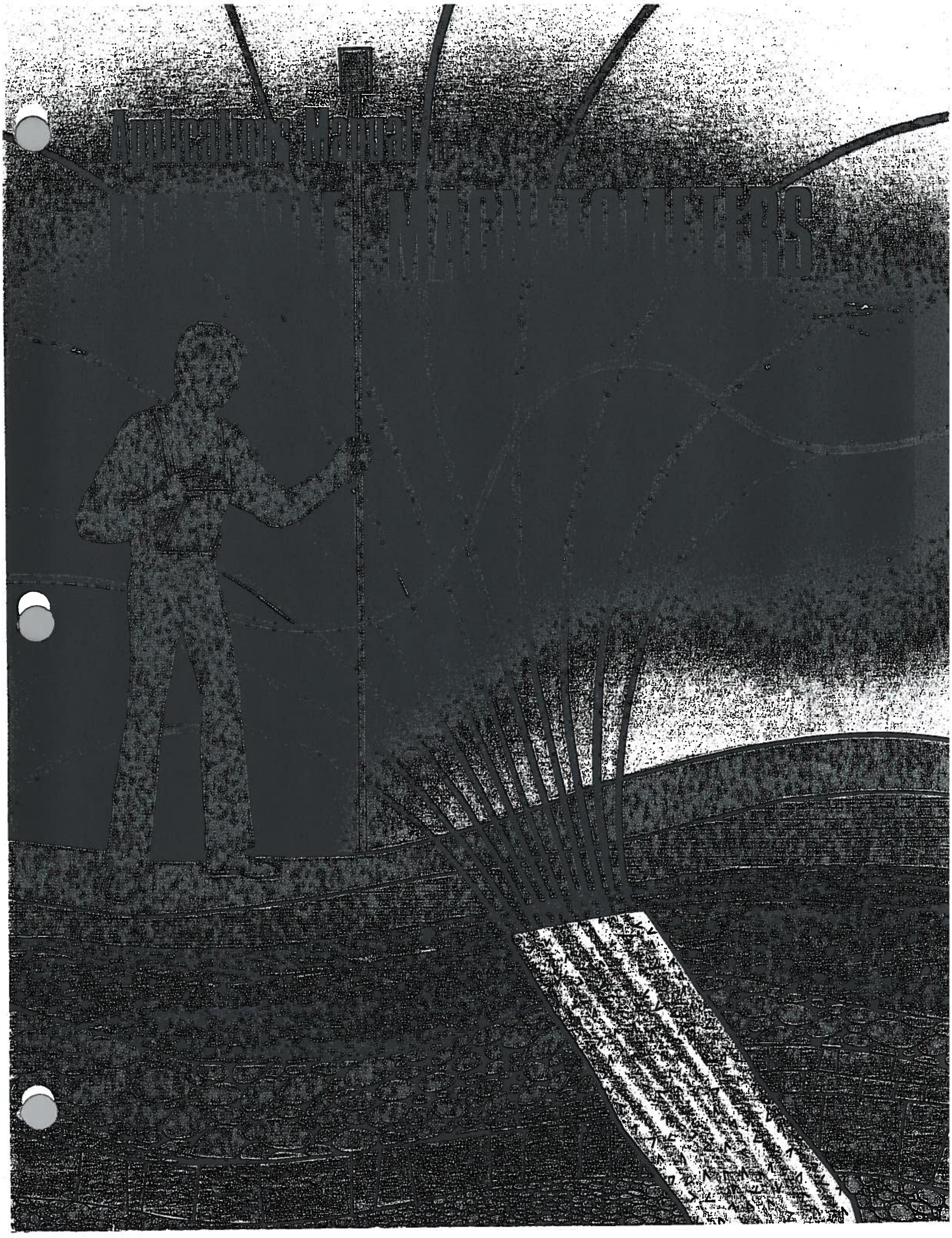
Applications Manual for [illegible] MAGNETOMETERS



APPLICATIONS MANUAL FOR PORTABLE MAGNETOMETERS

by

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V.

INTERPRETATION

Introduction

Total magnetic intensity disturbances or anomalies are highly variable in shape and amplitude; they are almost always asymmetrical, sometimes appear complex even from simple sources, and usually portray the combined magnetic effects of several sources. Furthermore, there are an infinite number of possible sources which can produce a given anomaly. The apparent complexity of such anomalies is a consequence of the net effect of several independent but relatively simple functions of magnetic dipole behavior. With an understanding of these individually simple functions however, and given some reasonable assumptions regarding the geology, buried object or whatever other source one is seeking to understand, a qualitative but satisfactory interpretation can usually be obtained for most anomaly sources.

The interpretation, explanation and guide presented here is directed primarily towards a qualitative interpretation for both geological reasons as well as search applications, i.e., an understanding of what causes the anomaly, its approximate depth, configuration, perhaps magnetite content or mass, and other related factors. But even if qualitative information is derived from the data, it is important to have applied a reasonable amount of care in obtaining precise measurements. Quantitative interpretations are possible, but are applied more to airborne data, entail relatively complex methods for depth determination, and are the basis for a relatively large body of literature on the subject, references to which are given in the Manual.

An anomaly represents a local disturbance in the earth's magnetic field which *arises from a local change in magnetization, or magnetization contrast* as it is termed. A profile, for example over a very broad uniformly magnetic surface, although magnetic itself, will not exhibit a magnetic anomaly as there is no local change in magnetization. A local increase or even decrease on the other hand would constitute such a change and produce a locally positive or negative anomaly.

The observed anomaly expresses only the net effect of the induced and remanent magnetizations which usually have different directions and intensities of magnetization. Since the remanent magnetization is so variable and measurements of its properties seldom made, *anomalies are all interpreted* in practice as though *induced magnetization were the total source of the anomalous effects.*

Asymmetry

The asymmetrical nature of total field anomalies is primarily a consequence of the directions of the field lines of the locally created magnet or source and the earth's-field-component nature of a total field magnetometer in the usually-inclined direction of the earth's magnetic field. Recall that a total field magnetometer measures only the component of any local perturbation which is in the direction of the earth's magnetic field at that point. Anomalies in the earth's field, whether created by induced or permanent magnetization, exist as arrangements of magnetic dipoles, monopoles (effectively), lines of dipoles and monopoles and sheet-like distributions of such poles. It is important therefore to understand the nature of the dipole or monopole field as it will be shown that a summation of such elementary forms will explain the most complex characteristics of anomalies and facilitate their interpretation. Notice, for example in *Figure 13*, the con-

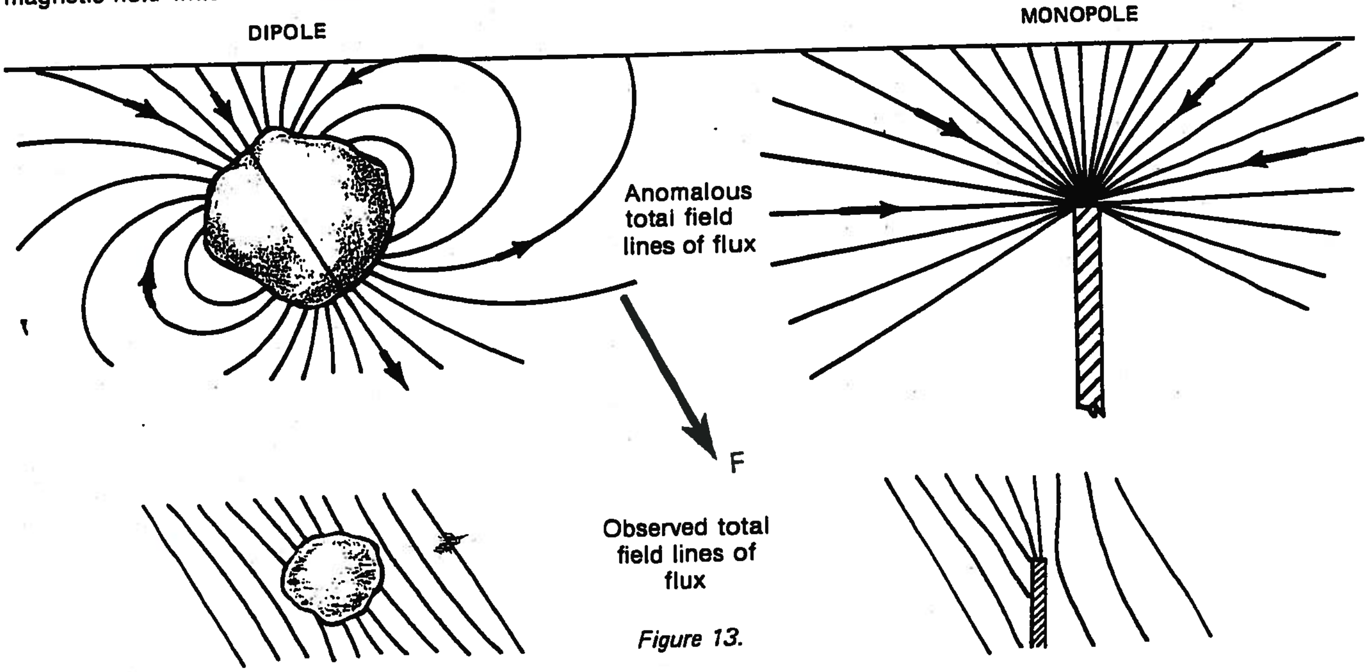


Figure 13.

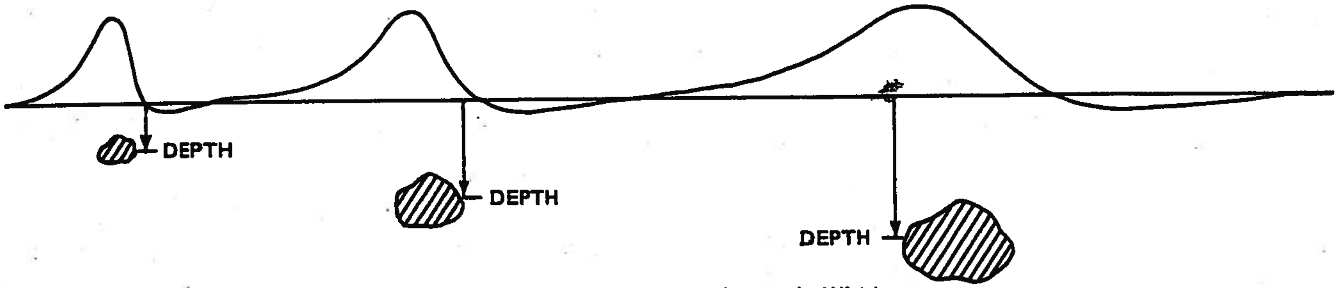


Figure 14. Effect of Depth on Anomaly Width

figuration for such fields as they would appear if one were to measure the direction of the anomalous field.

Depth Dependence

Another significant characteristic of a magnetic anomaly is its variation with the depth between the magnetometer and source, the deeper the source, the broader the anomaly as expressed in *Figure 14.* It is this property which enables one to determine the approximate depth to the source independent of any other information concerning the source. *If one familiarizes himself with only one subject in this discussion on interpretation, it should be the general characteristics of anomaly wavelength, or width, as a function of depth.* A knowledge of this subject allows rapid and easy interpretation of anomalies of interest when numerous anomalies arising from various depths appear in the observed total intensity profile.

Other Anomaly Shape Factors

Other factors which affect the anomaly shape and amplitude are the relative amounts of permanent and induced magnetization, the direction of the former, and the amount of magnetite present in the source compared to the adjacent rocks. The actual configuration of the source, that is, whether it is narrow, broad or long in one dimension and its direction in the earth's field, also control the anomaly signature.

Geological Models

Geological anomalies are interpreted in terms of much simplified geological models which very much facilitate interpretation procedures. The first simplification is the assumption that magnetization is uniform within some elementary prismatic form and that the magnetization is different outside this form, i.e., there is a magnetization contrast. Typical of the kinds of geologic sources that are assumed to cause anomalies are those which are shown in *Figure 15.*

As was stated, in any potential field method the given magnetic signature can be produced by an infinite combination of sources so that there is no unique interpretation. For example, the same anomaly could be produced by the peculiar distribution of magnetite (unrealistic geologically), and a uniform distribution of magnetite within the prismatic form (realistic), both of which are shown in *Figure 16.* It must be emphasized that not only are simplifications required, but a reasonable geologic framework must be used as a guide when considering the various possible sources. A typical set of anomaly signatures of various sources might appear as in *Figure 17.*

Elementary Dipoles and Monopoles

Since anomalies are explained herein in term of various arrays of dipoles and monopoles, it is important to examine their geometry and intensity characteristics. A magnetic dipole produces a field with imaginary lines of flux as shown in *Figure 18.* The intensity of the field, which is proportional to the density of the flux lines is drawn as lines of equal intensity to express this relationship. From *Figure 18,* notice that 1) the intensity of the dipole is twice as large off the ends of the dipole as it is at the same distance off the side of the dipole. This explains, for example, why the earth's magnetic field is approximately 30,000 gammas at the magnetic equator and 60,000 gammas at its poles; 2) the direction of the field off the side of the dipole is parallel to the dipole itself, but opposite in sense; 3) the direction of the tangent of the field lines of a dipole are parallel along any radial line from the dipole.

A monopole has field lines which point radially in or out from the positive or negative monopole respectively. The intensity is constant at a given distance and any direction from a monopole. In actual fact, there are no magnetic monopoles, but only dipoles whose ends are far apart. For all practical purposes, however, monopoles exist in terms of the distance to the source and such geological configuration as shown in *Figure 13.*

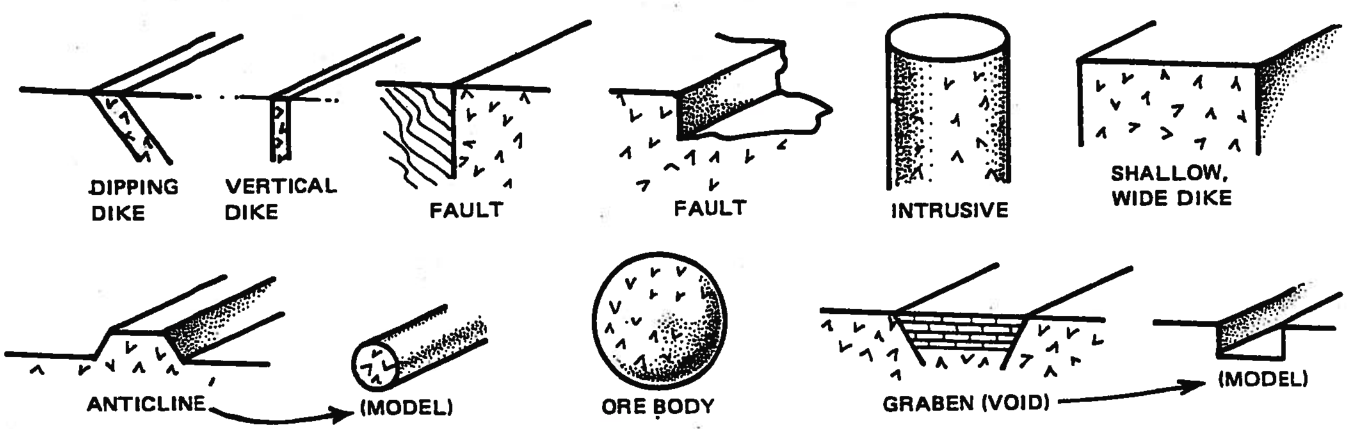


Figure 15. Geological Model Representations of Common Magnetic Anomaly Sources

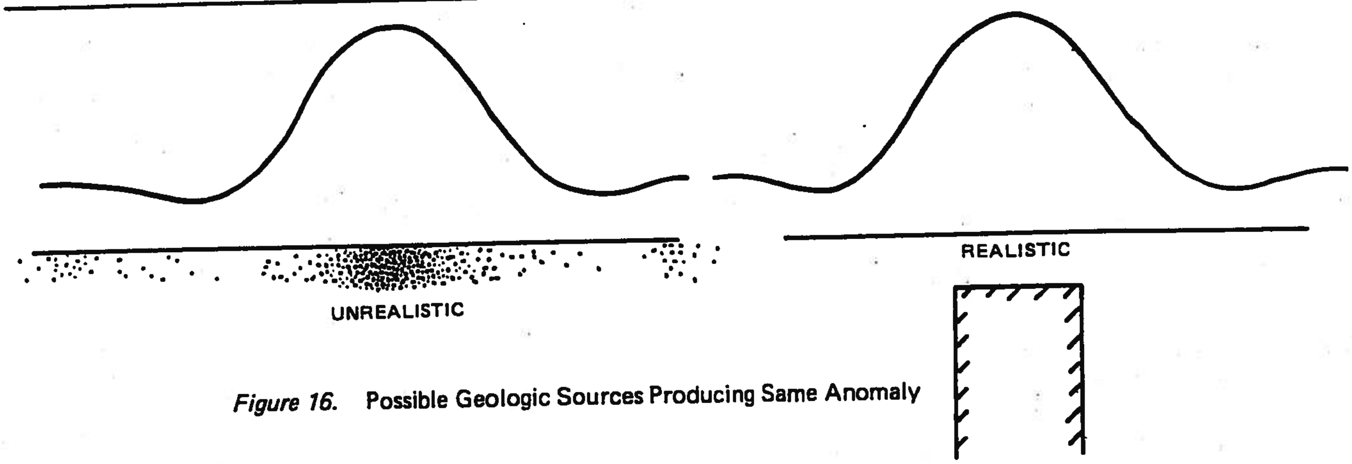
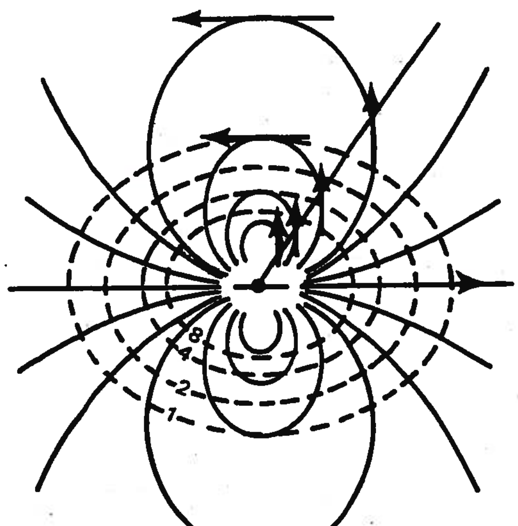


Figure 16. Possible Geologic Sources Producing Same Anomaly



LINES OF FLUX (——)
AND
LINES OF EQUAL INTENSITY (— —)
FOR A DIPOLE

Figure 18.

Having outlined the qualitative geometry of the intensity T from a dipole, the quantitative aspects can be considered as follows:

The intensity, T, from a dipole can be expressed as

$T = \frac{2M}{r^3}$ along the axis, i.e., off the end of the dipole,

and $T = \frac{M}{r^3}$ along a line at right angles to the dipole, i.e., off the side of the dipole,

and for a monopole

$T = \frac{M}{r^2}$ in any direction from a monopole, where

M = magnetic moment and r is the distance to the pole. A more detailed mathematical formulation for the intensity due to a dipole is given subsequently in this Chapter.

Simplified Method for Total Field Signature

From the above description of a dipole and monopole and with the knowledge of the earth's-field-component-nature of the total field magnetometer, it is possible to sketch the signature of an anomaly for any given orientation of the dipole (orientation caused by field direction, the direction of remanent magnetization, or by the configuration of the geology). It is helpful to draw such signatures at various inclinations of the magnetic field to understand where the sources would be located with respect to the signature, the dip of the magnetization producing the anomaly, and even for information related to the depth of the source. Remember that all anomalies can be considered as caused by various distributions of dipolar and monopolar sources and it is possible to produce any anomaly simply by the super-position of such dipole or monopole signatures derived here.

