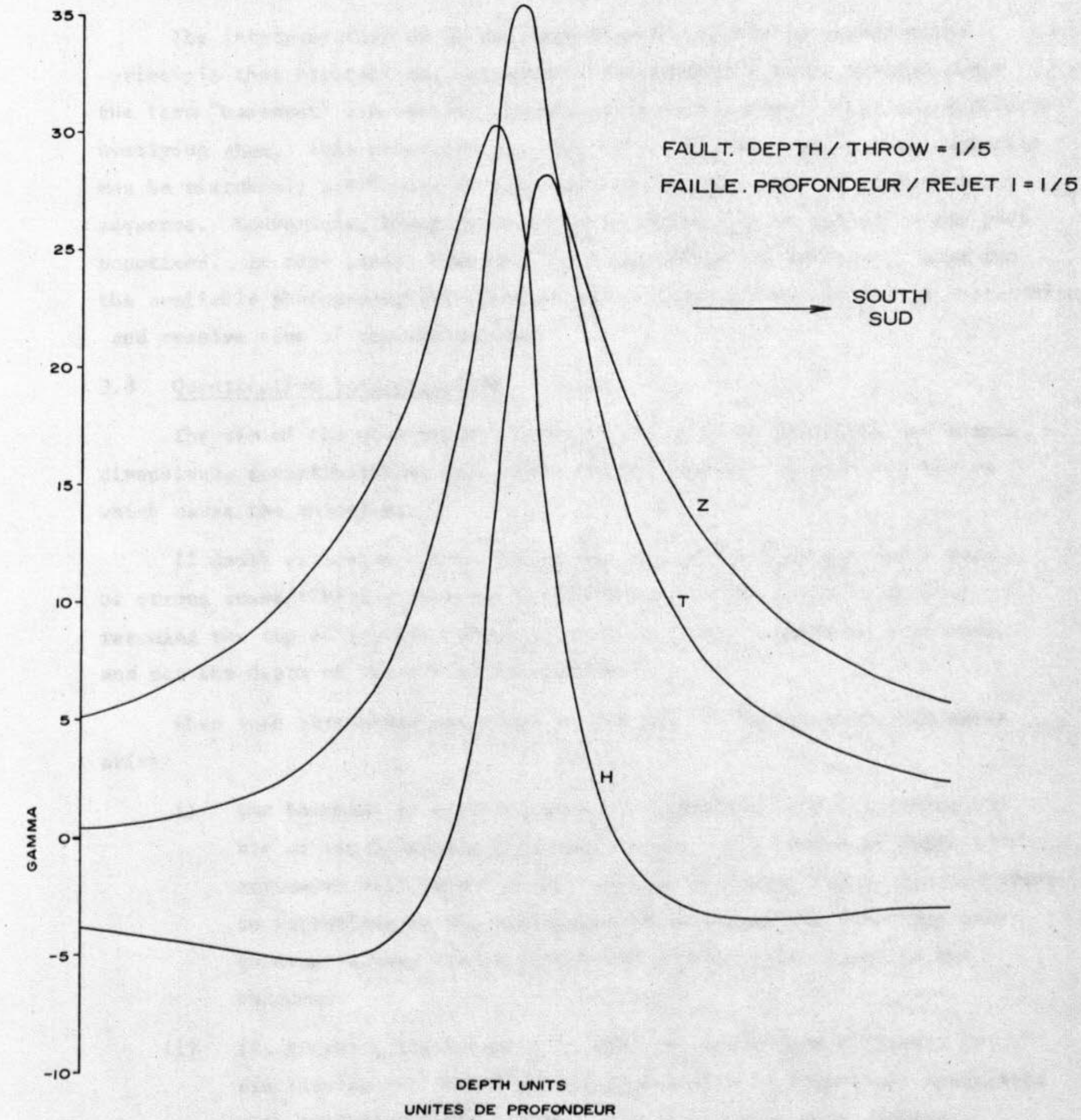


FIGURE 2e

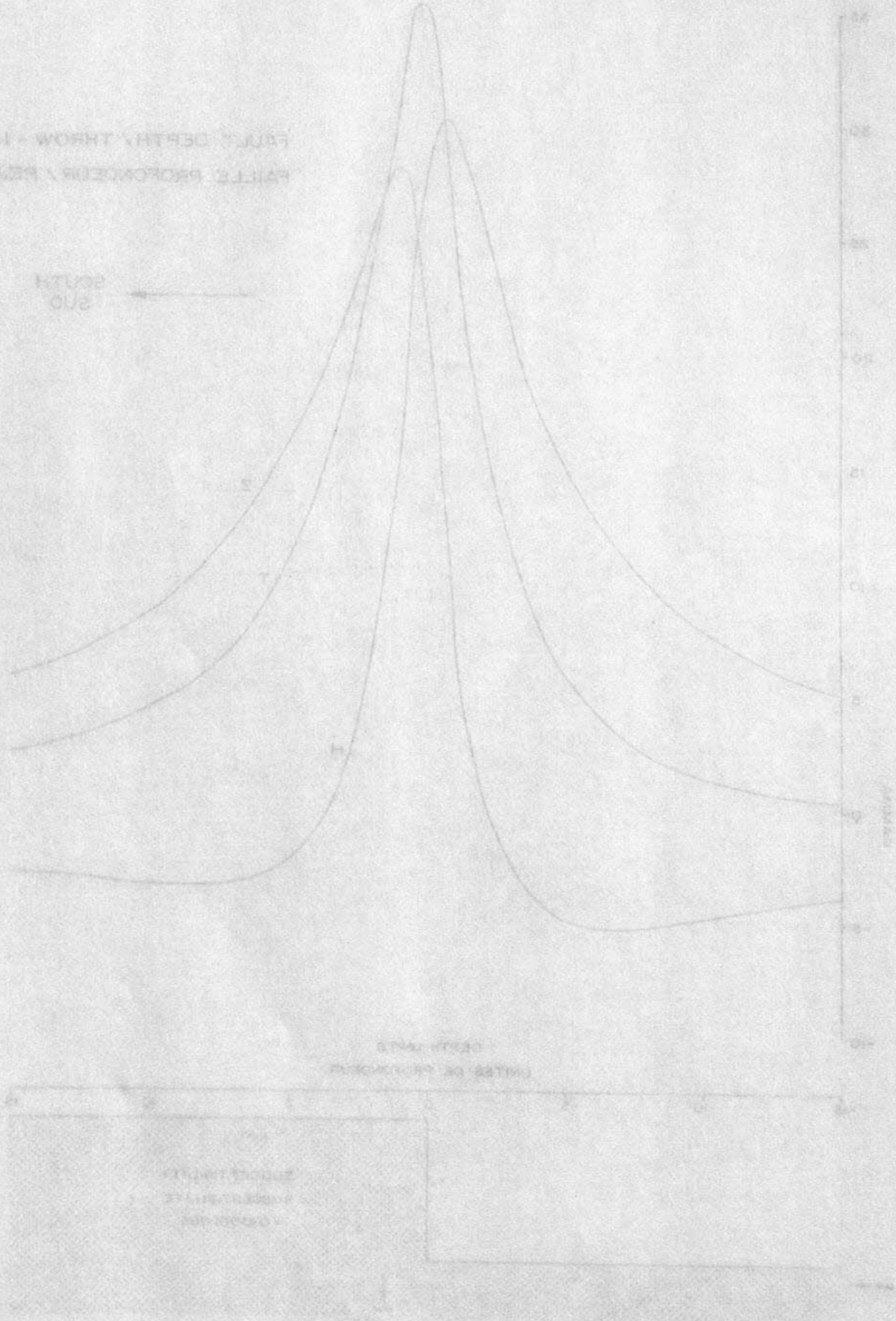
MAGNETIC MODEL ANOMALIES AT INCLINATION 50°S

ANOMALIES DES MODELES MAGNETIQUES A L'INCLINATION 50°S



MAGNETIC MODEL ANOMALIES AT INCLINATION 90°S

ANOMALIES DES MODELES MAGNETIQUES A L'INCLINATION 90°S



Magnetic zones which possibly coincide with geological units are often indicated by the outline of particular magnetic patterns, the difference in magnetic levels and changes in anomaly strike direction.

The interpretation of an oil type magnetic survey is based on the principle that crystalline, metamorphic and intrusive rocks grouped under the term "basement" are usually significantly more magnetic than the sediments overlying them. This principle can however break down: grits with magnetite may be mistakenly attributed to the basement, as may lavas in a sedimentary sequence. Conversely, homogeneous granites containing no magnetite may pass unnoticed. In many cases, however, the topographic and geological maps and the available photogeological information can help greatly in the interpretation and resolve some of the ambiguities.

3.3 Quantitative Interpretation

The aim of the quantitative interpretation is to determine the shapes, dimensions, suceptibilities and depths to the tops of the magnetic bodies which cause the anomalies.

If depth estimates aim to define the top of the basement and a rock of strong susceptibility contrast is intruded into the basement without reaching the top of it, the calculations will give the depth of this body and not the depth of the top of the basement.

When such intrusions penetrate to the top of the basement, two cases arise:

i) the basement is deep and magnetic sediments or basic intrusions are at significantly different levels. Two series of depth estimates will be obtained, one with scattered values corresponding to intrusions in the sediments whilst the other, with more homogeneous values, can be attributed without major error to the basement.