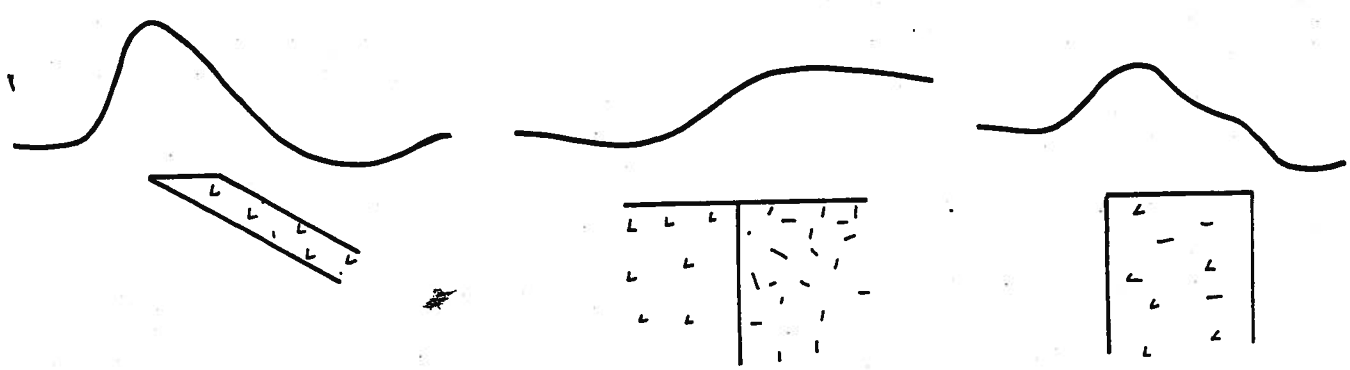


Figure 17. Typical Anomalies for Simple Geologic Models

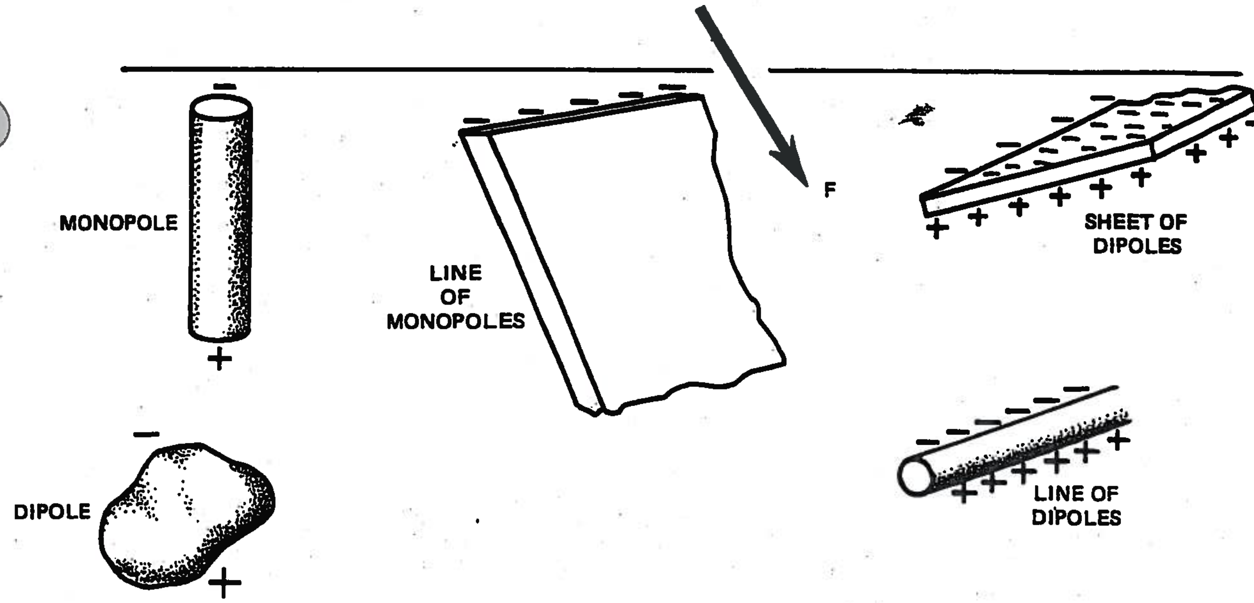


Figure 19.

Earth's Field Component Behavior

This method of predicting or drawing the anomaly signature depends upon one property of the field, namely, inclination, and three properties peculiar to the dipole or monopole source, whichever is assumed. The dip of the earth's field is first considered because this is the direction, the only direction, of the components of any local magnetic anomalies which are measured by a total field magnetometer. (If one is using a vertical component magnetometer, this guide still applies except that instead of using the earth's field as the direction of measurement, simply use the vertical.) In other words, the magnetometer will only measure the component of a local perturbation in this direction, i.e., as projected into this direction. See *Figure 20.*

Dipoles vs. Monopoles vs. Arrays of Poles

The decision to use dipoles, monopoles, or other configurations as the model is based upon the manner in which the earth's field induces a local field and this in turn depends upon the configuration of the geologic body which exhibits the magnetization contrast and the direction of the field. For example, a long body which nearly parallels the earth's field will tend to be magnetized along its long dimension. Furthermore, if the body is sufficiently long with one end near the magnetometer, the anomaly will appear as a monopole seeing only the upper pole with the lower pole removed effectively to infinity. If the same long, thin body were normal to the field, it would then be magnetized through its thinest dimension producing the sheet-like array of dipoles as shown in *Figure 19.*

One may wish to draw on the typical models depicted in *Figure 15,* the array of poles from a uniform earth's field at various inclinations and orientations of the source. Whether the monopoles or the dipoles (and its equivalent line or sheet distributions) are close or far apart, determines if the model is to be considered a dipole or monopole, respectively *(see, for example, Figure 34).*

Configuration of Field Lines

The first property of the dipole or monopole which is to be considered is the configuration of the field lines *(see Figure 13).* When superimposed upon the component which is measured by the total field magnetometer, it can be seen that the relative lengths of the disturbance vectors that are measured are those shown in *Figure 21* for an induced dipole and monopole source. It is the relative length of these disturbance vectors drawn along the total field direction that is measured, each disturbance vector, in turn, weighted by the intensity functions described below.

Dipole and Monopole Fall-Off Factor

The next factor to be considered is the variation of intensity with distance, i.e., $1/r^3$ and $1/r^2$ factors for the dipole or monopole fields respectively and as expressed in the preceding equations. The relative intensity for dipoles or monopoles as a function of distance to their centers as would be observed along a traverse is presented in *Figure 22* and described mathematically under "Anomaly Amplitude" below. This factor multiplies the length of net vectors in *Figure 21.*

Dipole Factor-of-Two

The last consideration really only applies to the dipole and that is a factor of 2 when one is off the end of the dipole compared to a position off the side. In other words, at a given distance, the intensity varies by a factor of 2 as a function of the angle between the radial line to the dipole and the dipole axis. This function is shown approximately in *Figure 23* for the dipole used in the example. The monopole possesses radial symmetry and therefore requires no such consideration.

Application of Method

A dipole and monopole signature is thus constructed in *Figure 24.* The amplitude is dimensionless, but can be compared to a real anomaly by multiplying by a single factor derived below from considerations of volume, susceptibility, etc. However, applying these factors even qualitatively should allow one to draw the dipole and monopole signatures for variously inclined fields and geometries. *Figure 25,* for example, is drawn free-hand for anomalies in vertical field (90° inclination), magnetic equator and mid-southern latitudes. By simply sketching in the earth's field direction and the dipole's field lines

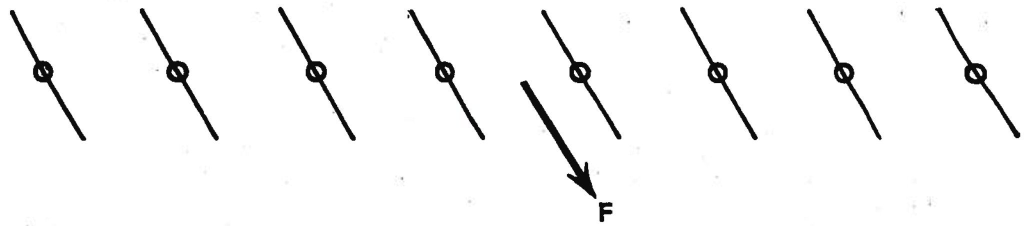


Figure 20. Direction of Components Measured by Total Field Magnetometer

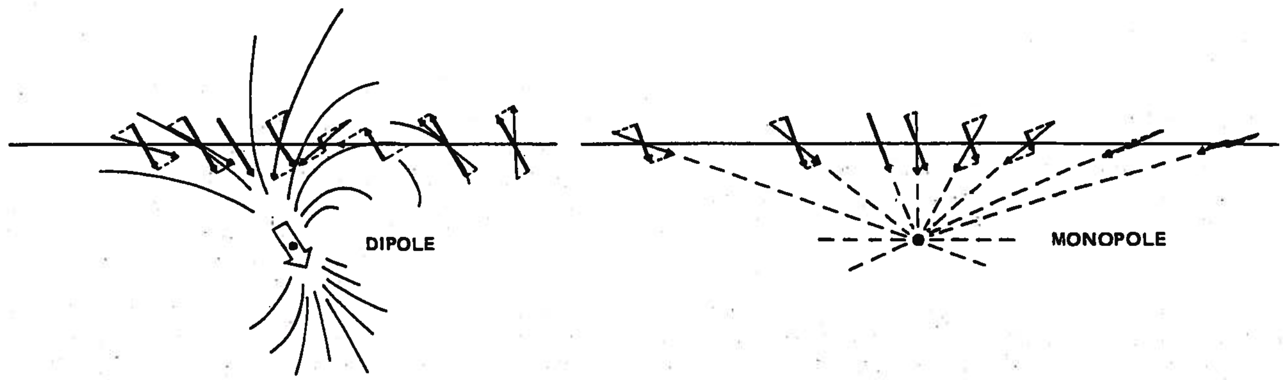


Figure 21. Total Field Components of Tangent to Field Lines of Dipole and Monopole

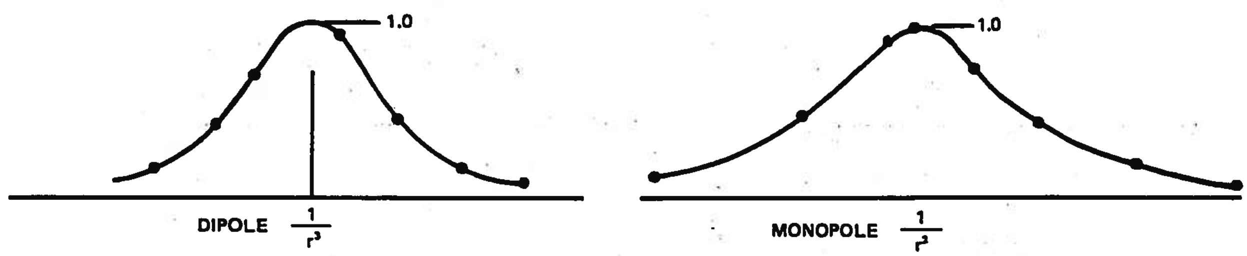


Figure 22. Fall-off Rate
(Relative intensity or length of vectors in Figure 21)

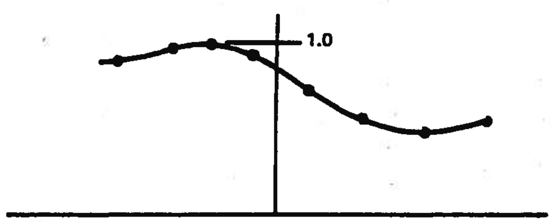


Figure 23. Aspect Factor
(Relative Intensity of Dipole of Figure 21 with Respect to Angle from Axis at Various Points Along Profile)

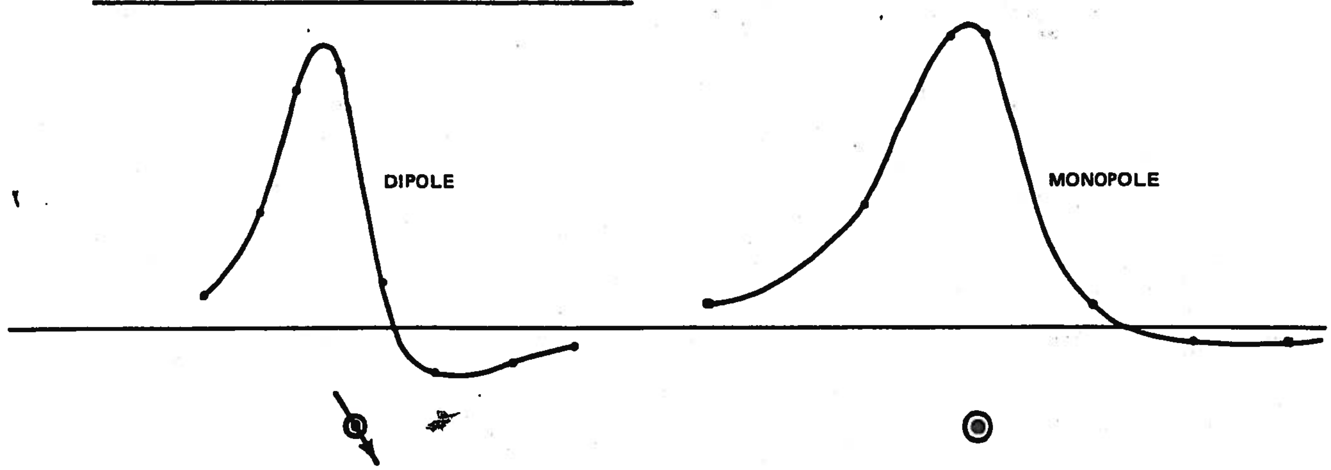


Figure 24. Dipole and Monopole Signatures (Constructed from Figures 20-23 according to methods described in text.)

without consideration of the other last two factors, it is possible to appreciate the basis for:

a negative anomaly over sources at the magnetic equator,

absence of anomalies in the central portion of elongate N-S anomalies at the equator,

both positive and negative fields for almost any anomaly,

changes in anomaly character for different directions of the dipole,

asymmetry of anomalies,

monopole which has only positive sense yet for most inclinations still produces a total intensity anomaly with both positive and negative portions.

The simple exercise of drawing such anomalies may also elucidate other characteristics of signatures, which to many not familiar with magnetics or such behavior as shown here, appear to be complex and difficult to comprehend.

Based upon the above procedures, applied qualitatively, and upon the manner in which lines of flux are induced in various configurations of geologic bodies and ambient field directions and inclinations, it is possible to derive the various signatures shown in *Figure 26* (drawn freehand). By varying the effect of depth as it produces an anomaly of longer wavelength, and by building composite anomalies such as summing the effect of 2 faults to create a single wide, shallow dike, it is also possible to generate a composite curve demonstrating the effect of different sources and different depths which is the typical observation.

Contour Presentation of Dipole and Prism Anomalies

Profiles of total intensity are usually the only form of presentation from ground measurements even when data are taken on a 2-dimensional array. If measurements are taken properly, however, it is possible to construct a contour map by the methods described in Chapter IV. It is therefore useful to examine a few special cases of contour maps that would be expected over simple sources such as a dipole and a wide, vertical prism in various latitudes. Such a contour map also allows one to extract, even by simple inspection, how a given profile would appear at various positions over such simple-shaped forms which is useful information both in search and in

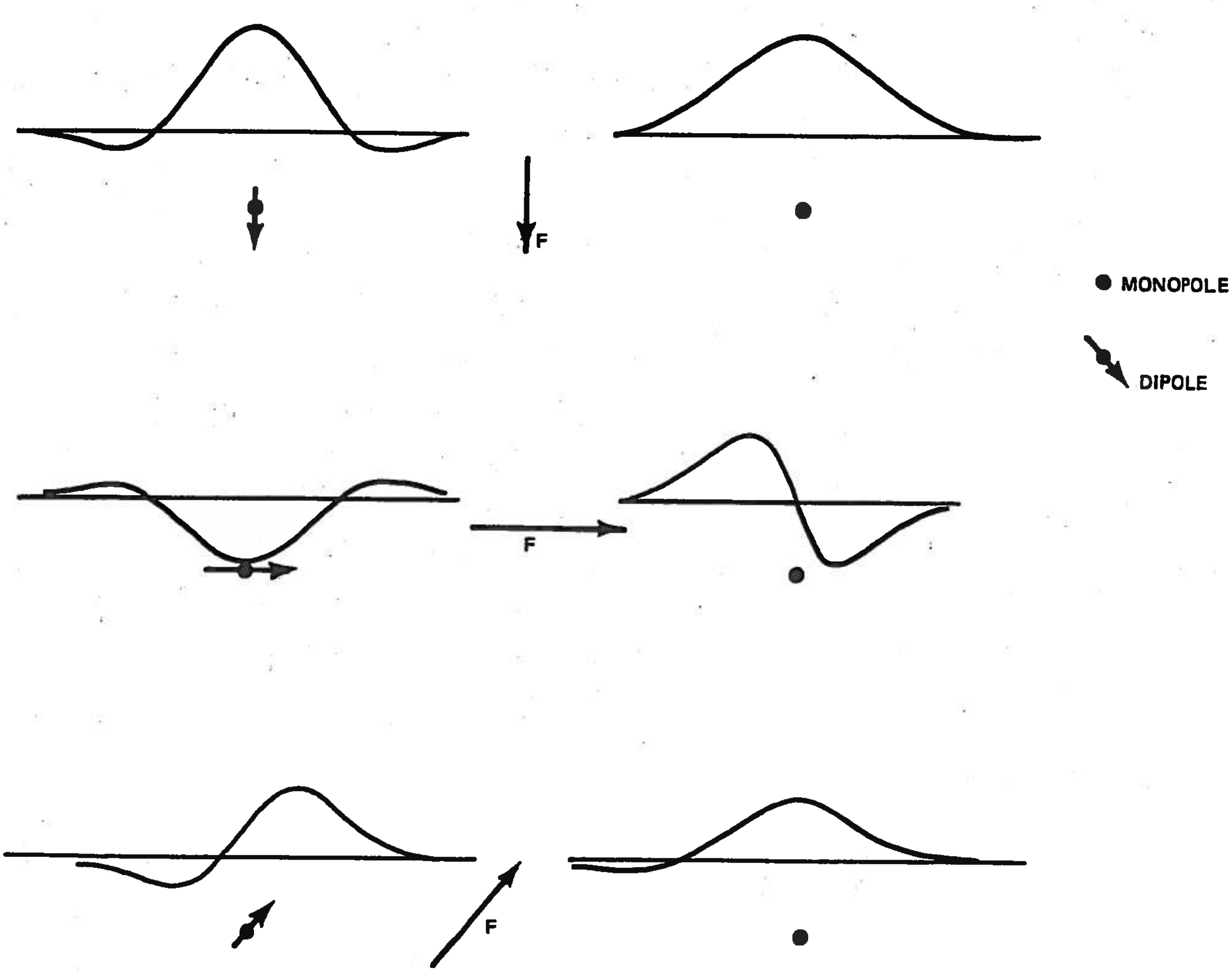


Figure 25. Free Hand Sketch of Dipole and Monopole for Various Inclinations

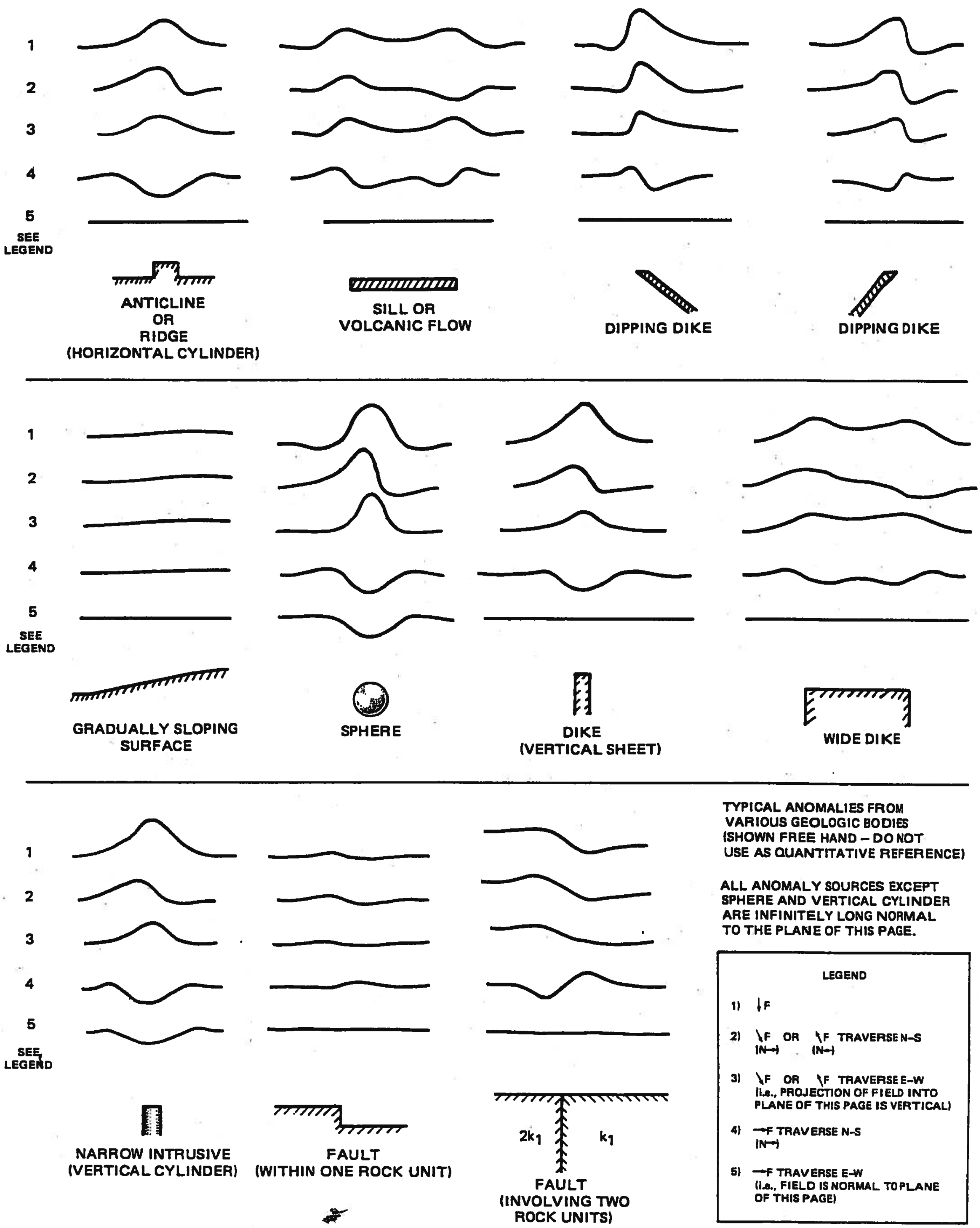


Figure 26. Anomalies for Geologic Bodies at Various Orientations and Different Inclinations of the Field

geological exploration. Contour maps and selected profiles drawn across the anomaly are sketched in *Figure 27.*

Anomaly Amplitude

Amplitude Estimates for Common Sources

The large amplitude commonly observed anomalies (several hundred gammas or larger) are almost always the result of a large magnetization contrast, i.e., change in lithology where one igneous rock is in juxtaposition with another or with a sedimentary or metamorphic rock of much lower susceptibility. It must be remembered that magnetization of common rocks varies over 6 orders of magnitude. Anomalies due to structure alone, i.e., varying configuration of a uniformly magnetized rock, seldom produces anomalies larger than 10 or 100 gammas.

The relative amplitude of a given anomaly (signature) has been shown to be a function of the earth's field direction, the configuration of the source and the remanent magnetization if any. The *maximum* amplitude of an anomaly is, on the other hand, largely a function of the depth and the contrast in the mass of magnetite (or iron, etc. in the case of search), and to a lesser extent, the configuration of the source. It is of interest to be able to estimate the maximum amplitude for a given source in order to 'model' it for the sake of interpretation. This estimated amplitude can be used with the normalized, i.e., dimensionless, anomaly signatures above and in *Figure 26* to produce the anomaly one wishes for comparison with the observed. Estimation of the maximum anomaly amplitude is also useful in planning a survey or planning the grid and coverage necessary in search applications.

For a few generalized configurations, it is relatively simple to estimate the maximum anomaly amplitude (at a single point above the source) assuming a depth, susceptibility and much simplified shape of the source. Expressions are given in the literature for calculation of anomalies of more complex figures and later in this section the calculation of the complete signature, i.e., the amplitude as a function of distance along the profile for a few simple forms. The methods described herein are merely order-of-magnitude techniques, but are useful for the applications covered by the Manual.

Estimation of the maximum anomaly for comparison with a given source requires first that the signature be studied for the nature of the source; namely, whether the source can be approximated as an isolated dipole, monopole, or line or sheet-like array of such. In the case of the latter two, adjacent traverses or a contour map may be required to determine if it is 2-dimensional, i.e., very long normal to the traverse. A depth is then assumed or crudely estimated (according to procedures that follow). In addition, the susceptibility is assumed or if source rocks are accessible, it is measured following methods outlined in Chapter VI. The formulae below can then be used remembering that they are based upon simplifications and assumptions and are often no better than a factor of two.

The basic expression for estimating the maximum amplitude of any anomaly is

$$T = \frac{M}{r^n}$$

where T is the anomaly, M the magnetic moment, r the distance (depth) to the source, and n a measure of the rate of decay with distance, or fall-off rate (n = 3 for a dipole, n = 2 or a monopole, etc.).

Since the magnetic moment M (and k) is usually given in centimeter-gram-second (cgs) units, r must be in centimeters, n is dimensionless and T is in gauss. To express T in gammas, multiply M by 10^5; if r is in feet, multiply r by 30 and raise the quantity 30r to the exponent n, e.g., if the source is a dipole, then n = 3, and if say, r = 2 feet, M = 1000 cgs,

$$\text{then } T = \frac{1000 \times 10^5}{(2 \times 30)^3} = 460 \text{ gammas.}$$

Dipole and Monopole Signatures in Vertical and Horizontal Fields

The very generalized expression for the maximum anomaly one may expect from a dipole or monopole was presented above in its very simplest form. It may be of interest, however, to construct the signature of a dipole or monopole in a vertical or horizontal earth's field as would be observed by a total field magnetometer along a traverse over the source.

Apart from any total field considerations, a dipole has a field with magnitude and direction given by the radial and tangential components, T_r and T_θ, according to the following expression and for the geometry shown.

$$T_r = \frac{2M\cos\theta}{r^3}$$

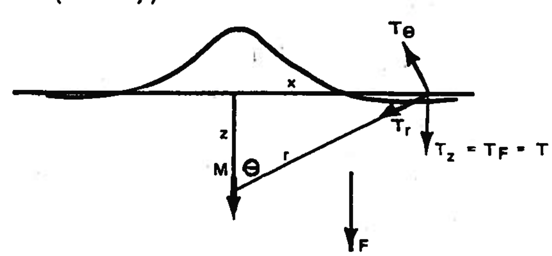
$$T_\theta = -\frac{M\sin\theta}{r^3}$$

Where the earth's field is vertical or nearly vertical (dip 70° to 90°), the dipole, if induced, would also be vertical and the total field magnetometer would measure the component, T_z, along this vertical direction, where

$$T_z = T_r\cos\theta + T_\theta\sin\theta$$

$$= \frac{2M\cos^2\theta - M\sin^2\theta}{r^3}$$

$$= \frac{M(2z^2 - x^2)}{(x^2 + z^2)^{5/2}}$$



As before, $T_z = T_F = T$, the anomaly.

At x = 0, $T = \frac{2M}{z^3}$

at $x = \pm z$, $T = \frac{0.175M}{z^3}$

at $x = \pm\sqrt{2}\,z$, $T = 0$

at $x = \pm 2z$ $T = \frac{-0.04M}{z^3}$

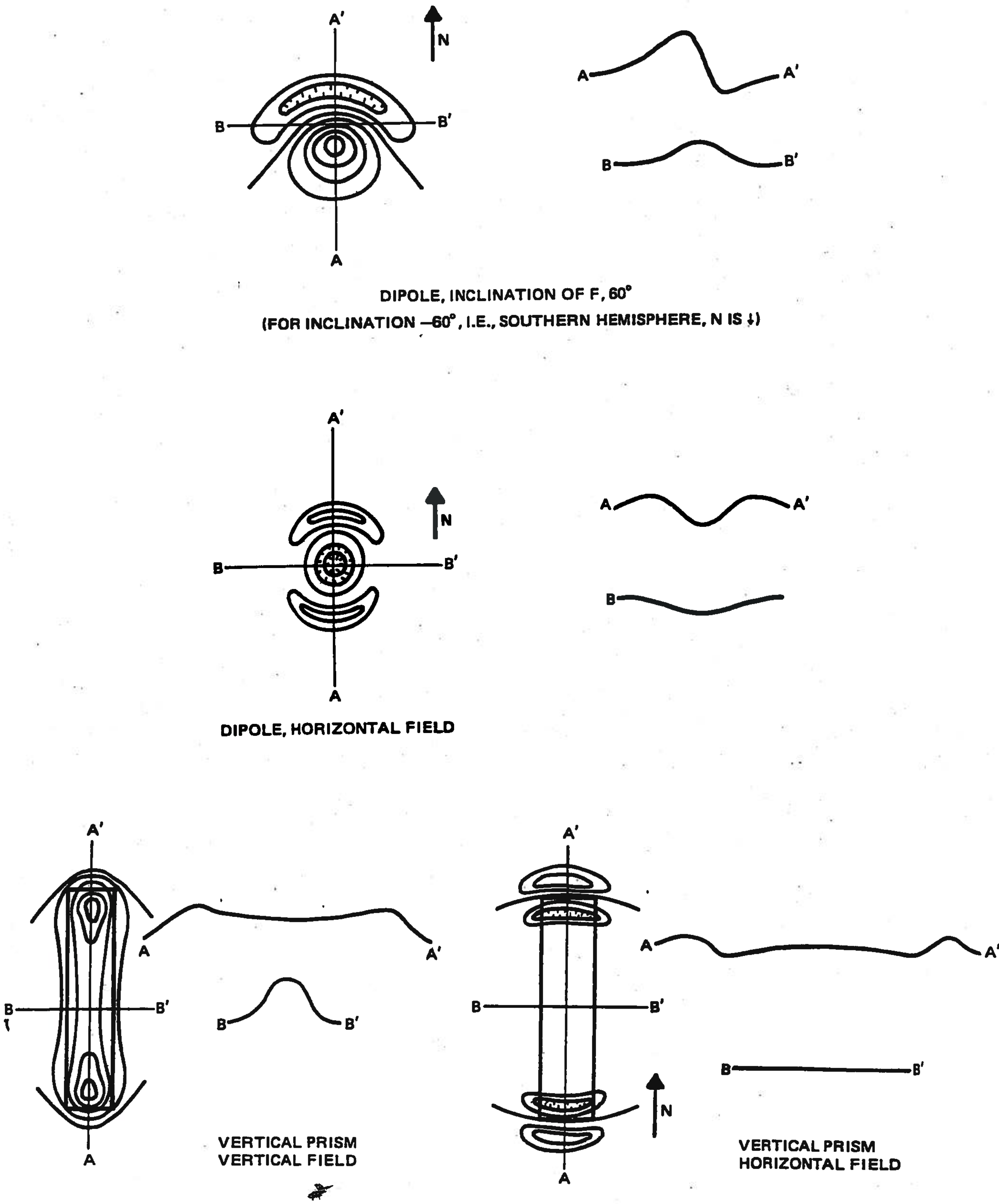
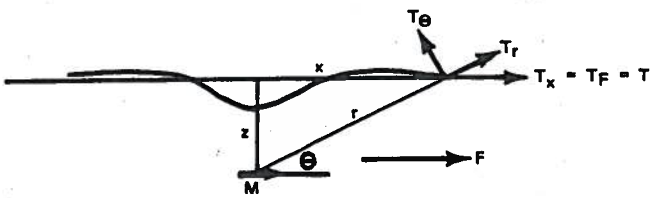


Figure 27. Contour Maps of Total Intensity

For magnetic equatorial fields, the induced anomaly is horizontal and the total field magnetometer would measure the components shown and expressed by

$$T_x = T_r \cos\theta + T_\theta \sin\theta$$

$$= \frac{2\,M\cos^2\theta - M\sin^2\theta}{r^3}$$



$$= \frac{M\,(2x^2 - z^2)}{(x^2 + z^2)^{5/2}}$$

as before, $T_x = T_F = T$ the total field anomaly, where,

at $x = 0$,

$$T = -\frac{M}{z^3}$$

at $x = \pm\frac{z}{\sqrt{2}}$,

$$T = 0$$

at $x = \pm z$,

$$T = \frac{0.175\,M}{z^3}$$

at $x = \pm 2\,z$,

$$T = \frac{0.125\,M}{z^3}$$

The monopole shown here has only radial components whose intensity is expressed by

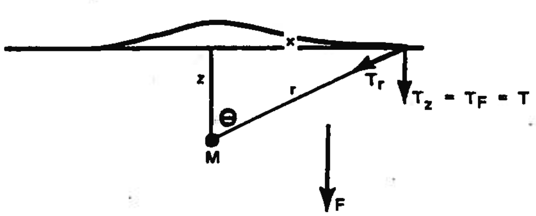
$$T_r = \frac{M}{r^2}$$

The monopole anomaly in a vertical field as measured by a total field magnetometer would be the component in the z direction (vertical) or

$$T_z = T_r \cos\theta$$

$$= \frac{M\cos\theta}{r^2}$$

$$= \frac{Mz}{(x^2 + z^2)^{3/2}}$$



assigning $T_z = T$, the anomaly

at $x = 0$,

$$T = \frac{M}{z^2}$$

at $x = \pm z$,

$$T = \frac{0.35\,M}{z^2}$$

at $x = \pm 2\,z$,

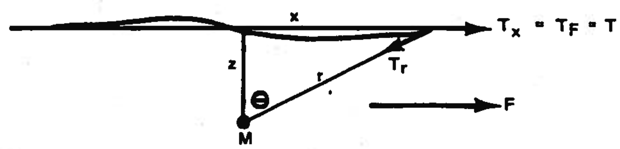
$$T = \frac{0.09\,M}{z^2}$$

The monopole field in a horizontal field would be measured by a total field magnetometer as the horizontal component, T_x where

$$T_x = T_r \sin\theta$$

$$= -\frac{M}{r^2}\sin\theta$$

$$= -\frac{Mx}{(x^2 + z^2)^{3/2}}$$



Again, $T_x = T_F = T$, the anomaly, where

at $x = 0$,

$$T = 0$$

at $x = z$,

$$T = -\frac{0.35\,M}{z^2}$$

at $x = -z$,

$$T = \frac{0.35\,M}{z^2}$$

at $x = 2\,z$,

$$T = -\frac{0.18\,M}{z^2}$$

at $x = -2z$,

$$T = \frac{0.18M}{z^2}$$

Maximum Amplitude Given Magnetization and Generalized Form

The magnetic moment M is more usefully expressed as

$$M = IV$$

where I is the magnetization (i.e., magnetization contrast) per unit volume and V the volume. This magnetization is composed of a usually unknown proportion of remanent magnetization, I_r, and induced magnetization I_i. The latter as expressed in Chapter III is

$$I_i = kF$$

where k is the magnetic susceptibility per unit volume and F the earth's field or ambient inducing field. (NOTE: Since I_r is seldom known, an effective magnetization, $I = I_i + I_r$, will always be used. Also it is assumed that $k < 10^{-2}$, i.e., the source under consideration contains less than 10% magnetite; then one can ignore what is known as demagnetization effects in the calculation of anomaly amplitude).

Therefore, for a dipole which can always be assumed for a source all of whose dimensions are small with respect to the distance (less than ⅕ or 1/10) to the magnetometer,

$$T = \frac{M}{r^3} = \frac{IV}{r^3} = \frac{kFV}{r^3}$$

If the source is approximately spherical, then

$$T = \frac{kF\left(\frac{4}{3}\pi R^3\right)}{r^3}$$

where R is the radius of the source as in *Figure 28*

If the measurement is made along the axis of the dipole (see *Figure 29*), then

$$T = \frac{2kF\left(\frac{4}{3}\pi R^3\right)}{r^3}$$

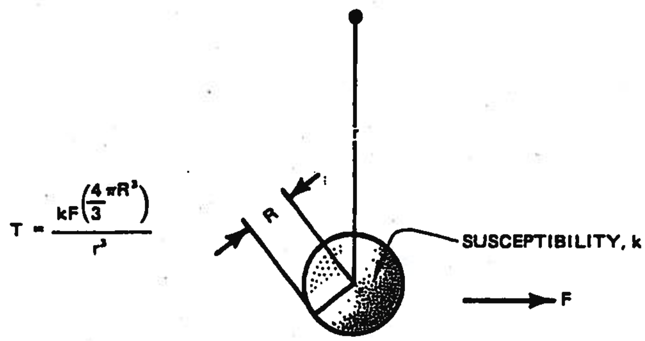


Figure 28. Anomaly of Sphere in Horizontal Field

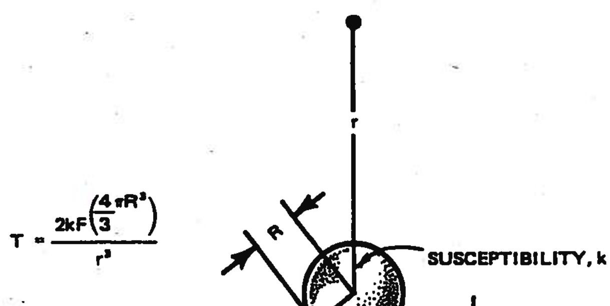


Figure 29.
Anomaly of Sphere in Vertical Field

As an example, consider an ore body 100 feet wide (R = 50), 500 feet deep comprised of 10% magnetite (k = 0.3), in a steeply dipping field (60° to 90° latitude) in a field of 60,000 gammas:

$$T = 2\,(0.10 \times 0.3) \times 6 \times 10^4 \left(\frac{4\pi}{3}\right)\left(\frac{50}{500}\right)^3 = 14.4 \text{ gammas}$$

For the same ore body in an equatorial field where F = 30,000 gammas and the induced dipole is now observed at a point on a line normal to the axis (no factor of 2)

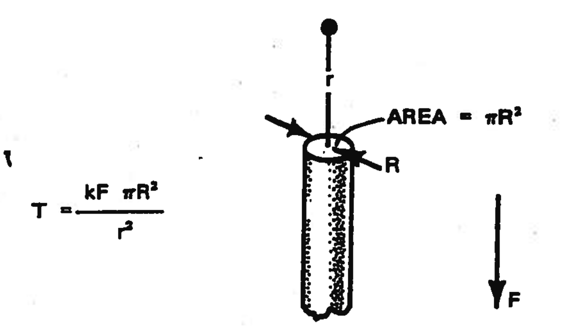
$$T = -3.6 \text{ gammas}$$

Thus a given dipolar source in an equatorial field will have only ¼ the maximum anomaly amplitude it would have in a polar region.

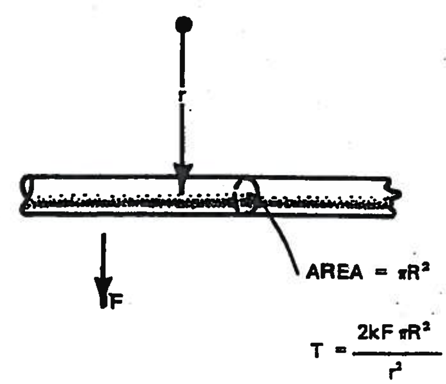
The above expressions are usually valid only for such sources as a small distant ore body (containing magnetite), small structure in deep basement, or most objects involved in search applications (see Chapter VII). The magnetization is expressed in gauss or gammas as desired. Since the anomalies are also expressed in terms of magnetic units, it follows that the units of dimension in the numerator must be of the same order as the denominator since they must cancel. Therefore, for a dipole whose anomaly varies as $\frac{1}{r^3}$ (said to have a fall-off of $\frac{1}{r^3}$), the volume, V, has dimensions of R^3. In the case of a monopole, which varies as $\frac{1}{r^2}$, the magnetic moment, M, is equal to IA where A is surface area and has dimensions of R^2. Consider for example, a vertical basement intrusive in a polar region with an upper surface 1000 feet in diameter at a depth of 5000 feet, with a susceptibility contrast of 10^{-2} in a field of 60,000 gammas. Thus,

$$T = \frac{kF\,\pi R^2}{r^2} = 10^{-2} \times 6 \times 10^4 \times \pi\left(\frac{50}{500}\right)^2 = 18 \text{ gammas.}$$

Horizontal prisms or cylinders also vary as $\frac{1}{r^2}$, with magnetic moment M equal to 2IA (IA for E-W horizontal prisms in equatorial regions) where A is the cross-sectional area of the prism *(see Figure 30)*. (NOTE: The long horizontal prism varies as $\frac{1}{R^2}$ not because it appears to be comprised of a monopole, but because it is a line of dipoles (in steeply dipping fields) and the effect of adjacent dipoles along an infinitely long line is 'seen' more by the magnetometer at a distant point of measurement than if all the magnetization were concentrated at a point as in an isolated dipole).



(NOTE: ALSO VALID FOR END OF N–S HORIZONTAL CYLINDER IN HORIZONTAL FIELD)



(NOTE: ALSO VALID FOR E–W HORIZONTAL CYLINDER IN HORIZONTAL FIELD)

Figure 30. Anomaly of Vertical and Horizontal Cylinders

A narrow, vertical dike in steep field or the edge of a horizontal sheet in a horizontal field can be considered as a line of monopoles varying as 1/r which is a lower rate of fall-off than a single monopole for the same reasons given above for a horizontal cylinder *(see Figure 31)*. The magnetic moment M = It where t = width of dike. Since the anomaly varies as 1/r, the dimensions of t are simply length. As an example, a vertical dike might be 100 feet wide, at a depth of 500 feet, with $k = 10^{-3}$ in a field of 50,000 gammas, or

$$T = \frac{kFt}{r} = \frac{10^{-3} \times 5 \times 10^{4} \times 10^{2}}{5 \times 10^{2}} = 10 \text{ gammas}$$

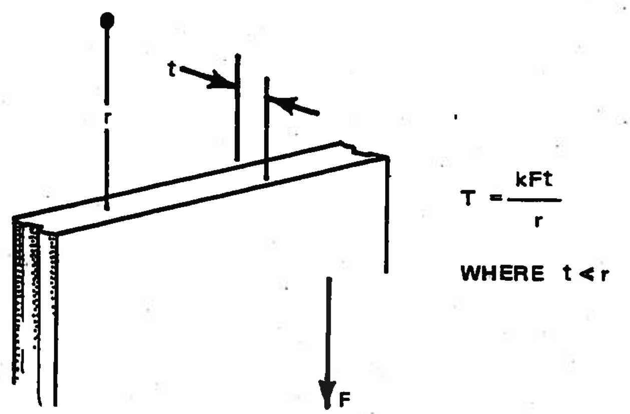


Figure 31. Anomaly of Narrow Vertical Dike

A common point of ambiguity arises with such simplified schemes as these in the case of a dike which is nearly as wide as it is deep. In this case, the anomaly is approximated as something between a line of monopoles as above and a sheet of monopoles as shown in the following. Moreover, as the dike is even wider than its depth, it can be approximated simply by 2 faulted contacts with 'no anomaly' in between.

For a semi-infinite slab of material such as a rock surface of great thickness and breadth in a non-horizontal field, the flux lines do not vary in direction or density above the slab, therefore the field does not vary at all with distance to its surface (similar to the limit of the spherical dipole above where R = r) so that

$$T = \frac{M}{r^{0}} = \frac{2\pi I}{1}, \text{ or } T = 2\pi kF$$

which is useful in estimating the magnitude of the anomaly at a vertical fault *(see Figure 32)*. For example, consider two rock types at a vertical contact of $k = 10^{-3}$ and $k = 10^{-5}$ for an effective susceptibility contrast of $k = 10^{-3}$ ($10^{-5} \approx 0$ relative to 10^{-3}) and where F = 50,000 gammas. Thus

$$T = 2\pi \times 10^{-3} \times 5 \times 10^{4} = 300 \text{ gammas}$$

If the rocks had $k = 10^{-4}$ and 10^{-3}, the effective susceptibility contrast would be

$$10^{-3} - 10^{-4} = 10 \times 10^{-4} - 10^{-4} = 9 \times 10^{-4} \text{ and}$$

$$T = 2\pi \times 9 \times 10^{-4} \times 5 \times 10^{4} = 270 \text{ gammas}$$

This simple example of two adjacent rock types is probably applicable in more instances in interpretation than any of the other geometries discussed above.