ii) if, however, the basement is shallow, it is more difficult to distinguish the anomalies associated with it from those associated with intrusive rocks. The distinction can be made, however, provided that certain characteristic structures, identifiable from the magnetics and in agreement with existing knowledge, can be considered as unique to the basement.

When the magnetic record is flat, it can be deduced that either the basement is sufficiently deep not to affect the magnetometer or that it is homogeneous and lies at an undetermined depth.

Regional geological knowledge as well as the experience gained from the study of similar problems, often allows doubts to be removed or a choice to be made from several alternatives arising from the calculations.

Bearing these remarks in mind, the results of the survey concern a basement which will be called the "magnetic basement" and which will, in places, differ from the geological basement.

3.4 Depth Estimates

3.4.1 Approximate Methods

Straight slope methods: In this method the horizontal length of the straight part of anomaly inflections is used as a depth index. For anomalies of amplitude greater than a few tens of nT (gammas) and where the straight slope occupies about half of the total amplitude, the straight slope length is divided by unity; the model assumed in this case is the bottomless prism (Vacquier et al, 1951). Alternatively , for anomalies of a few tens of nT (gammas) or less, the index length was divided by 0.7; the model implicit in this case being a depth limited prism or plate (Steenland, 1965).

Peters' half slope methods: This method (Peters, 1949) uses the horizontal distance between the points either side of an inflection at which the slope of the anomaly curve is one half of the maximum slope (i.e. that at the point of inflection). This method is inaccurate when a horizontal component of magnetisation is present, as occurs at the ambient geomagnetic inclinations in the present survey. Thus the Peters method frequently gives larger depth estimates than other methods.

Max - Min method: This method is very approximate: it uses the horizontal distance between the maximum and minimum of an anomaly divided by a factor usually 3.