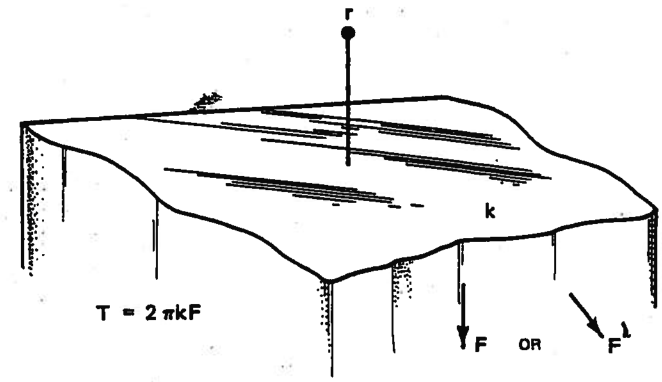


Figure 32. Anomaly of Semi-infinite Slab

Anomaly Depth Characteristics

In a very approximate fashion, the wavelength, or, effective width (or 'half-width' described in the following) of the anomaly and, with more accuracy, the width of certain characteristics of the anomaly such as slope, are measures of the depth to its source. However, recognition of the anomaly, the anomaly 'zero' and certain slopes would not only appear as different values as determined by different interpreters, but they also depend upon what is removed as the regional gradient. More objective criteria are used in some cases such as the nearly straight portions of a slope, and distances and angles between inflection points, peak values and other anomaly characteristics.

Anomaly Width

In general, the anomaly width as shown in *Figure 33* is on the order of 1 to perhaps 3 times the depth. Thus, when an anomaly appears to have a width as such of 100 feet, it is definitely not produced by a source at 1000 feet or at 10 feet, but more likely by a source between 30 and 100 feet deep (or distant). Such criteria, approximate as it is, is nevertheless useful for cursory interpretation of profiles and maps.

Anomaly Depth Estimation

Much is written on the variety and relative merit of methods for estimating the depth to the source of anomalies. Since the magnetometer is primarily a tool for subsurface mapping and detection, it follows that determination of the depth as well as edges of bodies is important in its application to geological exploration and search. The basis for depth determination is presented here in brief which, together with the foregoing background on anomaly behavior, should allow one to at least appreciate how a variation in depth affects an anomaly. In most cases, one needs only to apply this knowledge qualitatively through visual inspection of a profile. Whatever the requirement, depths may be estimated by visual inspection, several rules of thumb, modeling (i.e., calculation of assumed source and comparison with observed), measured gradient techniques (see Chapter VIII), or various computer-oriented procedures. As was demonstrated earlier, a given anomaly could have an infinite number of possible sources and source depths, but the realistic models that are assumed usually produce maximum depth estimates.

Knowledge of the depth of a particular formation or source may have considerable geological significance as it determines the nature or configuration of a forma-

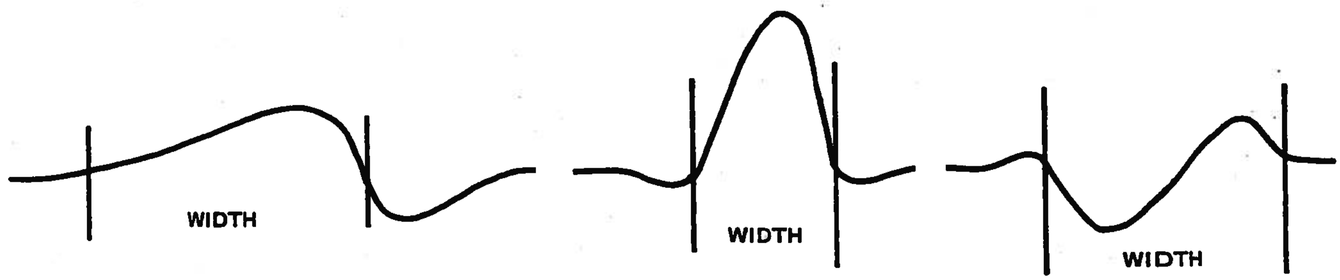


Figure 33. Anomaly 'Width'

tion, the slope of its surface and its discontinuities. The depth to various points on the surface of crystalline rock or magnetic basement allows one to map that surface and its topography and structures to depths exceeding 30,000 feet and to infer thickness of sediments or conformable sedimentary structures above it for exploration of petroleum, sedimentary ores, placer deposits or groundwater. Areas underlain by pediment or other sedimentary deposits may be ruled economic or noneconomic according to depth. The depth to ore deposits associated with pyrrhotite, magnetite or ilmenite may be estimated as an aid to a drilling program or even for estimation of total tonnage of magnetic iron ore deposits. Black sand deposits of rutile, zircon, monazite, diamonds, gold, platinum, etc. are often associated with other high density, very resistant yet magnetic minerals, namely, magnetite or ilmenite. The depth to objects of search whether buried iron or man-made structures is invaluable in guiding the subsequent excavation efforts.

Identification of Anomaly

The anomaly of interest must be identified and discriminated against the obscuring effects of others. Recognition of the anomaly itself is usually the most difficult aspect of depth determination because of the composite effects of multiple sources, sources at various depths and at various distances in any direction from the magnetometer. Only the net effect of all anomalies are measured by the magnetometer since it has no inherent discrimination ability at the disposal of the operator. The anomaly should be inspected to ascertain the probable source and, if complex, the possible combination of sources. For example, a wide, shallow dike will appear as two anomalies which may or may not coalesce depending upon the relative width and depth. A very broad anomaly or regional gradient (described in Chapter IV). is usually caused by anomalies which are extremely deep or distant or by the normal variation in the earth's magnetic field. If one wishes to remove this gradient, it can be done either by drawing a straight line through the non-anomalous portions of the profile (away from the anomaly of interest) or by drawing a very smooth but broad wavelength curve through the data of much longer wavelength than any anomalies of interest. This regional gradient or background is then subtracted from the anomaly and the remaining, or residual anomaly, replotted. It is this anomaly which is then interpreted for either depth or for amplitude or general configuration of sources as described in Chapter IV.

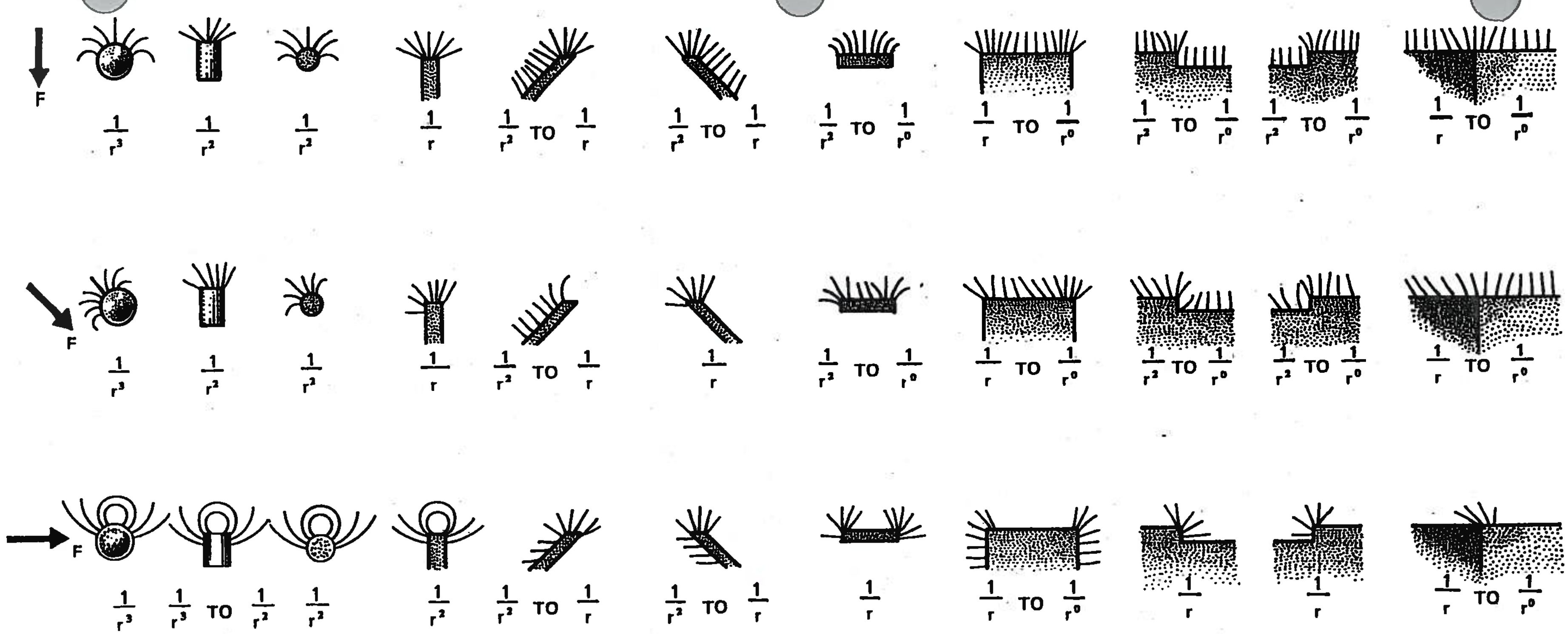
Fall-Off Rate

The variation of anomaly amplitude with distance, or fall-off rate, is important in the interpretation of anomalies for it relates the anomaly to depth, it describes in a general way the configuration of the source, and it assists in determining susceptibility and mass of the causative magnetite. Recall that the anomaly from a dipole varies as $\frac{1}{r^3}$ and that of a monopole as $\frac{1}{r^2}$. The fall-off rate, in actual practice, does not involve precisely such factors or exponents but, in fact, is typically $\frac{1}{r^{2.5}}$, $\frac{1}{r^{0.6}}$, etc., or even $\frac{1}{r^0}$ as described above. In other words, various configurations of dipoles, monopoles, lines and sheet-like distributions of these poles constitute a continuous series of fall-off rates even in the vicinity of a single anomaly as one is much closer or further away from the source.

Representing various geologic sources as simple prismatic bodies, one may assume the following fall-off rates: a dipole will be produced by a source all of whose dimensions are small (less than $1/10$ compared to the distance between the source and magnetometer). Such a body is rarely seen in nature except as a very confined, usually magnetite-rich ore body. A monopole varying as $\frac{1}{r^2}$ will be produced by a long, thin, vertical prism, such as a narrow vertical intrusive in steeply dipping fields or a horizontal cylinder striking N-S in equatorial fields (e.g., a N-S anticlinal structure on the basement, one end of which is near the magnetometer). A line of dipoles is produced by a long, horizontal cylinder magnetized through its short dimension as in steeply dipping latitudes or striking E-W in equatorial regions. Such a cylinder will also vary as $\frac{1}{r^2}$. A line of monopoles would effectively be observed near one edge of a dike dipping in the direction of the field and would vary approximately as $\frac{1}{r}$. At a point above a horizontal semi-infinite sheet, the field would vary inversely as $\frac{1}{r^0} = 1$, which is another way of expressing the fact that the field does not vary at all with distance from a horizontal semi-infinite sheet of monopoles or dipoles. A wide vertical dike in a steep field or the edge of a fault might represent combinations between a line of dipoles or sheet-like distribution of monopoles and may thus vary as $\frac{1}{r^2}$ or $\frac{1}{r^{0.5}}$ or less. *Figure 34* indicates these variations.

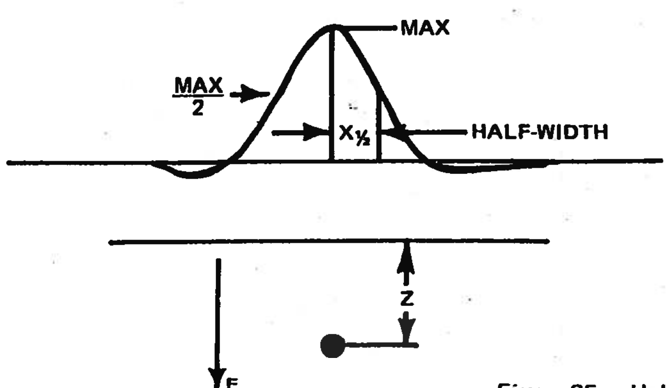
Assumptions on Maximum Amplitude and Depth Estimates

Unless the remanent magnetization is actually measured, it is generally disregarded, and only the induced magnetization and susceptibility are utilized in these expressions. The magnetic anomaly calculated from these



(FLUX LINES SUPERIMPOSED ON REPRESENTATIVE GEOLOGIC MODELS FOR VARIOUS ORIENTATIONS OF INDUCING FIELD. ANOMALY AMPLITUDE PROPORTIONAL TO INDICATED TERM OF $1/r^n$.)

Figure 34. Field Lines and Fall-Off Rates of Various Geologic Models



SPHERE (DIPOLE)	$Z = 2X_{1/2}$
VERTICAL CYLINDER (MONOPOLE)	$Z = 1.3X_{1/2}$
EDGE OF NARROW DIKE (LINE OF MONOPOLES)	$Z = X_{1/2}$
HORIZONTAL CYLINDER (LINE OF DIPOLES)	$Z = 2X_{1/2}$

Figure 35. Half-width Rules — Vertical Field

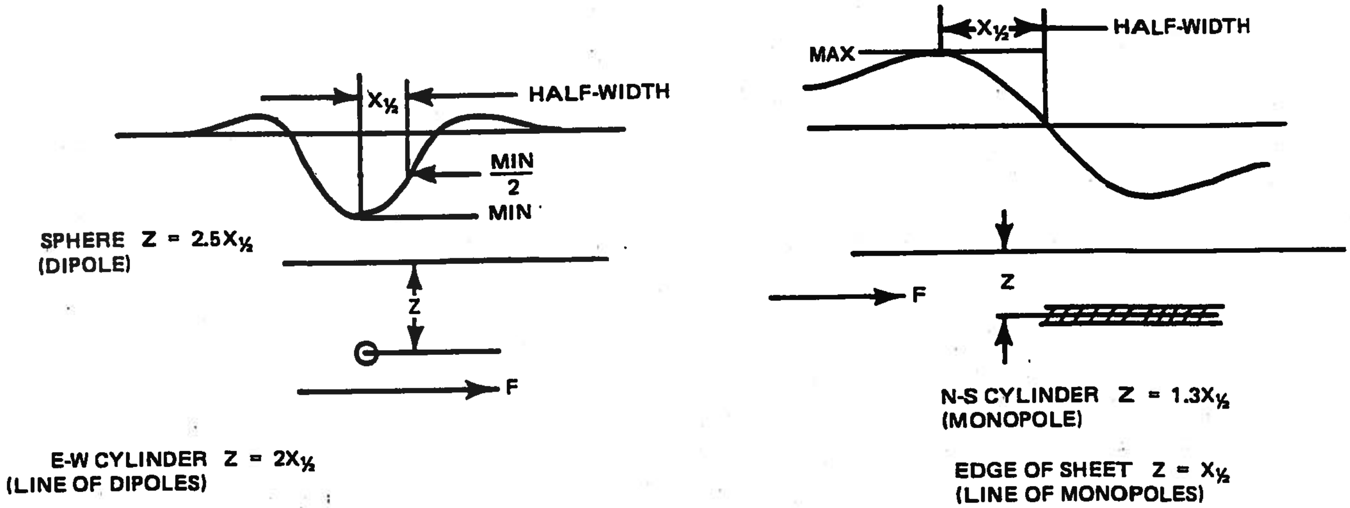


Figure 36. Half-width Rules — Horizontal Field (Equatorial)

highly simplified expressions represents the maximum amplitude from the local zero, non-anomalous field to the positive peak value in the northern and sourthern latitudes and to the minimum negative value in equatorial regions. It does not represent the peak-to-peak value which includes both positive and negative portions of the anomaly signature. The depth estimates derived from any of the techniques described are seldom more accurate than 10% of the actual depth and sometimes as poor as 50%. By theory most of the estimates are maximum estimates so that the actual source will actually be at a shallower depth. Moreover, the 'poles' or source described frequently throughout their chapter are within the geologic body or object of search and not simply on the surface; therefore, such depths are again maximum depths.

Half-Width Rules

In vertical or horizontal fields, it can be shown, from the previous expressions for dipoles and monopoles, that for simple forms of anomaly sources, the depth to their centers is related to the half-width of the anomaly. The half-width is the horizontal distance between the principal maximum (or minimum) of the anomaly (assumed to be over the center of the source) and the point where the value is exactly one-half the maximum value *(see Figure 35)*. This rule is only valid for simple-shaped forms such as a sphere (dipole), vertical cylinder (monopole), and the edge of a narrow, nearly vertical dike (line of monopoles) in the polar regions. At the magnetic equator, the half-width rules are somewhat different with the sphere remaining unchanged, an E-W horizontal cylinder being a line of dipoles, a N-S cylinder being a monopole, and the edge of an E-W striking horizontal sheet representing a line of monopoles. The rules presented in *Figure 36* apply according to the corresponding array of poles and in the case of the latter two, the half width being the horizontal distance between the point of maximum (or minimum) and zero anomaly. The half width rules are derived from formulae given above in "Dipole and Monopole Signatures in Vertical and Horizontal Fields".

Slope Techniques

Perhaps the most commonly used set of methods for estimating depth are those which utilize criteria involving the measurement of the horizontal gradient or slope at the inflection points of the anomaly. Based upon empirical observations utilizing computed models, these slopes are measured according to the horizontal extent of the 'straight' portion of the slope *(see Figure 37)* or the horizontal extent determined by different combinations of the tangent or slope at the inflection point, maximum of the anomaly and half slopes, etc. Each of these horizontal distance measurements when multiplied by an empirically-determined factor equals the depth to the top of the anomaly source. (The straight-slope, for example, is multiplied by a factor between 0.5 and 1.5). Detailed explanations of these methods are available in the references cited.

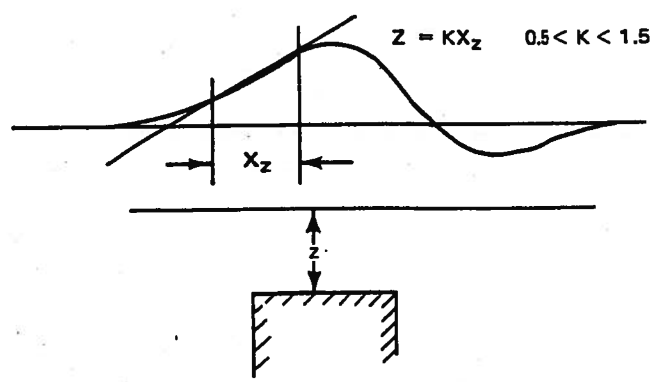


Figure 37.

Other Depth Estimating Methods

Modeling techniques require that one examine the observed anomaly for its likely source configuration. A model is assumed, the anomaly calculated, compared with the observed and repeatedly altered until a satisfactory fit to the observed data is finally achieved, with such work usually performed on a computer. Other computer-oriented depth estimating methods include programs utilizing Fourier and Hilbert transforms, convolution and other semi-automated programs which are usually applied to large volumes of data. Gradiometer measurements made with sensors at two points usually vertically arranged can also be used for depth estimates (see Chapter VIII).

Interpretation Summary

Interpretation is facilitated if one can thoroughly familiarize himself with how and why a given source produces an anomaly in the earth's field, the nature of total field measurements and the general behavior of an anomaly signature with increasing depth. What at first may have appeared complex in the interpretation of field profiles and maps is more readily understood when the above phenomena are examined one at a time.

The first procedure that should be followed in the interpretation of a given profile is to focus on the anomaly width and shape and attempt to construct at least a mental image of the source in realistic geologic terms (or object in the case of search) and its depth. Use the eye to discriminate against noise and the regional gradient or filter by one of the suggested techniques. Anomalous horizontal gradients should then be used, for lack of any other specific criteria, as an indicator of the edge of subsurface structures producing a magnetization contrast. Most anomalies on any given profile or map represent a simple contrast in magnetization or lithology, i.e., the edge of a body. Attempt to correlate such features on adjacent lines or interpret them as contacts on a total intensity contour map. The cessation, displacement or interruption of otherwise long or continuous features may also represent significant geologic structural information. However, one must realize also that a magnetic survey is only able to map a contact where there is a magnetization contrast so that, for example, different lithologies on either side of a long continuous fault will be mapped only in segments where such contrasts occur.

Changes in the character of the short wavelength anomalies (noise) may also represent mappable information if one is careful to evaluate their typical depth so as not to be mapping irrelevant soil anomalies. Negative anomalies arising from features of locally lower magnetization are as important geologically as the more common positive anomalies. Furthermore, the *most geologically significant anomalies on a given map are probably the more subtle ones and not necessarily the largest, most prominent anomalies.* Lastly, the total intensity profiles and maps are not an end in themselves, but are rendered usable only when expressed in terms of geology (or objects of a search). The more geological information one has (or size, magnetic or depth information for an object of search) the more valuable the total intensity data becomes and vice-versa.

WORK PLAN FOR SUPPLEMENTAL SITE INVESTIGATION

PREPARED FOR:

HERCULES, INC.

CHEMICAL SPECIALTIES

HATTIESBURG, MISSISSIPPI

APRIL, 2003

PREPARED BY:

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<u>FIGURES</u>

<u>APPENDICES</u>

1.0 INTRODUCTION

Eco-Systems, Inc. (Eco-Systems) has been retained by Hercules Incorporated (Hercules) to conduct supplemental site investigation at the Hercules facility in Hattiesburg, Mississippi. The site location is shown on Figure 1. The supplemental site investigation is being conducted in response to a request from the Mississippi Department of Environmental Quality (MDEQ) in a letter dated February 3, 2003. The February 3, 2003 letter from MDEQ was sent after review by the MDEQ of the *Interim Groundwater Monitoring Report* (Eco-Systems, January 2003). *The Interim Groundwater Monitoring Report* was submitted voluntarily by Hercules after receipt of groundwater analytical results for groundwater monitoring conducted in accordance with the *Hercules' Site Investigation Work Plan* (Eco-Systems, February 1999) and additional comments of the MDEQ approval letter dated April 5, 1999.