3.4.2 More Accurate Methods:

Bean's Method: The method due to Bean (1965) uses both limbs of an anomaly and yields measurements of inclination of magnetisation, and susceptibility in addition to estimated depth. It is accurate, rapid to use, and can be used on incompletely defined anomalies.

Modified Peters' Method: This method uses the half maximum slope separations on both major limbs of asymmetric anomalies in addition to the

ratio of the gradients of the two slopes.

Taféev Method: This method is applicable either to symmetric anomalies or to the symmetric part of asymmetric anomalies (Powell, 1965, 1967; Koulomzine et al, 1970). In the Taféev method, the bi-logarithmic plot of the observed anomaly amplitude (expressed as a fraction of the maximum amplitude) against distance from the anomaly peak is matched with master curves upon which the distance scale is normalised in terms of the depth of the magnetic body. When the matched master and observed curves are superimposed, the length between the "distance divided by depth" equals unity line, on the master curve and the origin on the observed curve gives the depth of the magnetic body. One set of master curves exists for isometric (circular) anomalies, and a second set exists for protruded (oval or linear) anomalies.

Inflection Tangent Intersectional Method: This method was outlined by Naudy (1965). Hunting have developed it by means of computer programs which generate model anomalies, diagnose their type, and then analyse the various critical horizontal and vertical parameters which are then plotted as master curves, normalised both in depth and magnetisation units. The critical horizontal and vertical parameters are then measured on each observed anomaly and the resulting set of values is compared with the master curves.

The above methods are primarily two dimensional (i.e. the anomaly length is greater than about 5 times the width). Three dimensional anomalies were generally interpreted by the straight slope method applied to several limbs, or rarely, by the CASE methods (Martin, 1965; Grant & Martin, 1967).

All depth estimates have been related to sea level, being negative below sea level and positive above. Magnetic intensities are quoted in either gamma (1 gamma = 10^{-5} Oersted) or in nanotesla, nT (1 nT = 10^{-9} weber metres $^{-2}$). Gamma and nanotesla are numerically equivalent.

3.5 Model Anomalies

In calculating a depth estimate it was necessary to assume that a hypothetical model approximated to the geologic feature causing the observed anomaly. In the majority of cases a two dimensional model approximation was considered more than adequate. Three basic two dimensional models were assumed, all with horizontal and vertical faces:

ratio of the gradients of the two slopes.

Tarkov Method: This method is applicable either to symmetric anomalies or to the symmetric part of asymmetric anomalies (Powell, 1965, 1967; Koulomzine et al, 1970). In the Tarkov method, the bi-logarithmic plot of the observed anomaly amplitude (expressed as a fraction of the maximum amplitude) against distance from the anomaly peak is matched with master curves upon which the distance scale is normalised in terms of the depth of the magnetic body. When the matched master and observed curves are superimposed, the length between the "distance divided by depth" equals unity line, on the master curve and the origin on the observed curve gives the depth of the magnetic body. One set of master curves caters for isometric (circular) anomalies, and a second set caters for protracted (oval or linear) anomalies.

Inflection Tangent Intersection Method: This method was outlined by Moody (1965). Hood et al have developed it by means of computer programs which generate model anomalies, of various dyke types, and then analyse the various critical horizontal and vertical parameters which are then plotted as master curves, normalised both to depth and magnetisation units. The critical horizontal and vertical parameters are then measured on each observed anomaly and the resulting set of values is compared with the master curves.

The above methods are primarily two dimensional (i.e. the anomaly length is greater than about 3 times the width). Three dimensional anomalies were generally interpreted by the straight slope or half slope method (Peters, 1949), or, rarely, by the Hall method (Smith, 1961; Hood & Merlin, 1967).

All depth estimates have been related to sea level, being negative below sea level and positive above. Magnetic intensities are quoted in either gammas (1 gamma = 10^{-5} oersted) or in nanoteslas, nT (1 nT = 10^{-9} weber metres^{-2}); gammas and nanoteslas are numerically equivalent.

1.5 Model Anomalies

In calculating a depth estimate it was necessary to assume that a hypothetical model approximated to the geologic feature causing the observed anomaly. In the majority of cases, a two dimensional model approximation was considered more than adequate. Three basic two dimensional models were assumed, all with horizontal and vertical faces:

a) The bottomless prism

b) The step or fault

c) The plate. e.g. dyke (a vertical plate)

These models are illustrated in figures 2a - 2e. The horizontal plate anomaly can be generated by a superposition of two offset fault anomalies of equal but opposite throws. The geomagnetic inclination of this survey area is 50^{o}S. The model anomalies shown in figures 2a - 2e have been computed for $I = 50^{o}$S and east - west strike.

Where the strike varies from east west by the angle A, the amplitude is reduced by the factor $(1-\cos^2 I \cos^2 A)$, the angle I being the geomagnetic inclination.

Two ASGA-UNESCOmaps were found useful in the geophysical interpretation of this survey:

1) Geological 1:5,000,000 1963

2) Tectonic 1:5,000,000 1968

Depth estimates were primarily calculated from the magnetic analogue profiles. Due to the presence of high frequency, shallow body interference, a number of profiles required hand smoothing prior to basement depth estimation.

Note that basement depth estimates are displayed on the accompanying interpretation sheets as circled values in kilometers. Depths of shallow bodies, generally volcanics, are not circled. Negative values refer to depths below sea level.

4. INTERPRETATION

The contoured magnetic data can be split into 3 regions:

1) a predominantly volcanic region containing short wavelength, high magnetic relief within Sheet 1 and extending in a subdued form along the southern margin of Sheet 2. Basement interpretation is a problem in this region.

2) a region relatively free of short wavelength interference within the northern half of Sheet 2 undoubtedly reflecting basement structure and extending into the NE corner of Sheet 1.

3) another long wavelength region occurring in the SW corner of Sheet 1.

The survey appears to define one relatively large region of sedimentary basin which is shown to lie towards the north east corner of the area within Sheet 2. The basin is about 40 kms wide and lies between flight lines 16 and 24 and its north-south extent is approximately 33 kms from the northern boundary to half way down the survey area. The estimated depth extent of the basin is from 8 kms to a maximum depth of greater than 11 kms below sea level. Bounding the south eastern side of the basin is the major fault (11), to the south of which the basement becomes shallow and relatively flat. This shallow basement region appears to run along the bottom of Sheet 2 and into the south east corner of Sheet 1.

It would appear that another and possibly deeper basin develops immediately to the north of Sheet 2; however it is by no means fully defined.

Sheet 1 shows a general deepening of basement towards the north west but little else can be said due to the lack of interpretation detail. Separating this region and the sedimentary basin of Sheet 2 would appear to be a NNW-SSE ridge of shallow basement, reaching a minimum depth of about 4 kms.

Anomaly A in the SW corner of Sheet 1, is the only well defined anomaly considered to originate within the basement. It is essentially three dimensional and appears elongated in a south easterly direction. This elongation may be due to the effect of a barely resolved anomaly to the south east or more likely, due to the presence of a NW - SE fault (4) downthrown to the north, whose magnetic effect in the main has been over-whelmed by that of anomaly A. The magnetic gradient to the north east of fault (4) is the combined effect of the body causing anomaly A and fault (4). Considering the peak to peak amplitude of

anomaly A, which is about 350 gammas, its most likely cause is an intrabasement increase of magnetization, possibly a gabbroic region occurring at a depth of just over 4 kms below sea level and of a north-south extent of about 9 kms. It is interesting to note the correlation of anomaly A with the Sarodrano region of high ground.

Sheet 1 reflects predominantly the presence of Cenomanian basalts in which numerous faults and magnetic lineations are observed. Were it not for the relatively wide flight line separation of 5 kms, which tends to smooth out near surface, short wavelength anomalies, the magnetic contours within this high magnetic relief region would appear even more contorted than they are here. The volcanic region runs south eastwards in a band of 18-25 kms in width and appears to terminate on the western edge of Sheet 1. Geological mapping shows that the volcanic region is likely to continue across the bottom of Sheet 2. The relatively high frequency but low amplitude data in the south of Sheet 2 does not rule this out and would imply that while the volcanics do not become significantly deeper, the marked decrease in magnetic relief is caused possibly by successive layers of basalts containing opposing remanent magnetizations, having been lain down during periods of successive geomagnetic reversal. If this is true, then the volcanics in this region may be considerably thicker than those in Sheet 1, but this is purely conjecture.

The volcanic band within Sheet 1 can be split generally into a region of magnetic high to the north and magnetic low to the south. Towards the east of this region, the magnetic variations can be confidently hand smoothed, particularly on flight lines 11 and 12, giving interpreted regional depths, presumably to basement, of 5.2 km and 4.7 kms below sea level respectively. The amplitude of this smoothed feature is at least 500 gammas which suggests the cause is that of magnetization contrast rather than change in basement topography. The feature, which as about 15 kms in width, is probably intrabasement and closely follows the band of volcanics west northwestwards and as such confirms structural information already available. The survey however provides fresh information in terms of NE-SW faulting, which in the volcanic region of Sheet 1 is observed as discontinuities of magnetic lineation. A quantitative basement interpretation is difficult for Sheet 1. As best we can say that the depth of 5 kms, averaged between flight lines 11 and 12 is likely to increase immediately to the NW due to the NE-SW downthrown region inferred by faults (7) and (8) and from the trend of the computed basement depth contours.

anomaly A which is about 250 gammas, its most likely cause is an intrabasement increase of magnetisation, possibly a gabbroic region occurring at a depth of just over 4 kms below sea level and of a north south extent of about 9 kms. It is interesting to note the correlation of anomaly A with the [illegible] region of high ground.

Sheet 2 reflects predominantly the presence of Cainozoic basalts in which numerous faults and magnetic lineations are observed. Were it not for the relatively wide flight line separation of 3 kms, which tends to smooth out near surface, short wavelength, anomalies, the magnetic contours within this high magnetic relief region would appear even more contorted than they are now. The volcanic region has a north south aspect in a band of 18-25 kms in width and appears to continue on the western edge of Sheet 1. Geological mapping shows that the volcanic region is likely to continue across the bottom of Sheet 2. The relatively high frequency but low amplitude data in the south of Sheet 2 does not rule this out and would imply that while the volcanics do not become significantly thinner, the marked decrease in magnetic relief is caused possibly by successive layers of basalts carrying opposing remanent magnetisations, having been laid down during periods of successive geomagnetic reversals. If this is true, the volcanics in this region may be considerably thicker than those on Sheet 1, but this is purely conjecture.

The volcanic band within Sheet 4 can be split generally into a region of magnetic high to the north and magnetic low to the south. Towards the east of this region, the magnetic variations can be confidently [illegible], particularly at flight lines 11 and 13, give interpreted magnetic depths, presumably to basement, of 2.2 km and 4.7 kms below sea level respectively. The amplitude of this anomalous feature is at least 500 gammas which suggests the cause is that of magnetisation contrast rather than change in basement topography. The feature, which is about 10 kms in width, is probably intrabasement and closely follows the band of volcanics very much as [illegible] information is already available. The survey however provides [illegible] information in terms of NE-SW faulting, which in the north-eastern region of Sheet 3 is observed as discontinuities of magnetic formation. A quantitative basement interpretation is difficult for Sheet 3. At best we can say that the depth of 5 kms, averaged between flight lines 11 and 13 is likely to increase [illegible] to the SW due to the NE-SW downthrown region inferred by faults (7) and (8) and from the trend of the computed basement depth contours.