1.1 BACKGROUND

Work conducted under the previous *Hercules Site Investigation Work Plan* centered on efforts to determine whether the miticide, Dioxathion, was present in site soil and groundwater. The work plan included installation of 5 groundwater monitoring wells (MW-7, MW-8, MW-9, MW-10, and MW-11) to add to the 6 existing groundwater monitoring wells installed at the site during prior investigations. Monitoring wells MW-7, MW-8, MW-9, MW-10 and MW-11 were installed to provide groundwater quality information near the former Dioxathion production area and near former wastewater sludge pits. The work also included installation of 14 temporary piezometers and 4 staff gauges. The piezometers and staff gauges were installed to provide hydrogeologic information in the uppermost saturated interval and to establish the relationship, if any, of the uppermost saturated interval to Green's Creek. Monitoring wells, piezometers, stream gauges, and other sampling locations installed or implemented during the previous site investigation are shown on Figure 2. Field activities for the previous site investigations were conducted between April 1999 and March 2003. The results of the site investigations are discussed in the *Interim Groundwater Monitoring Report* (Eco-Systems, January 2003) and the *Hercules Site Investigation Report* (Eco-Systems, April 2003).

The findings of the site investigations that are discussed in the *Interim Groundwater Monitoring Report* and the *Hercules Site Investigation Report* included the detection of volatile organic compounds (VOCs) at concentrations above Target Remediation Goals (TRGs) identified in the MDEQ Brownfields program in groundwater samples collected from monitoring wells MW-4, MW-8, MW-9, and MW-11. The highest concentrations of VOCs were detected in the groundwater sample collected from monitoring well MW-8. Monitoring well MW-8 is located near the former dioxathion production area.

The February 3, 2003 letter from MDEQ requested that Hercules submit this supplemental site assessment work plan to delineate the vertical and horizontal extent of VOCs detected in shallow groundwater at the facility. The letter from MDEQ also requested that Hercules conduct a geophysical investigation to delineate the lateral limits of the closed landfill on the site and to locate accumulations of buried metal within the landfill. The MDEQ letter requested the location of buried drums; however, geophysics will allow for the identification of magnetic anomalies in subsurface soils that may be interpreted as accumulations of buried metallic objects.

1.2 Purpose and Scope

The purpose of this supplemental site investigation will be to investigate the lateral and vertical extent of the VOCs that were detected in the groundwater samples collected from monitoring wells MW-4, MW-8, MW-9, and MW-11. The supplemental site investigation will also include a geophysical investigation to delineate the lateral limits of the landfill and, if possible, locate accumulations of buried metal.

The scope of this investigation will include the following:

- Mobilize a hydraulic probing unit to the site,
- Install probe borings and temporary monitoring wells, as necessary,
- Collect groundwater samples and have those samples analyzed for constituents of concern,
- Collect hydrogeologic information from probe borings and temporary monitoring wells,
- Evaluate the lateral limits of the constituents of concern in groundwater and the effectiveness of the existing monitoring well system,
- Conduct single well response tests and analyze the test data to provide hydraulic conductivity estimates,
- Conduct a geophysical survey to delineate the lateral boundaries of the waste in the former landfill area and locate accumulations of buried metal within the landfill area, and
- Prepare a supplemental site characterization report.

2.0 SITE SETTING

2.1 Facility Location and Site Description

The Hercules facility is located on approximately 200 acres of land north of West Seventh Street in Hattiesburg, Forrest County, Mississippi. More specifically, the Site is located in Sections 4 and 5, Township 4 North, Range 13 West, just north of Hattiesburg, Mississippi (Figure 1). The facility has been in operation since 1923. The facility is bordered to the north by Highway 43 and Illinois-Central & Gulf Railroad, along with various residential and commercial properties. The southern property boundary is bordered by 7th Avenue; and by a cemetery and Zeon Chemical Company to the southwest. Across from these locations are residential areas. The eastern and western boundaries are bordered by sparsely populated residential areas.

The facility's historical operations consisted of wood grinding, shredding extraction, fractionation, refining, distillation, and processing of rosin from pine tree stumps. Historically, over 250 products were produced from the above-referenced operations and included: modified resins, polyamides, ketene dimer, crude tall oil wax emulsions, and Delnav, an agricultural miticide. Structures at the facility include offices, a laboratory, a powerhouse, production buildings, a wastewater treatment plant, settling ponds, a landfill, and central loading and packaging areas.

2.2 Topography and Surface Drainage

Surface water drainage patterns at the Site conform generally to the topography which slopes toward Green's Creek on either side (Figure 2). Topography slopes generally to the south in the Wastewater Sludge Disposal Area, and to the north/northwest in the Former Industrial Landfill Area and the Former Delnav Production Area. A topographic divide located south/southwest of the Former Delnav Production Area separates north flowing surface water drainage to more east/southeast-trending drainage. The east-trending, perennial stream Green's Creek and its natural and man-made tributaries are the main surface drainage features in the area. Green's Creek leaves the Site at its northeast corner and subsequently runs into Bowie River, located approximately one (1) mile to the north/northeast.

2.3 Site Geology and Hydrogeology

The Site is located within the Pine Hills physiographic region of the Coastal Plain physiographic province. The topography of the region is characterized by a maturely dissected plain which slopes generally toward the southeast. The topography is dominated by the valleys of the Bowie and Leaf Rivers coupled with the nearly flat or gently rolling bordering terrace uplands.

The geologic formations beneath the Site are as follows (in descending order): Pleistocene alluvial and terrace deposits, the Miocene-aged Hattiesburg and Catahoula Sandstone formations, the Oligocene-aged Baynes Hammock Sand and Chickasawhay Limestone formations, and the Oligocene-aged Bucatunna Clay member of the Byron formation of the Vicksburg group. A conceptual cross section of the regional geology is shown on Figure 3.

The recent-aged alluvial and terrace deposits consist of flood plains and gravel, silts, and clays. The thicknesses of the alluvial and terrace deposits are variable due to erosion. Based upon drillers logs of wells located in the vicinity of the Site, thickness of the alluvial and terrace deposits is estimated to be approximately 50 feet.

Beneath the alluvial and terrace deposits lies the Hattiesburg formation, which is comprised predominantly of clay. Regionally, beneath Forrest County, the formation contains at least two (2) prominent sand beds from which a viable water supply is obtained. Logs from area wells indicate that the Hattiesburg formation ranges from approximately 130 feet to 260 feet in thickness.

The Catahoula sandstone underlies the Hattiesburg formation. It is not exposed near the facility, but is penetrated by numerous wells in the area. A drillers log of a municipal well approximately 1.25 miles northwest of the facility indicated that approximately 770 feet of Catahoula sandstone was encountered.

Near the Site, the Catahoula sandstone overlies the Chickasawhay limestone. Neither the Chickasawhay limestone nor the Bucatunna formation are considered to be very viable aquifers. The Bucatunna formation is comprised of clay and effectively act as a confining layer for the underlying Oligocene aquifer.

The Miocene aquifer is comprised of both the Hattiesburg and Catahoula sandstone formations. The aquifer system is composed of numerous interbedded layers of sand and clay. Because of their interbedded nature, the Hattiesburg and Catahoula sandstone cannot be reliably separated. The formations dip southeastward approximately 30 feet to 100 feet per mile. While this dip steepens near the coast, the formations thicken. The shallowest portions of the aquifer system are unconfined with the surficial water table ranging from a few inches to greater than six (6) feet below land surface. Deeper portions of the aquifer are confined, with artesian conditions common.

3.0 TECHNICAL APPROACH

The supplemental site investigation will be conducted in one mobilization. During the mobilization a Geoprobe® will be used to investigate site conditions and define the lateral extent and vertical extent of the VOCs detected in groundwater samples collected from MW-4, MW-8, MW-9, and MW-11. A geophysical survey will also be conducted during this mobilization. The geophysical survey will involve data collection with non-intrusive instrumentation to delineate the lateral limits of the landfill area and to locate accumulations of buried metal within the waste matrix.

3.1 GROUNDWATER INVESTIGATION

Groundwater samples will be collected in the vicinity of wells where VOCs have been previously identified in groundwater samples to delineate the lateral extent of the constituents of concern in the uppermost saturated interval. Previous investigation indicates that the uppermost saturated interval occurs within approximately 10 feet to 12 feet of ground surface. Initially, groundwater samples will be collected in close proximity to monitoring well MW-8, where samples containing the highest concentrations of VOCs have been detected during previous investigations. The initial samples will be analyzed for VOCs as quickly as possible by Bonner Analytical and Testing Company (BATCO) located in Hattiesburg, Mississippi. If VOCs are detected in the initial groundwater samples, additional groundwater samples will be collected from locations surrounding the initial locations. The additional groundwater samples will also be analyzed by BATCO, and the analytical results from the additional groundwater samples will be used to site other sampling locations. The investigation will continue using this iterative process until the lateral extent of the constituents of concern in the uppermost saturated interval is defined. It is estimated that up to 15 groundwater samples may be collected, depending on site conditions.

Groundwater samples collected during the Geoprobe® investigation will be collected from temporary monitoring wells installed using the Geoprobe®. The temporary monitoring wells will be screened across the uppermost saturated interval. After sample collection, the temporary monitoring wells will be left in place until they can be surveyed.

Groundwater conditions at the site will be evaluated based on geologic, groundwater quality, and groundwater flow information obtained during the Geoprobe® investigation and previous investigations.

3.2 GEOPHYSICAL INVESTIGATION

A former landfill is located north of the active plant area. The landfill was reported to have operated from approximately 1950 to approximately the early 1970's. The landfill was reportedly used to dispose of boiler ash, miscellaneous trash and debris, and other metallic objects such as empty drums. The practice at the plant at that time was to burn any organic waste materials containing fuel value in the industrial boiler. The approximate boundaries of the former landfill can be topographically identified. A previous geophysical investigation was conducted in 1993 by Black and Veatch Waste Science and Technology Corporation (Black and Veatch) for the U.S. Environmental Protection Agency. The results of the previous geophysical investigation were discussed the *Site Inspection Report*. The landfill area investigated was reported to have the approximate dimensions of 150 by 250 feet in the Black and Veatch report. A copy of the relevant portions of the Black and Veatch report is included as Appendix A.

A combination of ground conductivity and magnetic intensity methods will be used to delineate the boundaries of the former landfill area and to locate accumulations of buried metal within the landfill area. For this survey, data will be collected at ten-foot intervals along lines spaced ten feet apart. This spacing should provide sufficient overlap to adequately delineate the lateral limits of the fill materials and identify most accumulations of buried metal.

Electrical conductivities of subsurface materials will be measured using a Geonics, Ltd., Model EM31. The EM31 is useful in detecting buried metal, inorganic groundwater plumes, and landfill cells. Magnetic intensity enhances data interpretation for subsurface magnetic materials such as buried metallic objects and will be measured using a Geometrics, Inc., Model G-858 cesium vapor magnetometer. Details of the geophysical survey methods and procedures are described in Section 4.8.

4.0 METHODS AND PROCEDURES

Unless otherwise stated, field activities will be conducted in accordance with the Environmental Investigations Standard Operating Procedures and Quality Assurance Manual (EPA Region IV, November, 2001), (EISOPQAM).

4.1 BORING ADVANCEMENT

During the first mobilization, borings will be advanced using a direct-push technology, hydraulic probing apparatus (Geoprobe® or similar) equipped with a soil coring device (MacroCore® or similar). The MacroCore® device will be driven to the target depth by the Geoprobe, opened to allow soil to enter the device, and driven across the desired sample interval. A four-foot long soil core, collected from a precise interval, will then be retrieved from the boring. Each boring will be cored continuously from the surface to the total depth of the boring.

4.2 SOIL SAMPLE COLLECTION

During soil sample collection using the Geoprobe® with MacroCore®, 2.5-inch diameter, 4-foot long soil coring device, each soil sample will be collected in a new, disposable, plastic liner tube. Soil core lithology will be described based on visual characteristics, and the core will be screened in the field using a photo-ionization detector (PID).

4.3 GROUNDWATER SAMPLING

Groundwater samples will be obtained through the installation of temporary monitoring wells. Immediately following the completion of borehole advancement a temporary monitoring well will be installed into the open borehole. Temporary monitoring wells will be completed by installing a one-inch (I.D.) PVC screen and riser into the uppermost water-bearing interval. A filter sock will be applied and secured to the screened interval prior to installation into the borehole. 20/40 silica sand will be added around the screen to a depth of approximately two feet above the top of the screen. A two-foot thick bentonite seal will be placed above the sand, and the remaining portion of the open hole will be filled with a high solids bentonite seal, which will prevent surface water from entering the boring. After collection of groundwater samples and hydrogeologic information, temporary monitoring wells will be removed and the open borehole will be pressure sealed to the surface with a cement/bentonite grout.

4.3.1 Well Development

Temporary monitoring wells will be developed by pumping until the discharge from the well is relatively free and clear of suspended sediment.

4.3.2 Groundwater Sample Collection

Prior to collecting a groundwater sample, the temporary monitoring wells may be purged using either *low-flow/low-stress* or traditional volume-based bailer, or similar, techniques. The *low flow/low stress* technique will consist of slowly lowering dedicated tubing connected to a peristaltic pump (or similar device) into a region of adequate permeability within the water-bearing zone. If possible, the suction end of the tubing will be placed at the midpoint of the well screen for sampling. Purging will begin with withdrawal of water at a rate that creates an equilibrium with recharge (e.g., stabilized water table). Equilibrium is dependent upon the stabilization of temperature, pH, specific conductance, turbidity and dissolved oxygen.

As only a thin vertical slice of the water-bearing zone is affected, field parameters typically stabilize immediately and turbidity is quickly reduced. If the yield of each well is insufficient to support the application of the *low flow/low stress*, traditional volume-based purging using either disposable Teflon bailers or a peristaltic pump will be employed. However, the introduction and removal of the bailer will be conducted in a manner to minimize the disturbance to the screened portion of the well. Purging will be continued until at least three (3) volumes of water and/or representative water quality criteria (above-referenced not including turbidity) have been met. The water quality field parameters will be measured with calibrated instruments and recorded in the field book along with the cumulative amount of water evacuated and time of batch parameter testing.

Once field parameters have stabilized (regardless of the purge method), groundwater to be collected for analysis will be sampled simply by collecting water from the discharge stream (tubing or bailer) directly into the Teflon-lined sample containers for subsequent laboratory analysis. In the event that field replicates are collected for Quality Assurance/Quality Control (QA/QC) concerns, field personnel will exercise care in assuring that alternating aliquots are placed in each replicate bottle until each bottle is filled.

Subsequent to sampling, sample containers will be placed and sealed on ice and shipped to the designated offsite laboratory for analysis. Chain-of-custody documentation will accompany all coolers. Personnel involved in sampling will wear clean, disposable gloves, which will be changed between each sample collection. All non-disposable sampling equipment will be decontaminated as outlined in Section 4.5.

4.4 ANALYTICAL METHODS

Groundwater samples will be analyzed by BATCO for volatile organic compounds (VOC) according U.S. EPA SW-846 methodology. Specifically, the samples will be analyzed for VOCs according to Method 8260B.

4.5 Decontamination

Probe equipment used to collect subsurface soil and groundwater samples (rods and samplers, temporary downhole casings, screens points) and other equipment used in sample collection will be accomplished by the following procedure:

1) Phosphate-free detergent wash.
2) Potable water rinse.
3) Deionized water rinse.
4) Isopropanol rinse.
5) Organic-free water rinse or air dry.
6) Individual tin foil wrap.

For boring activities, separate decontaminated samplers will be used between sample intervals within the same boring, thereby requiring decontamination between boring locations only.

4.6 QA/QC Procedures

To attain Site QA/QC objectives in terms of accuracy, precision, completeness, comparability, and representativeness, QA/QC samples will be collected and sent to the analytical laboratory for analysis. QA/QC samples collected in the field will consist of field duplicates, splits, and equipment rinsate and trip blanks.

Field split samples of groundwater will be collected by alternating groundwater aliquots into an additional container from which the normal sample is collected. Split samples will also be collected in this manner for regulatory oversight and independent laboratory analysis, if required. Split samples are used to evaluate data reproducibility and, during this investigation, will be collected at a frequency of one (1) per ten (10) samples per matrix. Equipment rinsate blanks will be collected at a frequency of one (1) per twenty (20) samples per matrix. Equipment rinsate samples will be collected immediately following sampling equipment decontamination by running deionized water through decontaminated sampling equipment and collecting this water in sample containers. Trip blanks are supplied by the designated laboratory and consist of deionized water in a 40-ml vial. The trip blank will remain in the sample ice chest along with the investigation samples, and will be analyzed for target volatile compounds only.

4.7 Derived Waste Management

Investigative-derived waste (IDW), (e.g., soil cuttings, plastic sampling tubes, decontamination water, well purge water, personal protective equipment, etc.) will be containerized immediately following generation and staged in a readily-accessible area to facilitate subsequent management. Containers generated during investigative activities will be identified and documented in the log book to facilitate subsequent management actions. Best Management Practices (BMPs), as outlined in the EISOPQAM, will be followed to minimize waste volumes and minimize client liability. These BMPs will be based on review of historical analytical data and qualitative and quantitative field screening results and may allow for onsite spreading of non-impacted soils and/or water. Containerized waste containing constituents of concern will be reviewed for hazardous waste characteristics and transported and disposed of accordingly in an approved landfill within 14 days of receipt of all characterization data. Waste characterization review may include historical data, site sampling data, and applicable Toxicity Characteristic Leaching Procedure (TCLP) testing, if necessary.

4.8 GEOPHYSICAL SURVEY

4.8.1 Electromagnetic Terrain Conductivity

Ground conductivity is a non-intrusive method of measuring lateral variation in the electrical conductivity of subsurface materials. Measurements of electrical conductivity will be made with an EM31 Meter. The device is manufactured by Geonics Limited, of Mississauga, Ontario. The EM31 is simple in form, consisting of a magnetic field transmitting coil, a magnetic field receiving coil, and associated electronics. The coils of the instrument are held co-planar, at a fixed inter-coil spacing of twelve (12) feet. The transmitter coil is energized with an audio frequency alternating current. The resulting primary magnetic field (Hp) induces small electrical currents in the ground. These currents induce secondary magnetic fields (Hs) which, together with the primary field, are sensed by the receiver coil. Electrical conductivities of subsurface materials are deduced from the ratios of secondary to primary fields.

The EM31 is constructed in such a way that the secondary to primary magnetic field ratio (Hs/Hp) is proportional to ground conductivity. The phase of the secondary field lags that of the primary by at least 90°, due to inductive coupling between the transmitter coil and the target conductive material. Additional lag is determined by the properties of the conductor as an electrical circuit. For very poor conductors, the additional lag is close to zero. For very good conductors, it is close to 90°. Generally, the secondary field is somewhere between 90° and 180° out of phase with the primary. That portion of Hs which is only 90° out of phase is called the quadrature component. The EM31 is calibrated to provide quadrature values directly in standard conductivity units of milliSiemens per meter (mS/m). The fraction of Hs which is fully 180° out of phase with Hp is called the inphase component. Inphase values are provided in parts per thousand (ppt) of the primary field.

Both quadrature and inphase values will be simultaneously recorded by an automatic data logger for each survey point in the subject area. Both are influenced by the broad range of subsurface conductivities resulting from minute dissolution of soil particles, inorganic groundwater plumes, fill materials and buried metals. Being generally more sensitive to variations in relatively poor conductors, quadrature readings are used to interpret such features as relative inorganic groundwater concentrations. Being generally more sensitive to good conductors, on the other hand, inphase readings are the primary indicators of subsurface metal. Both quadrature and inphase values will be recorded during this survey.

The secondary field signal received and processed by the EM31 does not represent ground conductivity at a particular depth. Instead, it represents an integration of conductivities through thicknesses of tens of feet. Eighty (80%) percent of the instrument reading, for example, is due to materials lying at depths shallower than about thirty (30) feet. The thirty (30) foot level may be considered an "effective" exploration depth for detection of significant groundwater plumes. The maximum depth for detection of metallics is a function of the type and amount of buried material. Tightly packed accumulations low-grade steel can be found at depths of over 20 feet.

The EM31 will be calibrated according to manufacturer instructions, at the beginning of each survey session. Calibrations will be carried out at a fixed location within the survey area. Both quadrature and inphase values will be recorded. After data collection, the device will be taken back to the calibration point. Quadrature and inphase values will, again, be recorded. The differences in the two data sets will be used to determine and correct for "machine drift".

Additional information regarding the operation of terrain conductivity meters is included in Appendix B.

4.8.2 Magnetic Intensity

Total magnetic field intensity will be measured with a Geometrics, model G858 cesium vapor magnetometer. The device measures total field intensities by detecting a self-oscillating split-beam cesium vapor mechanism. The G-858 will be rigged with one sensor at waist height of the operator. The device has a data logging capability that will be used to record total magnetic field intensity at each survey location. A series of manual readings will also be collected at a fixed location at approximately one-hour intervals. The intensity versus time curves generated from the manual readings will be used to correct the G-858 survey data for diurnal variations of the earth's magnetic field. The data set produced will reflect the anomalous fields produced by buried magnetic material. The effective exploration depth of the device is a function of the amount of underlying metal. A manual summarizing the theory and operation of magnetometers is provided by the manufacturer (Breiner, 1973).

Additional information regarding collection and utility of magnetic intensity methods is included in Appendix C.

4.9 HEALTH AND SAFETY CONSIDERATIONS

Eco-Systems and all subcontractors of Eco-Systems will comply with a site-specific Health and Safety (H&S) Plan to be prepared in accordance with OSHA (29 CFR 1910.120) regulations. All individuals working at the site will have successfully completed an approved 40-hour safety training course and yearly 8-hour refresher courses, as necessary. All individuals working at the site will also receive Hercules' health and safety training for contractors provided at the facility or work under the direct supervision of personnel who have received the training from Hercules.

Prior to performing field activities associated with this Work Plan, all personnel will be required to sign a compliance agreement certifying that they have read, understand, and will abide by all provisions of the H&S Plan.

4.10 Other Procedures

Procedures for soil boring and well installation, sample collection, sample containerization and packing, sample shipment, cross-contamination control, drummed material disposal, field documentation, chain-of-custody, data review, and other work items not specifically covered in this document will be conducted in accordance with the EISOPQAM.