The prevalent NE - SW faulting within the survey area agrees with the general geological trend and photogeological findings to the north east of Majunga. A degree of correlation between faulting and topography is often observed and where this occurs, the proposed faulting is regarded with more certainty.

Faults (1), (2) and (3) are minor, are of NNE - SSW strike and were detected as magnetic lineation discontinuities. Although not in the prevalent NE - SW fault direction these faults lie parallel to the major fault along the east coast of Madagascar. Little topographic correlation is observed except for a long escarpment to the east of Forêt de Belambo which is close to and parallel to fault (1). Faults (7), (8) and (9) strike NE - SW and again were detected as lineation discontinuities within the volcanics. Fault (7) is probably longest, extending from the SW corner to the NE corner of Sheet 1 and is probably downthrown to the south. Faults (8) and (9) are particularly well defined within the volcanics. Fault (8) correlates at its southern end with the Mangily River course and its associated valley.

Fault (4) has a NW - SE strike and is downthrown to the north. Its position is a little unclear due to interference from magnetic anomaly A to the south west and the magnetic edge effect of the volcanic region to the north east. Had the flight line separation been smaller, resolution of the effect of the fault itself may have been possible. The occurrence of fault (4) on or at least near to the volcanic region's southern boundary need not be coincidental, as it is possible that the original lava flow(s) was truncated to the south by NW - SE fault controlled topography. Lineation (5) is regarded as an effect of interference between the volcanic magnetic high to the south and the broad, probably basement, magnetic low to the north. The probable cause of lineation (6) is the northern edge effect of a deeper part of the volcanic region, occurring within the intersection of the main volcanic boundary (13) and fault (7). To the south east of fault (7) the volcanics would appear to be significantly deeper than to the north west.

Faults (10) and (11) strike NE - SW and split what might otherwise be a single magnetic anomaly into three, anomalies B, C and D. The significance of this multiple anomaly is rather obscure, especially as it strikes approximately north-south, like few other anomalies within the survey area. However it may in all probability be due to an isolated north-south 'tongue' of volcanics laid down along an ancient north-south topographic trough. As the magnetic amplitude is relatively high for this region, it is considered to be distinct from the volcanics to the east. Fault (11) would appear to be a major fault, both directly from the magnetics and also on inspection of the basement depth contour maps which

The prevalent NE - SW faulting within the survey area agrees with the general geological trend and photogeological findings to the south east of Mahanga. A degree of correlation between folding and topography is often observed and where this occurs, the proposed faulting is regarded with more certainty.

Faults (1), (2) and (3) are minor, are of NNE - SSW strike and were detected as magnetic lineation discontinuities. Although not in the prevalent NE - SW fault direction these faults lie parallel to the major fault along the east coast of Madagascar. Little topographic correlation is observed except for a long escarpment to the east of Fanon.. at Belambo which is close to and parallel to fault (1). Faults (7), (8) and (9) strike NE - SW and again were detected as lineation discontinuities within the volcanics. Fault (7) is probably longest, extending from the SW corner to the NE corner of Sheet 1 and is probably downthrown to the south. Faults (8) and (9) are particularly well defined within the volcanics. Fault (8) correlates at its southern end with the Manaly river course and its associated valley.

Fault (6) has a NW - SE strike and is downthrown to the north. Its position is a little unclear due to interference from magnetic anomaly A to the south west and the magnetic high south of the volcanic region to the north east. Had the flight line separation been smaller, resolution of the effect of the fault itself may have been possible. The occurrence of fault (6) on or at least near to the volcanic region's southern boundary need not be coincidental as it is possible that the original lava flow(s) was truncated to the south by NW - SE fault controlled topography. Lineation (5) is regarded as a ridge of interference between the volcanic magnetic high to the south and the broad, probably basement, magnetic low to the north. The probable cause of lineation (5) is the northern edge effect of a deeper part of the volcanic region, occurring within the intersection of the main volcanic boundary (13) and fault (6). To the south east of fault (7) the volcanics would appear to be significantly deeper than to the north west.

Faults (10) and (11) strike NE - SW and split what might otherwise be a single magnetic anomaly into three, anomalies B, C and D. The significance of this multiple anomaly is rather obscure, especially as it strikes approximately north-south, like few other anomalies within the survey area. However it may in all probability be due to an isolated north-south 'tongue' of volcanics laid down along an ancient north-south topographic trough. As the magnetic amplitude is relatively high for this region it is considered to be distinct from the volcanics to the east. Fault (11) would appear to be a major fault, both directly from the magnetics and also to justify the proposed depth contour zone which shows a distinct deepening of basement to the NW side of the fault. The throw along its northern half is probably in the region of a few kms. Both faults show a degree of topographic correlation; that is, fault (10) at its southern end correlating for about 12 kms with a linear break in slope to the south east of the Andreribe area of high ground; and fault (11) at its southern end correlating curiously with the south east boundary of the brush vegetation to the south of areas Antsalova and Antanambao, and near its northern end on the western side of Baie de Bombetoka where it correlates for 13 kms with a prominent change in topographic level to the south east of the Andrahibo and Amborondava Rivers.