5.0 REPORTING

Following receipt of the analytical results, a report documenting the field activities and the analytical results will be prepared. The report will include, at a minimum, the following:

1) a summary of investigative approach and field activities conducted,
2) field methods and procedures,
3) narrative of the investigative results with tabular and graphical presentation of the geochemical and/or geotechnical data,
4) iso-concentration maps may be generated for appropriate constituents of concern in groundwater to aid in visualizing the extent of impact,
5) analytical laboratory data sheets,
6) results of the QA/QC data review,
7) a summary of the findings, and
8) recommendations for further actions or management measures, if appropriate.

Field logs and construction diagrams will be included in appropriate appendices of the report.

6.0 IMPLEMENTATION SCHEDULE

Field activities will be implemented promptly following approval of this work plan by the MDEQ. Field work is anticipated to be completed within 50 days of project initiation, and the report of the field investigation results is anticipated to be submitted to the MDEQ within 120 days of project initiation following the authorization to proceed.

The schedule assumes that one mobilization for field work will be needed. The report will be prepared following receipt and review of complete laboratory data. The estimated schedule for project activities anticipated to complete this field investigation is shown below.

Activity	Days from Start
Procurement and Initiation of Field Activities	30
Completion of Field Activities	50
Receipt and Review of Laboratory Data	85
Report Preparation and Submittal to MDEQ	120

FIGURES

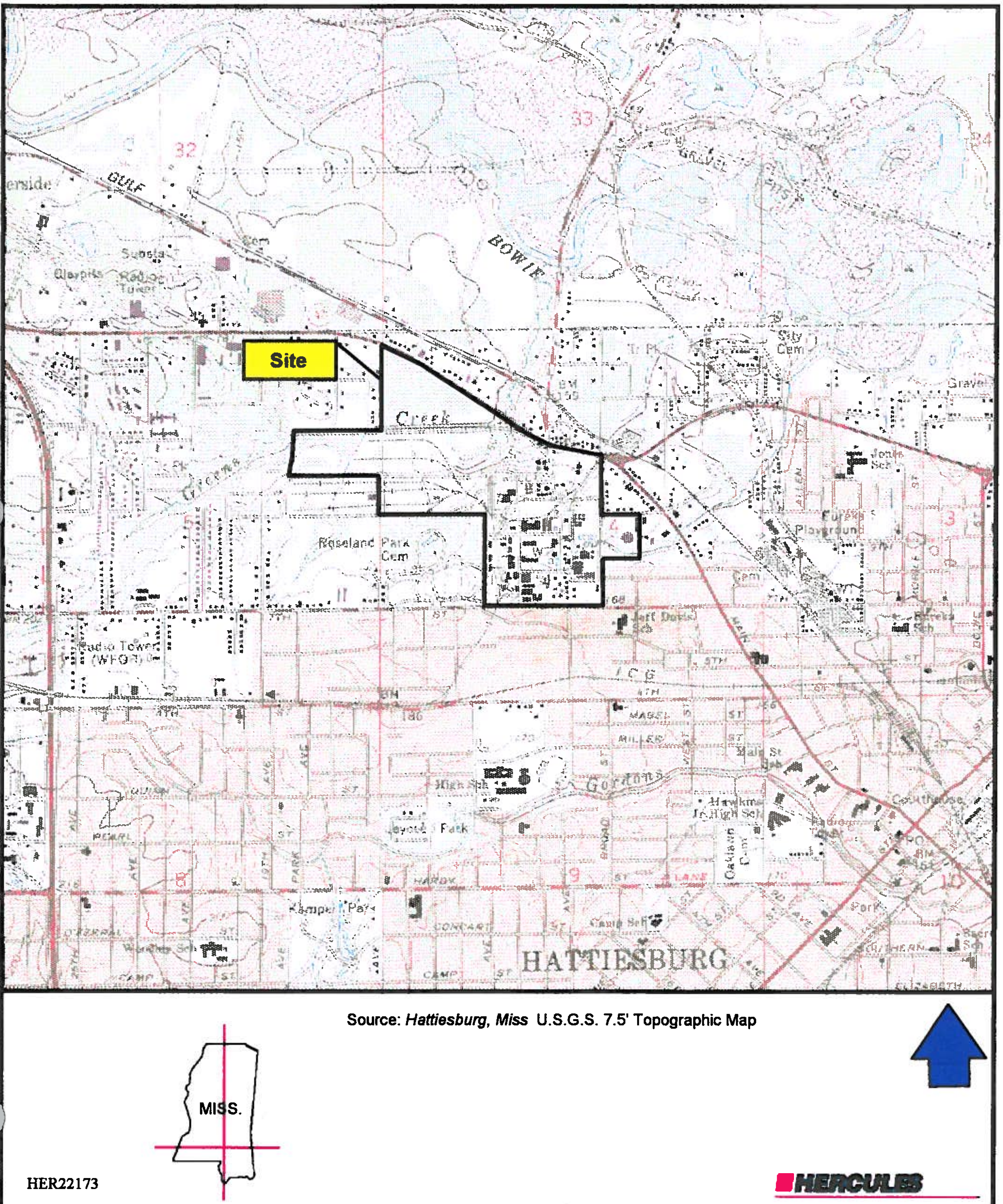
ESI

FIGURE 1

SITE LOCATION MAP

FIGURE 1

SITE LOCATION MAP
HERCULES, INC.
HATTIESBURG, MS



Source: *Hattiesburg, Miss* U.S.G.S. 7.5' Topographic Map

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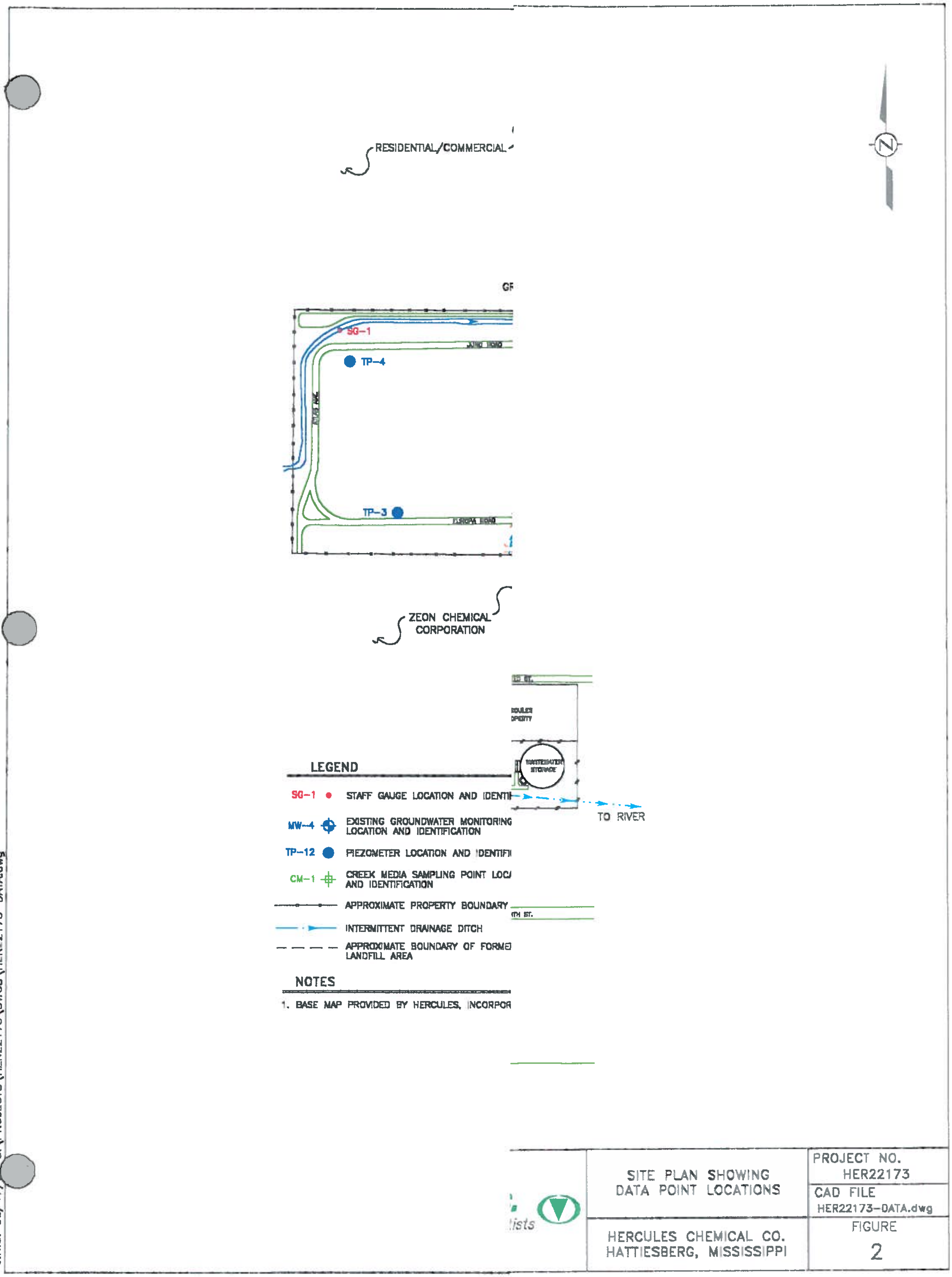
FIGURE 2

SITE PLAN SHOWING DATA POINT LOCATIONS


RESIDENTIAL/COMMERCIAL
SG-1
TP-4
TP-3
ZEON CHEMICAL CORPORATION
TO RIVER
LEGEND
SG-1 STAFF GAUGE LOCATION AND IDENTI
MW-4 EXISTING GROUNDWATER MONITORING LOCATION AND IDENTIFICATION
TP-12 PIEZOMETER LOCATION AND IDENTIFI
CM-1 CREEK MEDIA SAMPLING POINT LOCA AND IDENTIFICATION
APPROXIMATE PROPERTY BOUNDARY
INTERMITTENT DRAINAGE DITCH
APPROXIMATE BOUNDARY OF FORME LANDFILL AREA
NOTES
1. BASE MAP PROVIDED BY HERCULES, INCORPOR
SITE PLAN SHOWING DATA POINT LOCATIONS
HERCULES CHEMICAL CO.
HATTIESBERG, MISSISSIPPI
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CAD FILE
HER22173-DATA.dwg
FIGURE
2
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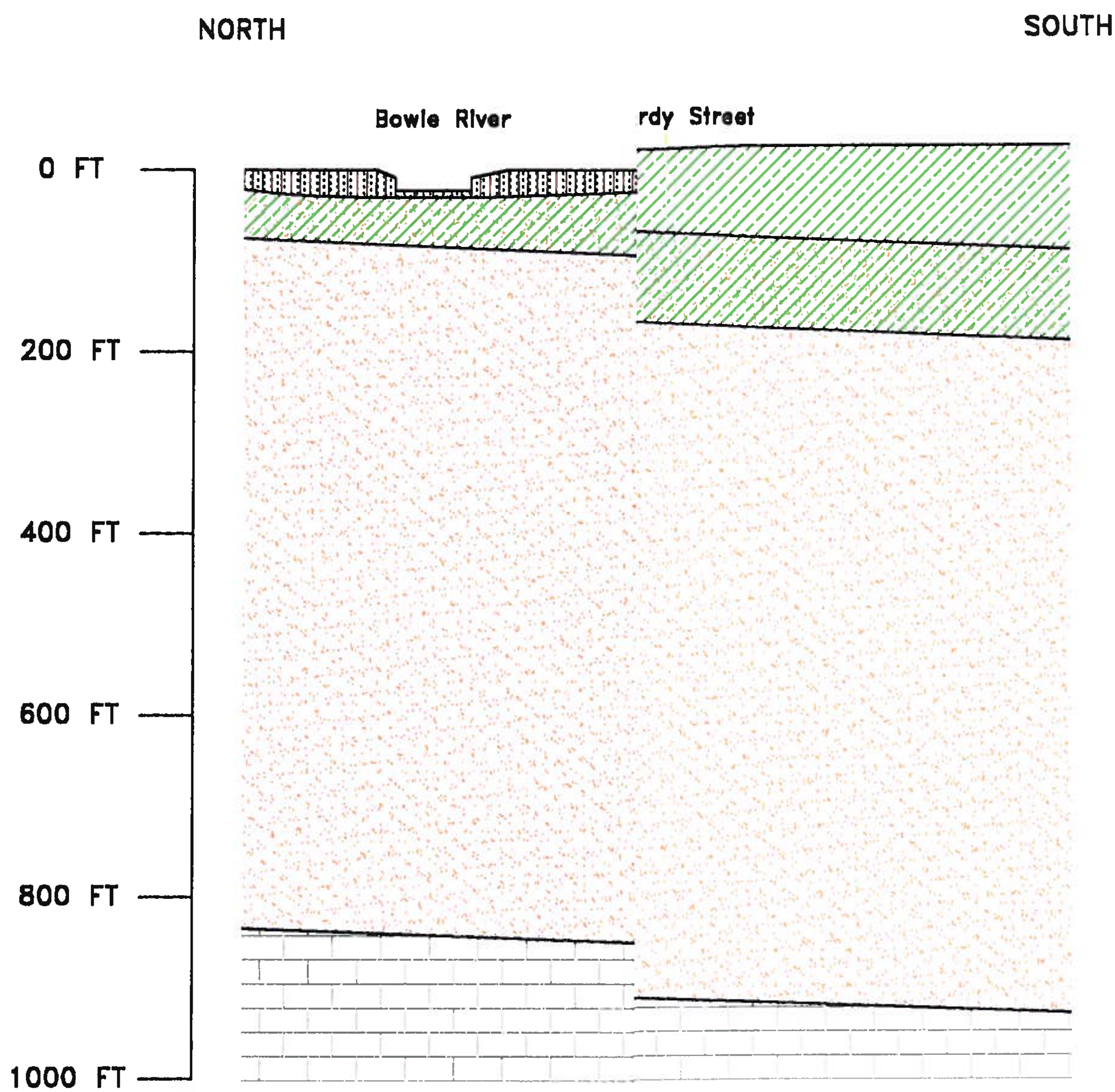
FIGURE 3

CONCEPTUAL REGIONAL CROSS SECTION



HERCULES CHEMICAL CO.
HATTIESBERG, MISSISSIPPI

PROJECT NO. HER22173

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CONCEPTUAL REGIONAL GEOLOGIC CROSS SECTION

FIGURE 3

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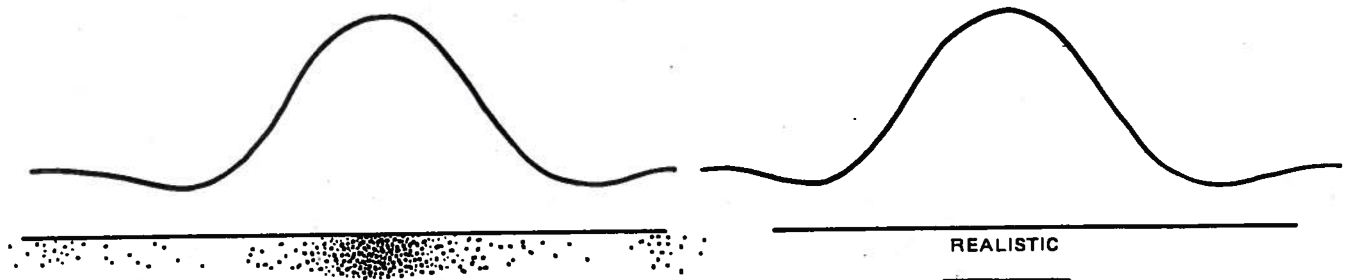
APPENDICES



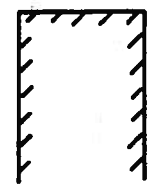
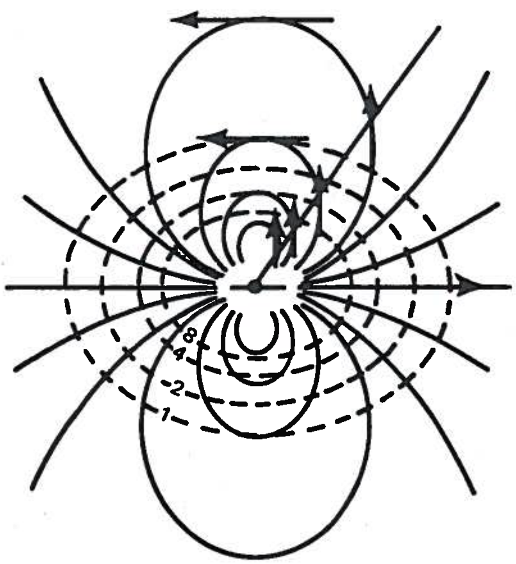


Figure 16. Possible Geologic Sources Producing Same Anomaly



LINES OF FLUX (——)
AND
LINES OF EQUAL INTENSITY (— —)
FOR A DIPOLE

Figure 18.

Having outlined the qualitative geometry of the intensity T from a dipole, the quantitative aspects can be considered as follows:

The intensity, T, from a dipole can be expressed as

$T = \frac{2M}{r^3}$ along the axis, i.e., off the end of the dipole,

and $T = \frac{M}{r^3}$ along a line at right angles to the dipole,i.e., off the side of the dipole,

and for a monopole

$T = \frac{M}{r^2}$ in any direction from a monopole, where

M = magnetic moment and r is the distance to the pole. A more detailed mathematical formulation for the intensity due to a dipole is given subsequently in this Chapter.

Simplified Method for Total Field Signature

From the above description of a dipole and monopole and with the knowledge of the earth's-field-component-nature of the total field magnetometer, it is possible to sketch the signature of an anomaly for any given orientation of the dipole (orientation caused by field direction, the direction of remanent magnetization, or by the configuration of the geology). It is helpful to draw such signatures at various inclinations of the magnetic field to understand where the sources would be located with respect to the signature, the dip of the magnetization producing the anomaly, and even for information related to the depth of the source. Remember that all anomalies can be considered as caused by various distributions of dipolar and monopolar sources and it is possible to produce any anomaly simply by the super-position of such dipole or monopole signatures derived here.

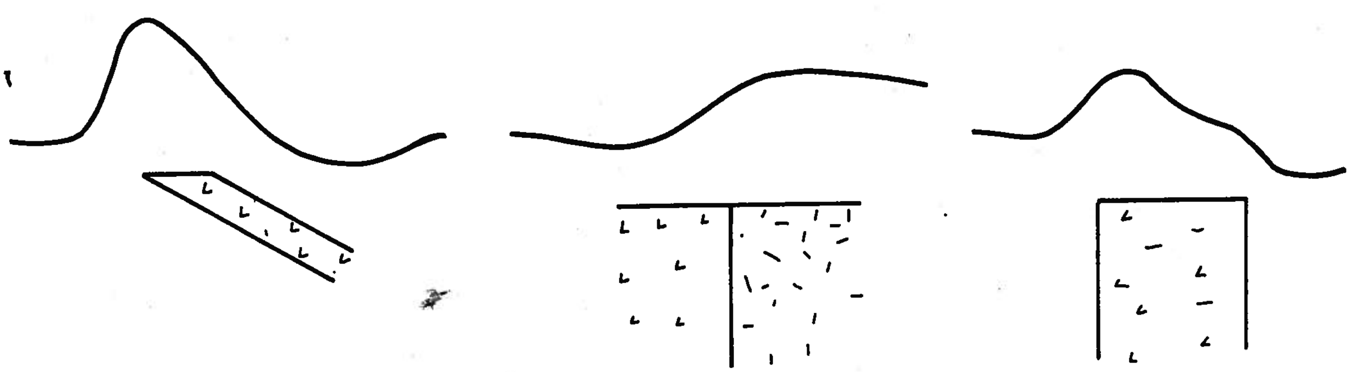


Figure 17. Typical Anomalies for Simple Geologic Models

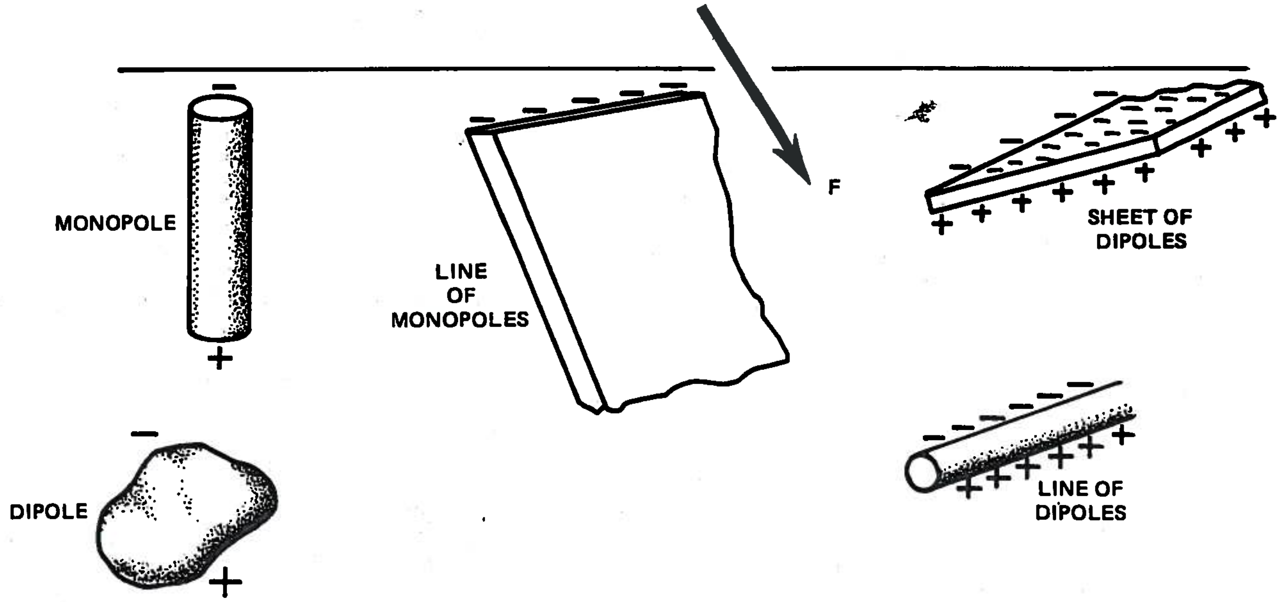


Figure 19.