A number of magnetic lineations within the volcanic region warrant further comment. Lineation (12), to the north of the area appears virtually continuous with the coastline to the west of Cap d'Amparafaka. This may have some significance, as for example it is possible that the shape of this region of coastline was determined by the northern boundary of the original Cretaceous lava flow, having since been overlain by a uniform thickness of sediments and eroded or downthrown to the east of Cap d'Amparafaka. Lineation (13) correlates reasonably well with the increased topographic level near the southern boundary of Foret de Tsiombikibo. Lineations (14) and (15) coincide remarkably well with the northern and southern boundaries of Lac Kinkony and it is possible that in this region, both superficial and internal drainage is restricted by the coincidence of a topographic basin and an underlying impermeable basin of volcanics.

shows a distinct deepening of basement to the SW side of the fault. The first along its northern half is probably in the region of a few kms. Both faults show a degree of topographic correlation; that is, fault (10) at its southern end correlating for about 12 kms with a linear break in slope to the south east of the Andrefe area of high ground, and fault (11) at its southern end correlating curiously with the south east boundary of the [illegible] vegetation to the south of areas Antsalova and Antsamomba, and near its northern end on the western side of Bale de Baly it is correlated for 10 kms with a prominent change in topographic level to the south east of the [illegible] and [illegible] Rivers.

A number of magnetic lineations within the volcanic region warrant further comment. Lineation (12), to the north of the area appears to be a fairly continuous with it, possibly to the west [illegible]. This may have some significance, as for example it is possible that the shape of this region of volcanics was determined by the north boundary of the deltaic Cretaceous [illegible] and [illegible] having since been overlain by a uniform thickness of sediments and lava flows, bounded by scarps to the east of the [illegible]. Lineation (13) correlates reasonably well with the [illegible] level near its northern boundary of [illegible]. Lineations (14) and (15) coincide reasonably well with the northern and southern boundaries of [illegible] and it is possible that in this region, both superficial and internal drainage is restricted by the occurrence of a topographic basin and an underlying impermeable basin of volcanics.

5. CONCLUSIONS AND RECOMMENDATIONS

Interpretation maps sheets, including basement depth contours have been produced and although in places Sheet 1 lacks basement information, the interpretation elsewhere is felt to be reasonably accurate in its location of geological structures relevant to the setting up of a detailed ground follow up.

The interpretation difficulty within Sheet 1 of shallow interference, may have been reduced had the survey been flown at a higher altitude, or if the survey had covered a larger area and linear filtering applied. Generally the only reliable information as to basement character within the area of volcanics is qualitative, inferred from deep seated faulting observed as volcanic lineation discontinuities.

The prime target for further investigation is the 4 km thick sedimentary basin within Sheet 2 lying fully onshore to the SW of Majunga and appears to cover an area of over 500 sq kms. Particular attention should be paid to the location of fault (11) which bounds the basin to the south east and to fault (10) which appears to intersect the basin about 10 kms to the east of centre. It would be advantageous at a later date to extend magnetic coverage over the apparent deepening of basement out to sea northwards of this basin.

With the relatively scant basement interpretation within Sheet 1, one can only postulate as to the development of basement structure towards the west of the survey area. The basement contours have been drawn in this region so as to show a north west deepening of basement in the form of a NW - SE trough. Whilst bearing in mind the uncertainty of this proposed structure, attention should be paid to its intersection with faults (7) and (8). Downthrown to the SE and NW respectively, the resultant basement structure and overlying sedimentary situation could conceivably be of importance in the location of oil.

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PART 2

OPERATIONS REPORT

1. INTRODUCTION

The airborne geophysical survey described in this report was carried out by Hunting Geology and Geophysics Limited on behalf of the Office Militaire National pour les Industries Strategiques between 11th - 12th April, 1977.

The survey consisted of 2141 line kilometres of airborne magnetic flying undertaken over an area with the Majunga Basin, to the south west of and including the town of Majunga in north west Madagascar. The area flown lies approximately between two lines defined as follows: one to the north, drawn between a point 7 kms north east of Majunga and the second to the south, drawn exactly east - west, of identical east - west coverage and approximately 40 kms south of Cap d'Amparafaka.

The flying was undertaken by our associate company Aerial Surveys Botswana (pty.) Limited using a Douglas DC-3 aircraft registration number A2 ZFD.

The survey team comprised:

S.J. Bullock	H.G.& G.	Party Leader and Senior Geophysicist
B.W. Smithers	Aerial Surveys	Pilot/Navigator
L. Oakenfull	Aerial Surveys	Pilot/Navigator
V. Seagrave	Aerial Surveys	Aircraft Engineer
M. Harvey	H.G.& G.	Data Compiler
P. Conway	H.G.& G.	Electronics Engineer

The survey was under the overall control of Mr. Augustin Andriamahefamanana, Chef du Department Mineraux Radioactifs de l'OMNIS and other members of the staff at OMNIS with whom a close liaison was maintained at all times.

2. FLYING OPERATIONS

The aircraft was based at Majunga.

The flight parameters of the survey were as follows:

Flight Line Direction	North - South
Tie Line Direction	East - West
Flight Line Spacing	5 kms
Tie Line Spacing	20 km
Mean Flying Height	2000 ft barometric (governed by cloud base)
Mean Flying Speed	120 - 130 knots
Navigation	Visual using 1:100,000 maps plus Doppler
Flying dates	11th and 12th April 1977
Sorties	13 and 14

3. GEOPHYSICAL AND ANCILLARY EQUIPMENT

3.1 Airborne Magnetometer

The instrument used for the survey was a digital fluxgate magnetometer which was developed by Hunting Geology and Geophysics from the original Mark III fluxgate magnetometer.