Earth's Field Component Behavior

This method of predicting or drawing the anomaly signature depends upon one property of the field, namely, inclination, and three properties peculiar to the dipole or monopole source, whichever is assumed. The dip of the earth's field is first considered because this is the direction, the only direction, of the components of any local magnetic anomalies which are measured by a total field magnetometer. (If one is using a vertical component magnetometer, this guide still applies except that instead of using the earth's field as the direction of measurement, simply use the vertical.) In other words, the magnetometer will only measure the component of a local perturbation in this direction, i.e., as projected into this direction. See *Figure 20.*

Dipoles vs. Monopoles vs. Arrays of Poles

The decision to use dipoles, monopoles, or other configurations as the model is based upon the manner in which the earth's field induces a local field and this in turn depends upon the configuration of the geologic body which exhibits the magnetization contrast and the direction of the field. For example, a long body which nearly parallels the earth's field will tend to be magnetized along its long dimension. Furthermore, if the body is sufficiently long with one end near the magnetometer, the anomaly will appear as a monopole seeing only the upper pole with the lower pole removed effectively to infinity. If the same long, thin body were normal to the field, it would then be magnetized through its thinest dimension producing the sheet-like array of dipoles as shown in *Figure 19.*

One may wish to draw on the typical models depicted in *Figure 15,* the array of poles from a uniform earth's field at various inclinations and orientations of the source. Whether the monopoles or the dipoles (and its equivalent line or sheet distributions) are close or far apart, determines if the model is to be considered a dipole or monopole, respectively *(see, for example, Figure 34).*

Configuration of Field Lines

The first property of the dipole or monopole which is to be considered is the configuration of the field lines *(see Figure 13).* When superimposed upon the component which is measured by the total field magnetometer, it can be seen that the relative lengths of the disturbance vectors that are measured are those shown in *Figure 21* for an induced dipole and monopole source. It is the relative length of these disturbance vectors drawn along the total field direction that is measured, each disturbance vector, in turn, weighted by the intensity functions described below.

Dipole and Monopole Fall-Off Factor

The next factor to be considered is the variation of intensity with distance, i.e., $1/r^3$ and $1/r^2$ factors for the dipole or monopole fields respectively and as expressed in the preceding equations. The relative intensity for dipoles or monopoles as a function of distance to their centers as would be observed along a traverse is presented in *Figure 22* and described mathematically under "Anomaly Amplitude" below. This factor multiplies the length of net vectors in *Figure 21.*

Dipole Factor-of-Two

The last consideration really only applies to the dipole and that is a factor of 2 when one is off the end of the dipole compared to a position off the side. In other words, at a given distance, the intensity varies by a factor of 2 as a function of the angle between the radial line to the dipole and the dipole axis. This function is shown approximately in *Figure 23* for the dipole used in the example. The monopole possesses radial symmetry and therefore requires no such consideration.

Application of Method

A dipole and monopole signature is thus constructed in *Figure 24.* The amplitude is dimensionless, but can be compared to a real anomaly by multiplying by a single factor derived below from considerations of volume, susceptibility, etc. However, applying these factors even qualitatively should allow one to draw the dipole and monopole signatures for variously inclined fields and geometries. *Figure 25,* for example, is drawn free-hand for anomalies in vertical field (90° inclination), magnetic equator and mid-southern latitudes. By simply sketching in the earth's field direction and the dipole's field lines

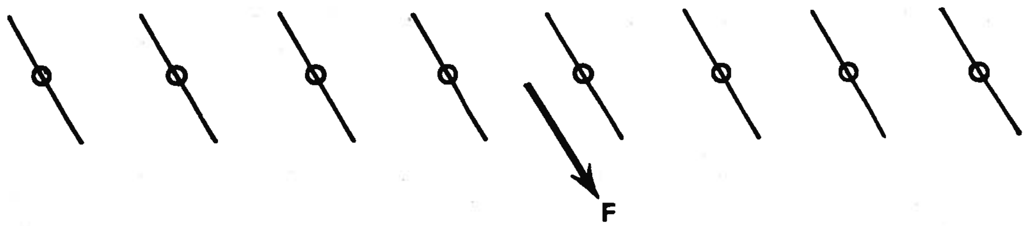


Figure 20. Direction of Components Measured by Total Field Magnetometer

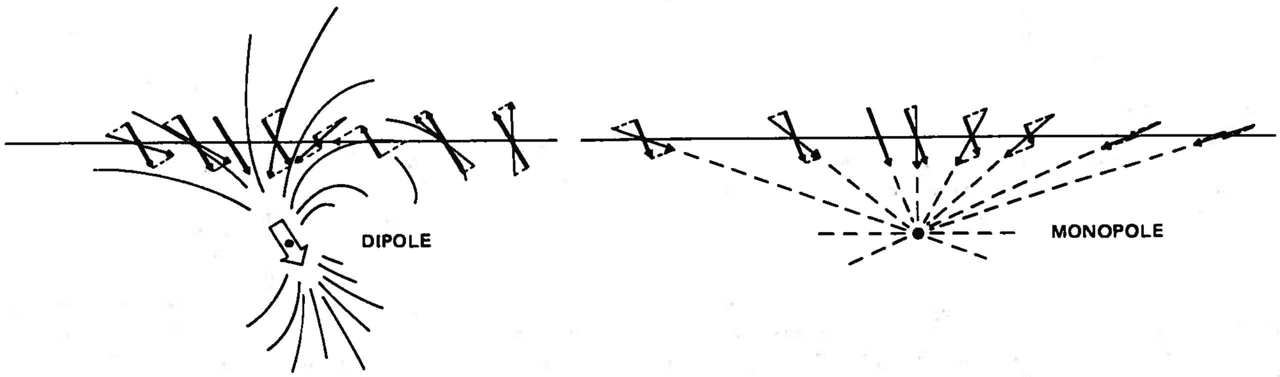


Figure 21. Total Field Components of Tangent to Field Lines of Dipole and Monopole

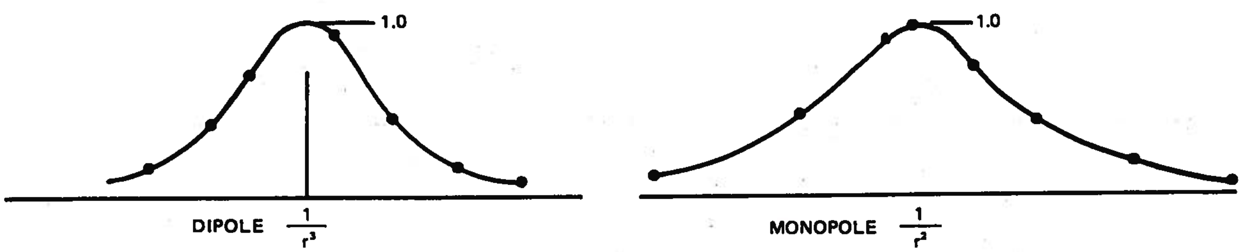


Figure 22. Fall-off Rate
(Relative intensity or length of vectors in Figure 21)

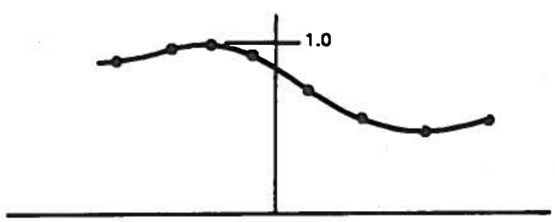


Figure 23. Aspect Factor
(Relative Intensity of Dipole of Figure 21 with Respect to Angle from Axis at Various Points Along Profile)

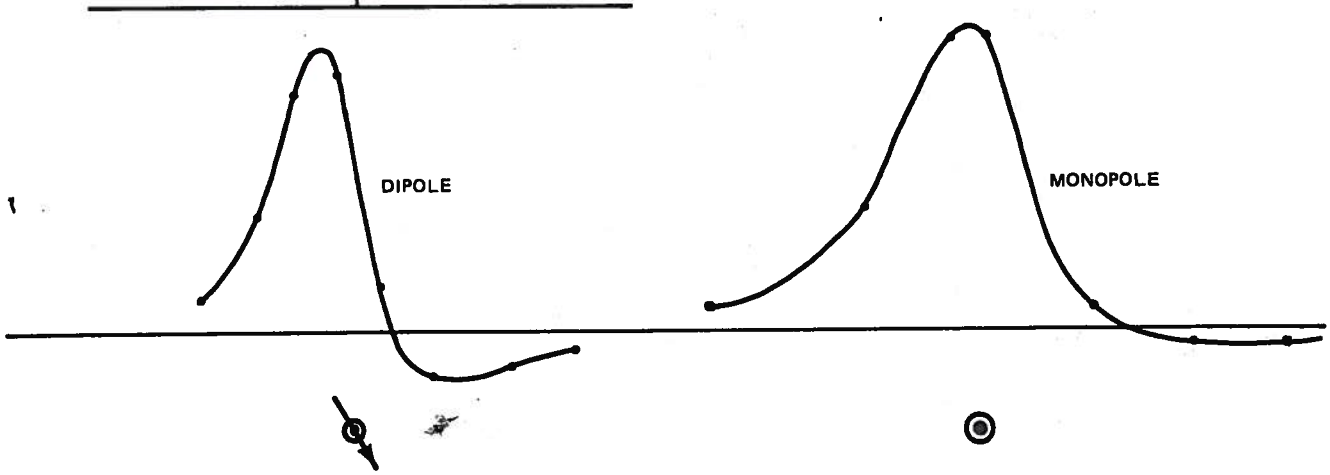


Figure 24. Dipole and Monopole Signatures (Constructed from Figures 20-23 according to methods described in text.)

without consideration of the other last two factors, it is possible to appreciate the basis for:

a negative anomaly over sources at the magnetic equator,

absence of anomalies in the central portion of elongate N-S anomalies at the equator,

both positive and negative fields for almost any anomaly,

changes in anomaly character for different directions of the dipole,

asymmetry of anomalies,

monopole which has only positive sense yet for most inclinations still produces a total intensity anomaly with both positive and negative portions.

The simple exercise of drawing such anomalies may also elucidate other characteristics of signatures, which to many not familiar with magnetics or such behavior as shown here, appear to be complex and difficult to comprehend.

Based upon the above procedures, applied qualitatively, and upon the manner in which lines of flux are induced in various configurations of geologic bodies and ambient field directions and inclinations, it is possible to derive the various signatures shown in *Figure 26* (drawn freehand). By varying the effect of depth as it produces an anomaly of longer wavelength, and by building composite anomalies such as summing the effect of 2 faults to create a single wide, shallow dike, it is also possible to generate a composite curve demonstrating the effect of different sources and different depths which is the typical observation.

Contour Presentation of Dipole and Prism Anomalies

Profiles of total intensity are usually the only form of presentation from ground measurements even when data are taken on a 2-dimensional array. If measurements are taken properly, however, it is possible to construct a contour map by the methods described in Chapter IV. It is therefore useful to examine a few special cases of contour maps that would be expected over simple sources such as a dipole and a wide, vertical prism in various latitudes. Such a contour map also allows one to extract, even by simple inspection, how a given profile would appear at various positions over such simple-shaped forms which is useful information both in search and in

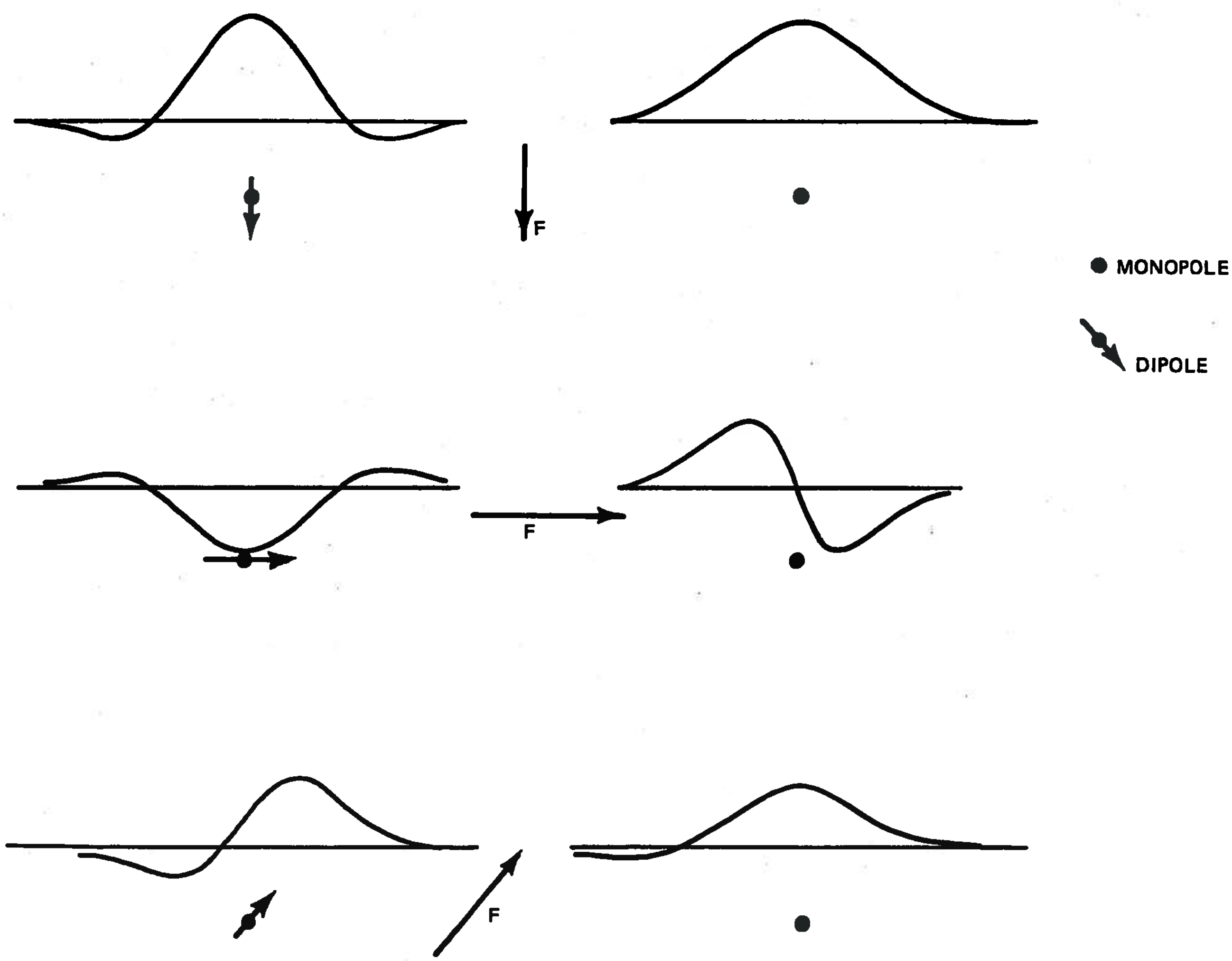


Figure 25. Free Hand Sketch of Dipole and Monopole for Various Inclinations

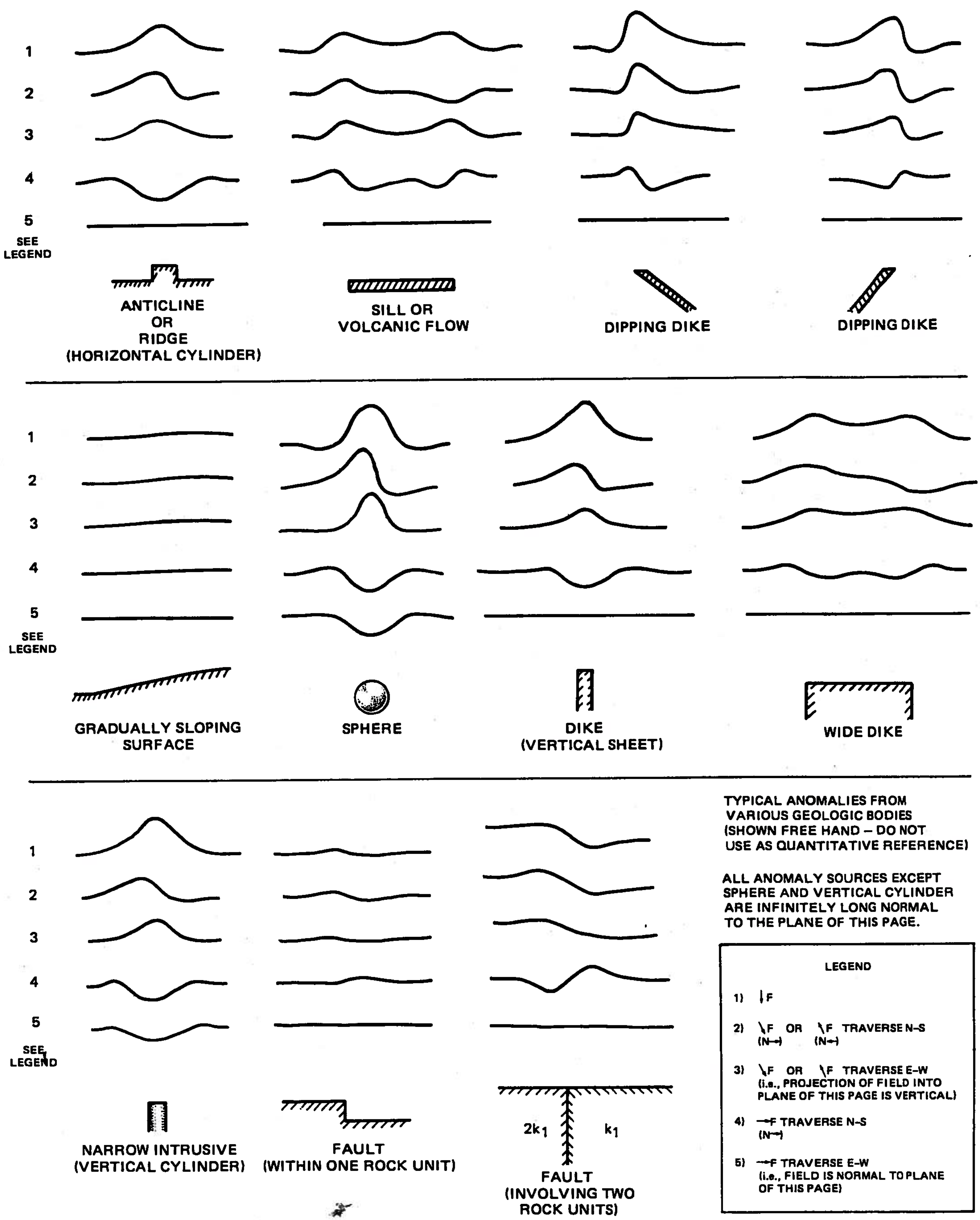


Figure 26. Anomalies for Geologic Bodies at Various Orientations and Different Inclinations of the Field

geological exploration. Contour maps and selected profiles drawn across the anomaly are sketched in *Figure 27*.

Anomaly Amplitude

Amplitude Estimates for Common Sources

The large amplitude commonly observed anomalies (several hundred gammas or larger) are almost always the result of a large magnetization contrast, i.e., change in lithology where one igneous rock is in juxtaposition with another or with a sedimentary or metamorphic rock of much lower susceptibility. It must be remembered that magnetization of common rocks varies over 6 orders of magnitude. Anomalies due to structure alone, i.e., varying configuration of a uniformly magnetized rock, seldom produces anomalies larger than 10 or 100 gammas.

The relative amplitude of a given anomaly (signature) has been shown to be a function of the earth's field direction, the configuration of the source and the remanent magnetization if any. The *maximum* amplitude of an anomaly is, on the other hand, largely a function of the depth and the contrast in the mass of magnetite (or iron, etc. in the case of search), and to a lesser extent, the configuration of the source. It is of interest to be able to estimate the maximum amplitude for a given source in order to 'model' it for the sake of interpretation. This estimated amplitude can be used with the normalized, i.e., dimensionless, anomaly signatures above and in *Figure 26* to produce the anomaly one wishes for comparison with the observed. Estimation of the maximum anomaly amplitude is also useful in planning a survey or planning the grid and coverage necessary in search applications.

For a few generalized configurations, it is relatively simple to estimate the maximum anomaly amplitude (at a single point above the source) assuming a depth, susceptibility and much simplified shape of the source. Expressions are given in the literature for calculation of anomalies of more complex figures and later in this section the calculation of the complete signature, i.e., the amplitude as a function of distance along the profile for a few simple forms. The methods described herein are merely order-of-magnitude techniques, but are useful for the applications covered by the Manual.

Estimation of the maximum anomaly for comparison with a given source requires first that the signature be studied for the nature of the source; namely, whether the source can be approximated as an isolated dipole, monopole, or line or sheet-like array of such. In the case of the latter two, adjacent traverses or a contour map may be required to determine if it is 2-dimensional, i.e., very long normal to the traverse. A depth is then assumed or crudely estimated (according to procedures that follow). In addition, the susceptibility is assumed or if source rocks are accessible, it is measured following methods outlined in Chapter VI. The formulae below can then be used remembering that they are based upon simplifications and assumptions and are often no better than a factor of two.

The basic expression for estimating the maximum amplitude of any anomaly is $T = \frac{M}{r^n}$

where T is the anomaly, M the magnetic moment, r the distance (depth) to the source, and n a measure of the rate of decay with distance, or fall-off rate (n = 3 for a dipole, n = 2 or a monopole, etc.).