The magnetometer measures the total intensity of the Earth's magnetic field to an accuracy of ± 1 nT and was used at a sampling rate of one reading per second.

The detector head, comprising three mutually perpendicular fluxgate elements, one for measuring the Earth's field and two to orientate the measuring element in the direction of the total field, was mounted in a stinger attached to the tail of the aircraft.

The output of the magnetometer is in the form of an analogue voltage which varies continuously with the magnetic field and is measured by a digital voltmeter every second. This voltage was recorded in analogue form on a twin channel Hewlett Packard 7100B recorder, and in digital form on magnetic tape as 5 B.C.D. characters. The HP 7100B was operated at a speed of 3 inches/minute and used chart paper which was 10 inches wide.

3.2 Digital Recording System

The digital recording system was a Static Device data acquisition system coupled to a Kennedy incremental tape recorder which is specially designed to record multi-channel geophysical data in B.C.D. form on 7 track magnetic tape. The unit incorporates a digital clock which generates fiducial data common to both the digital recorder as well as the various analogue recording devices.

The recording in the aircraft was made onto 600 ft spools of magnetic tape at 200 b.p.i. with the following format:

Block Format:

1 Block = 300 characters
= 10 scans of 1 second each
(i.e. 30 characters per scan)

Scan Format:

	I3	I5	I5
Channels	XXX	XXXXX	XXXXX
	Sortie No.	Time Secs.	Magnetic Field nT

3.3 Magnetic Storm Monitor

The magnetic storm monitor was a Gulf Fluxgate Magnetometer which measures changes in the total intensity of the Earth's magnetic field. The magnetometer output was recorded on an Esterline Angus strip chart analogue recorder running at a speed of 10 inches per hour with 250 nT being recorded over the full 4.5 inches wide chart paper.

3.4 35 mm Positioning Camera

A Vinten 35 mm frame-type tracking camera with secondary optics displaying the fiducial number of each frame, was used to record the aircraft's actual flight path. Individual exposures were taken at 1 second intervals which, using a 18.5 mm lens at the flying height of 400 ft, gave adequate overlap between adjacent frames to ensure that complete photographic coverage was achieved along each line.

3.5 Doppler Navigation

The Doppler system was a Decca Model 72. Generally the navigation for the survey was visual with the Doppler being used to monitor and correct for cross track drift whilst flying each flight.

3.6 Height Keeping

Flying altitude was maintained at 2000 feet ASL using the aircraft's barometric altimeter.

4. DATA COMPILATION

4.1 On-Site Compilation

On completion of each sortie the 35 mm tracking film was developed and the flight path recovered on 1:100,000 map sheets in the Fort Dauphin office. Generally no difficulty was encountered in plotting fiducial points except where the bush was very thick and uniform. This plotting established where the flight lines had been flown out of the required specification, and which lines or portions of lines would need reflying. Data quality control and annotating of records was also carried out.

4.2 Laboratory Compilation

The plotted fiducial points were transferred from the aerial photographs to the topographic maps. This was achieved by identifying features common to both map and photography and using proportional dividers to scale off distances to fiducials. By keeping a constant check on the scale relationship between map and photograph and by using features as close as possible to the fiducial points,

scale errors produced by photographic distortion were mainly eliminated.

For the control of the magnetic results the intersections of the tie lines with every flight line were located by direct comparison on the 35 mm film. All intersections were marked on the magnetometer analogue charts by reference to the camera fiducial marks. At each intersection the tie line minus the flight line magnetic values were calculated and these errors distributed throughout the control grid on the basis of a modified least squares method. This resulted in the flight lines and tie lines being reduced to a common datum plane.

A regional correction was applied to this datum plane using the International Geomagnetic Field (I.G.R.F.) supplied by the Department of Geomagnetism, Royal Greenwich Observatory, England.

Having produced a common datum plane, corrected for the regional field, this enabled a datum line to be drawn on each flight line.

Magnetic values (relative to the datum line) were then read from each profile at intervals of 10 nT, together with all minima, maxima and points of inflexion. These values were transcribed onto the flight line grid again by reference to camera fiducials, and contoured.

5. MATERIALS SUPPLIED TO THE CLIENT

The Mars analogue magnetic records were supplied to OMNIS before the Hunting team left Tananarive.

Dyelines of magnetic work sheets at 1:100,000 were sent to OMNIS prior to the submission of the final report.

The following material will have been supplied following compilation and interpretation.

Five copies of the final report in French

1 Durafilm copy of each final magnetic contour sheet at 1:100,000 scale

1 Ozaloft copy of each final magnetic contour sheet at 1:100,000 scale

1 Ozaloft copy of each interpretation map at 1:100,000 scale

1 Durafilm copy of each interpretation map at 1:100,000 scale

6. PROFESSIONAL SECRECY

Hunting Geology and Geophysics Limited wish to reaffirm to OMNIS its guarantee of strict professional secrecy. No information on the results of this survey will be divulged to any person without the written authority of the Client.

APPENDICES

APPENDIX 1

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MAJUNGA BASIN

FLIGHT LINE INDEX

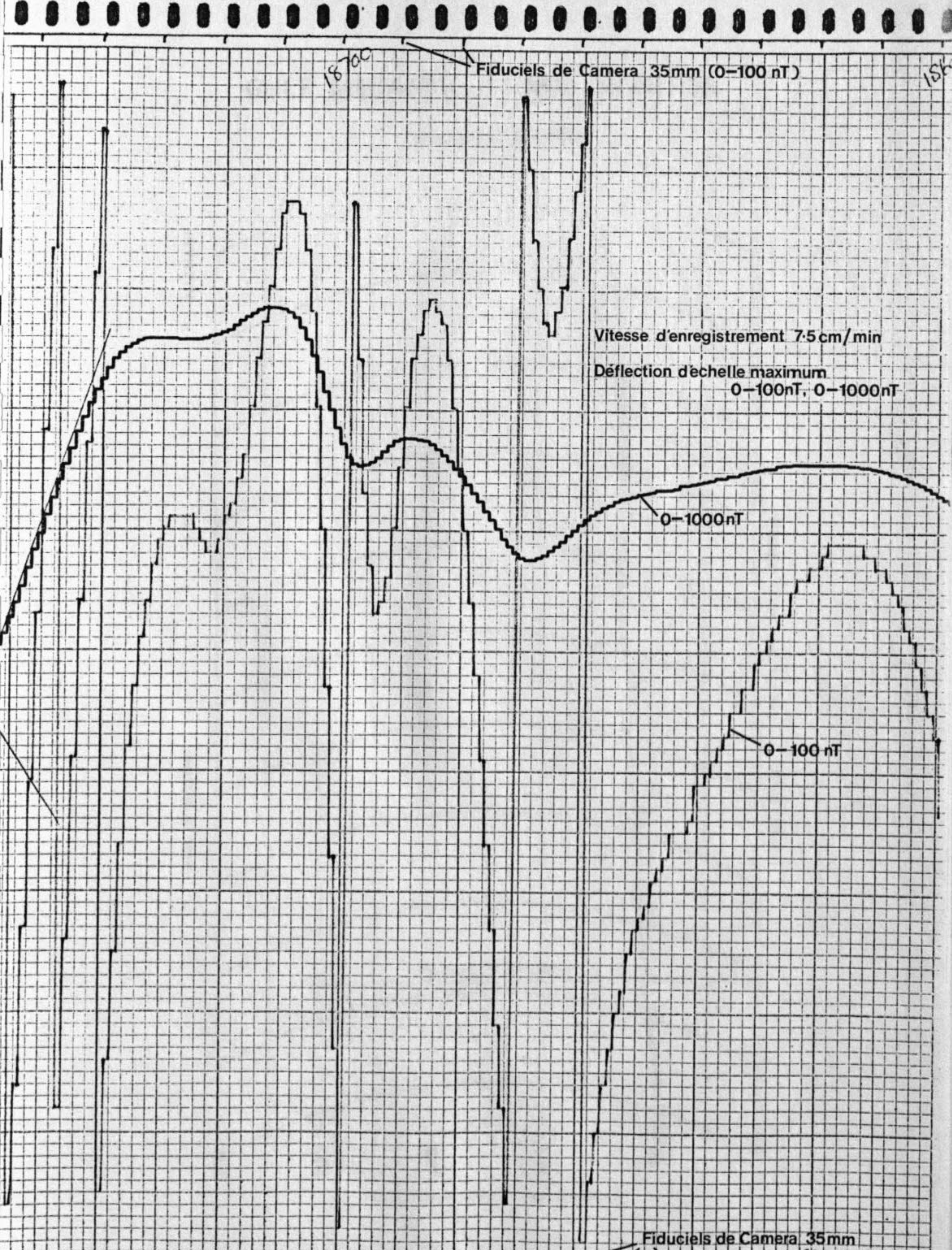
Line No.	Date	Sortie	Direction	Extent
1	11.4.77	13	South	TL 506 Ext - TL 501
2	11.4.77	13	North	TL 501 - TL 506 Ext
3	11.4.77	13	South	TL 506 Ext - TL 501
4	11.4.77	13	North	TL 501 - TL 506
5	11.4.77	13	South	TL 506 - TL 501
6	11.4.77	13	North	TL 501 - TL 506
7	11.4.77	13	South	TL 506 - TL 501
8	11.4.77	13	North	TL 501 - TL 506
9	11.4.77	13	South	TL 506 - TL 501
10	11.4.77	13	North	TL 501 - TL 504
11	11.4.77	13	South	TL 504 - TL 501
12	11.4.77	13	North	TL 501 - TL 504
13	12.4.77	14	South	TL 504 - TL 501
14	12.4.77	14	North	TL 501 - TL 504
15	12.4.77	14	South	TL 504 - TL 501
16	12.4.77	14	North	TL 501 - TL 504
17	12.4.77	14	South	TL 504 - TL 501
18	12.4.77	14	North	TL 501 - TL 504
19	12.4.77	14	South	TL 505 - TL 501
20	12.4.77	14	North	TL 501 - TL 505
21	12.4.77	14	South	TL 505 - TL 501
22	12.4.77	14	North	TL 501 - TL 505
23	12.4.77	14	South	TL 505 - TL 501
24	12.4.77	14	North	TL 501 - TL 505
25	12.4.77	14	South	TL 505 - TL 501
26	11.4.77	13	South	TL 505 - TL 501

217 7551

MAJUNGA BASIN

TIE LINE INDEX

Tie Line No.	Date	Sortie	Direction	Extent
501	11.4.77	13	West	FL 26 - FL 1
502	11.4.77	13	East	FL 1 - FL 26
503	11.4.77	13	West	FL 26 - FL 10
504	11.4.77	13	East	FL 10 - FL 20
505	11.4.77	13	East	FL 19 - FL 26
506	11.4.77	13	West	FL 10 - FL 4
506 Ext	11.4.77	13	East	FL 1 - FL 4



Enchantillon de l'enregistrement Magnétometre Aerien

GULF MAGNETIC STORM MONITOR

SPECIMEN RECORD