Since the magnetic moment M (and k) is usually given in centimeter-gram-second (cgs) units, r must be in centimeters, n is dimensionless and T is in gauss. To express T in gammas, multiply M by 10^5; if r is in feet, multiply r by 30 and raise the quantity 30r to the exponent n, e.g., if the source is a dipole, then n = 3, and if say, r = 2 feet, M = 1000 cgs,

$$\text{then } T = \frac{1000 \times 10^5}{(2 \times 30)^3} = 460 \text{ gammas}.$$

Dipole and Monopole Signatures in Vertical and Horizontal Fields

The very generalized expression for the maximum anomaly one may expect from a dipole or monopole was presented above in its very simplest form. It may be of interest, however, to construct the signature of a dipole or monopole in a vertical or horizontal earth's field as would be observed by a total field magnetometer along a traverse over the source.

Apart from any total field considerations, a dipole has a field with magnitude and direction given by the radial and tangential components, T_r and T_θ, according to the following expression and for the geometry shown.

$$T_r = \frac{2M \cos\theta}{r^3}$$

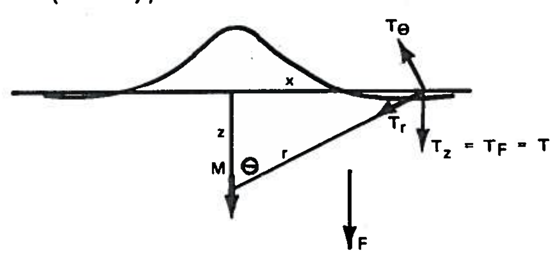
$$T_\theta = -\frac{M \sin\theta}{r^3}$$

Where the earth's field is vertical or nearly vertical (dip 70° to 90°), the dipole, if induced, would also be vertical and the total field magnetometer would measure the component, T_z, along this vertical direction, where

$$T_z = T_r \cos\theta + T_\theta \sin\theta$$

$$= \frac{2M \cos^2\theta - M \sin^2\theta}{r^3}$$

$$= \frac{M(2z^2 - x^2)}{(x^2 + z^2)^{5/2}}$$



As before, $T_z = T_F = T$, the anomaly.

At x = 0, $T = \frac{2M}{z^3}$

at $x = \pm z$, $T = \frac{0.175M}{z^3}$

at $x = \pm\sqrt{2}z$, $T = 0$

at $x = \pm 2z$ $T = \frac{-0.04M}{z^3}$

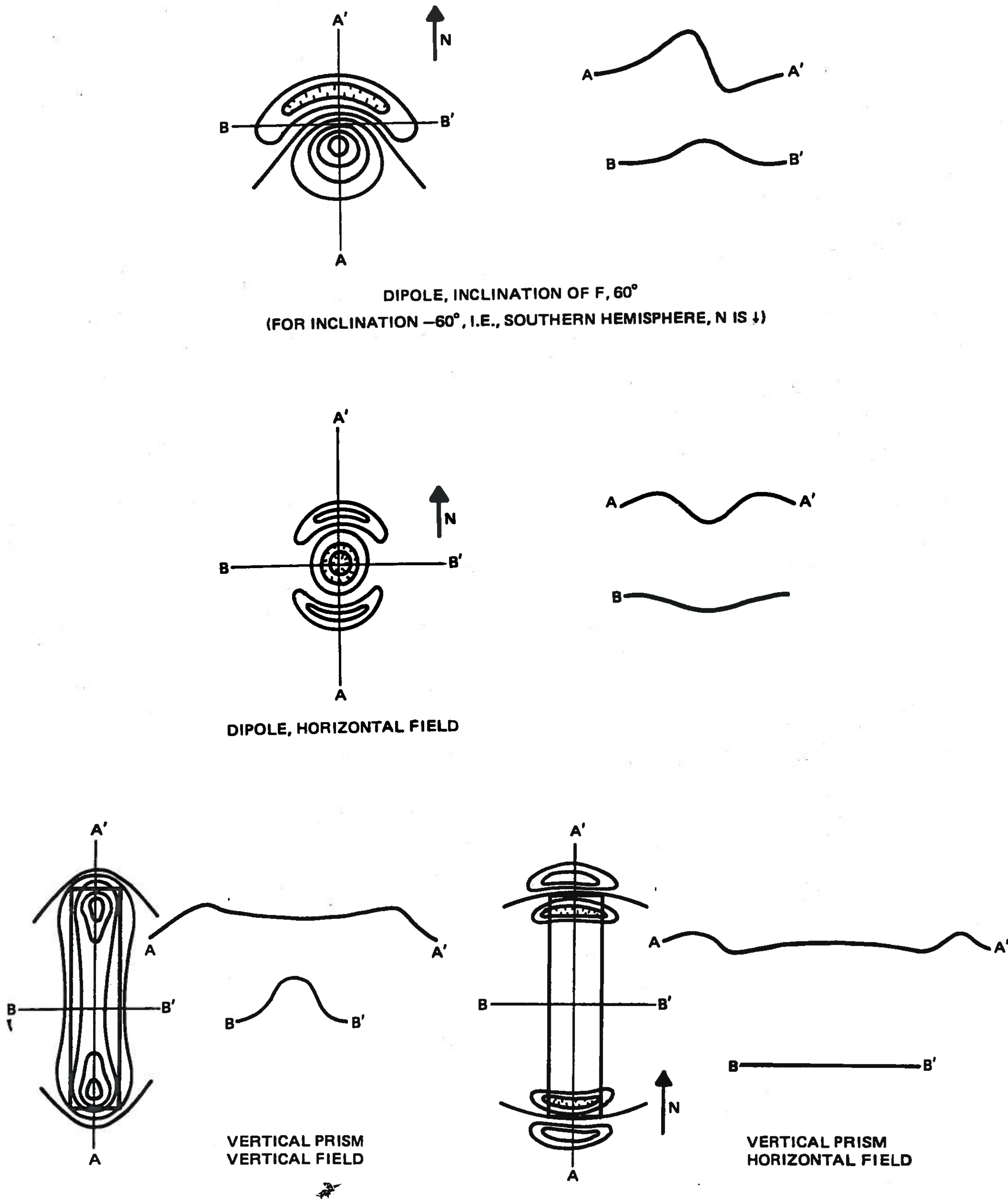
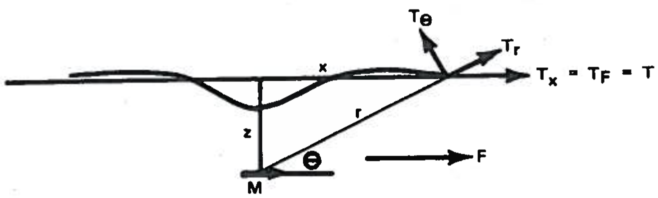


Figure 27. Contour Maps of Total Intensity

For magnetic equatorial fields, the induced anomaly is horizontal and the total field magnetometer would measure the components shown and expressed by

$$T_x = T_r \cos\theta + T_\theta \sin\theta$$

$$= \frac{2M\cos^2\theta - M\sin^2\theta}{r^3}$$



$$= \frac{M(2x^2 - z^2)}{(x^2 + z^2)^{5/2}}$$

as before, $T_x = T_F = T$ the total field anomaly, where,

at $x = 0$,

$$T = -\frac{M}{z^3}$$

at $x = \pm\frac{z}{\sqrt{2}}$,

$$T = 0$$

at $x = \pm z$,

$$T = \frac{0.175\,M}{z^3}$$

at $x = \pm 2z$,

$$T = \frac{0.125\,M}{z^3}$$

The monopole shown here has only radial components whose intensity is expressed by

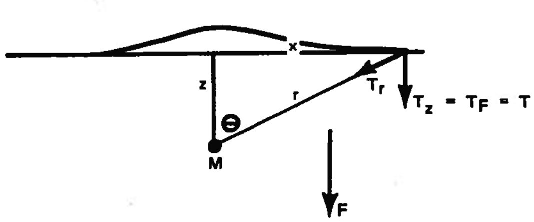
$$T_r = \frac{M}{r^2}$$

The monopole anomaly in a vertical field as measured by a total field magnetometer would be the component in the z direction (vertical) or

$$T_z = T_r \cos\theta$$

$$= \frac{M\cos\theta}{r^2}$$

$$= \frac{Mz}{(x^2 + z^2)^{3/2}}$$



assigning $T_z = T$, the anomaly

at $x = 0$,

$$T = \frac{M}{z^2}$$

at $x = \pm z$,

$$T = \frac{0.35\,M}{z^2}$$

at $x = \pm 2z$,

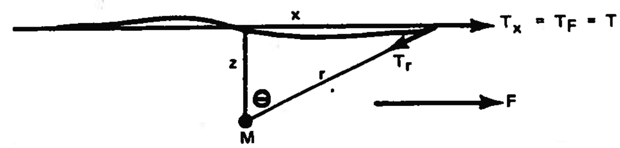
$$T = \frac{0.09\,M}{z^2}$$

The monopole field in a horizontal field would be measured by a total field magnetometer as the horizontal component, T_x where

$$T_x = T_r \sin\theta$$

$$= -\frac{M}{r^2}\sin\theta$$

$$= -\frac{Mx}{(x^2 + z^2)^{3/2}}$$



Again, $T_x = T_F = T$, the anomaly, where

at $x = 0$,

$$T = 0$$

at $x = z$,

$$T = -\frac{0.35\,M}{z^2}$$

at $x = -z$,

$$T = \frac{0.35\,M}{z^2}$$

at $x = 2z$,

$$T = -\frac{0.18\,M}{z^2}$$

at $x = -2z$,

$$T = \frac{0.18M}{z^2}$$

Maximum Amplitude Given Magnetization and Generalized Form

The magnetic moment M is more usefully expressed as

$$M = IV$$

where I is the magnetization (i.e., magnetization contrast) per unit volume and V the volume. This magnetization is composed of a usually unknown proportion of remanent magnetization, I_r, and induced magnetization I_i. The latter as expressed in Chapter III is

$$I_i = kF$$

where k is the magnetic susceptibility per unit volume and F the earth's field or ambient inducing field. (NOTE: Since I_r is seldom known, an effective magnetization, $I = I_i + I_r$, will always be used. Also it is assumed that $k<10^{-2}$, i.e., the source under consideration contains less than 10% magnetite; then one can ignore what is known as demagnetization effects in the calculation of anomaly amplitude).

Therefore, for a dipole which can always be assumed for a source all of whose dimensions are small with respect to the distance (less than ⅕ or $\frac{1}{10}$) to the magnetometer,

$$T = \frac{M}{r^3} = \frac{IV}{r^3} = \frac{kFV}{r^3}$$

If the source is approximately spherical, then

$$T = \frac{kF\,(\frac{4}{3}\pi R^3)}{r^3}$$

where R is the radius of the source as in *Figure 28*

If the measurement is made along the axis of the dipole (see *Figure 29)*, then

$$T = \frac{2kF\,(\frac{4}{3}\pi R^3)}{r^3}$$

$$T = \frac{kF\left(\frac{4\pi R^3}{3}\right)}{r^3}$$

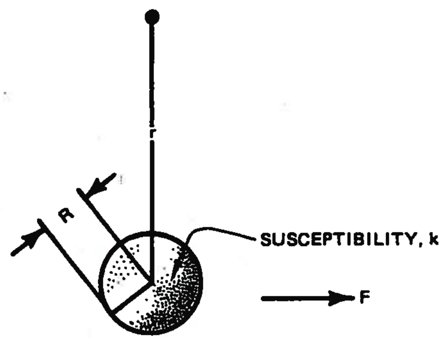


Figure 28. Anomaly of Sphere in Horizontal Field

$$T = \frac{2kF\left(\frac{4\pi R^3}{3}\right)}{r^3}$$

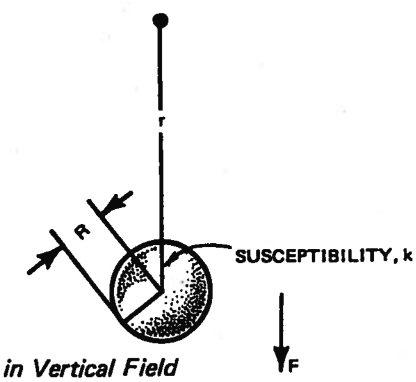


Figure 29.
Anomaly of Sphere in Vertical Field

As an example, consider an ore body 100 feet wide (R = 50), 500 feet deep comprised of 10% magnetite (k = 0.3), in a steeply dipping field (60° to 90° latitude) in a field of 60,000 gammas:

$$T = 2\,(0.10 \times 0.3) \times 6 \times 10^4 \left(\frac{4\pi}{3}\right)\left(\frac{50}{500}\right)^3 = 14.4 \text{ gammas}$$

For the same ore body in an equatorial field where F = 30,000 gammas and the induced dipole is now observed at a point on a line normal to the axis (no factor of 2)

T = - 3.6 gammas

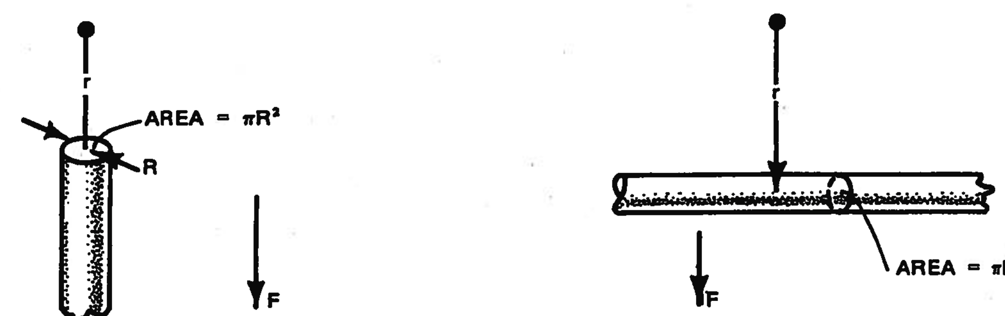
Thus a given dipolar source in an equatorial field will have only ¼ the maximum anomaly amplitude it would have in a polar region.

The above expressions are usually valid only for such sources as a small distant ore body (containing magnetite), small structure in deep basement, or most objects involved in search applications (see Chapter VII). The magnetization is expressed in gauss or gammas as desired. Since the anomalies are also expressed in terms of magnetic units, it follows that the units of dimension in the numerator must be of the same order as the denominator since they must cancel. Therefore, for a dipole whose anomaly varies as $\frac{1}{r^3}$ (said to have a fall-off of $\frac{1}{r^3}$), the volume, V, has dimensions of R^3. In the case of a monopole, which varies as $\frac{1}{r^2}$, the magnetic moment, M, is equal to IA where A is surface area and has dimensions of R^2. Consider for example, a vertical basement intrusive in a polar region with an upper surface 1000 feet in diameter at a depth of 5000 feet, with a susceptibility contrast of 10^{-2} in a field of 60,000 gammas. Thus,

$$T = \frac{kF\,\pi R^2}{r^2} = 10^{-2} \times 6 \times 10^4 \times \pi\left(\frac{50}{500}\right)^2 = 18 \text{ gammas.}$$

Horizontal prisms or cylinders also vary as $\frac{1}{r^2}$, with magnetic moment M equal to 2IA (IA for E-W horizontal prisms in equatorial regions) where A is the cross-sectional area of the prism *(see Figure 30)*. (NOTE: The long horizontal prism varies as $\frac{1}{R^2}$ not because it appears to be comprised of a monopole, but because it is a line of dipoles (in steeply dipping fields) and the effect of adjacent dipoles along an infinitely long line is 'seen' more by the magnetometer at a distant point of measurement than if all the magnetization were concentrated at a point as in an isolated dipole).

$$T = \frac{kF\,\pi R^2}{r^2}$$



$$T = \frac{2kF\,\pi R^2}{r^2}$$

(NOTE: ALSO VALID FOR END OF N-S HORIZONTAL CYLINDER IN HORIZONTAL FIELD)

(NOTE: ALSO VALID FOR E-W HORIZONTAL CYLINDER IN HORIZONTAL FIELD)

Figure 30. Anomaly of Vertical and Horizontal Cylinders

A narrow, vertical dike in steep field or the edge of a horizontal sheet in a horizontal field can be considered as a line of monopoles varying as 1/r which is a lower rate of fall-off than a single monopole for the same reasons given above for a horizontal cylinder *(see Figure 31)*. The magnetic moment M = It where t = width of dike. Since the anomaly varies as 1/r, the dimensions of t are simply length. As an example, a vertical dike might be 100 feet wide, at a depth of 500 feet, with $k = 10^{-3}$ in a field of 50,000 gammas, or

$$T = \frac{kFt}{r} = \frac{10^{-3} \times 5 \times 10^4 \times 10^2}{5 \times 10^2} = 10 \text{ gammas}$$

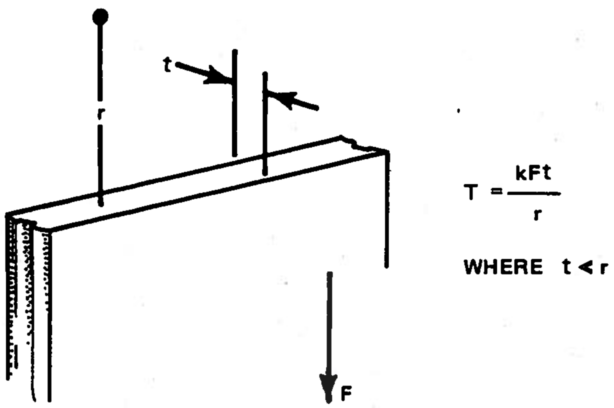


Figure 31. Anomaly of Narrow Vertical Dike

A common point of ambiguity arises with such simplified schemes as these in the case of a dike which is nearly as wide as it is deep. In this case, the anomaly is approximated as something between a line of monopoles as above and a sheet of monopoles as shown in the following. Moreover, as the dike is even wider than its depth, it can be approximated simply by 2 faulted contacts with 'no anomaly' in between.

For a semi-infinite slab of material such as a rock surface of great thickness and breadth in a non-horizontal field, the flux lines do not vary in direction or density above the slab, therefore the field does not vary at all with distance to its surface (similar to the limit of the spherical dipole above where R = r) so that

$$T = \frac{M}{r^0} = \frac{2\pi I}{1}, \text{ or } T = 2\pi kF$$

which is useful in estimating the magnitude of the anomaly at a vertical fault *(see Figure 32)*. For example, consider two rock types at a vertical contact of $k = 10^{-3}$ and $k = 10^{-5}$ for an effective susceptibility contrast of $k = 10^{-3}$ ($10^{-5} \approx 0$ relative to 10^{-3}) and where F = 50,000 gammas. Thus

$$T = 2\pi \times 10^{-3} \times 5 \times 10^4 = 300 \text{ gammas}$$

If the rocks had $k = 10^{-4}$ and 10^{-3}, the effective susceptibility contrast would be

$$10^{-3} - 10^{-4} = 10 \times 10^{-4} - 10^{-4} = 9 \times 10^{-4} \text{ and}$$

$$T = 2\pi \times 9 \times 10^{-4} \times 5 \times 10^4 = 270 \text{ gammas}$$

This simple example of two adjacent rock types is probably applicable in more instances in interpretation than any of the other geometries discussed above.

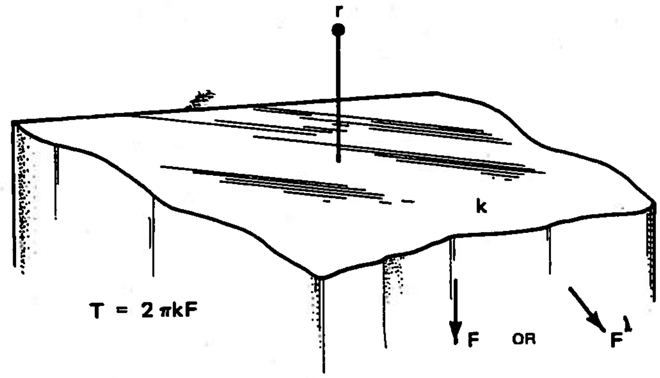


Figure 32. Anomaly of Semi-infinite Slab

Anomaly Depth Characteristics

In a very approximate fashion, the wavelength, or, effective width (or 'half-width' described in the following) of the anomaly and, with more accuracy, the width of certain characteristics of the anomaly such as slope, are measures of the depth to its source. However, recognition of the anomaly, the anomaly 'zero' and certain slopes would not only appear as different values as determined by different interpreters, but they also depend upon what is removed as the regional gradient. More objective criteria are used in some cases such as the nearly straight portions of a slope, and distances and angles between inflection points, peak values and other anomaly characteristics.

Anomaly Width

In general, the anomaly width as shown in *Figure 33* is on the order of 1 to perhaps 3 times the depth. Thus, when an anomaly appears to have a width as such of 100 feet, it is definitely not produced by a source at 1000 feet or at 10 feet, but more likely by a source between 30 and 100 feet deep (or distant). Such criteria, approximate as it is, is nevertheless useful for cursory interpretation of profiles and maps.

Anomaly Depth Estimation

Much is written on the variety and relative merit of methods for estimating the depth to the source of anomalies. Since the magnetometer is primarily a tool for subsurface mapping and detection, it follows that determination of the depth as well as edges of bodies is important in its application to geological exploration and search. The basis for depth determination is presented here in brief which, together with the foregoing background on anomaly behavior, should allow one to at least appreciate how a variation in depth affects an anomaly. In most cases, one needs only to apply this knowledge qualitatively through visual inspection of a profile. Whatever the requirement, depths may be estimated by visual inspection, several rules of thumb, modeling (i.e., calculation of assumed source and comparison with observed), measured gradient techniques (see Chapter VIII), or various computer-oriented procedures. As was demonstrated earlier, a given anomaly could have an infinite number of possible sources and source depths, but the realistic models that are assumed usually produce maximum depth estimates.

Knowledge of the depth of a particular formation or source may have considerable geological significance as it determines the nature or configuration of a forma-

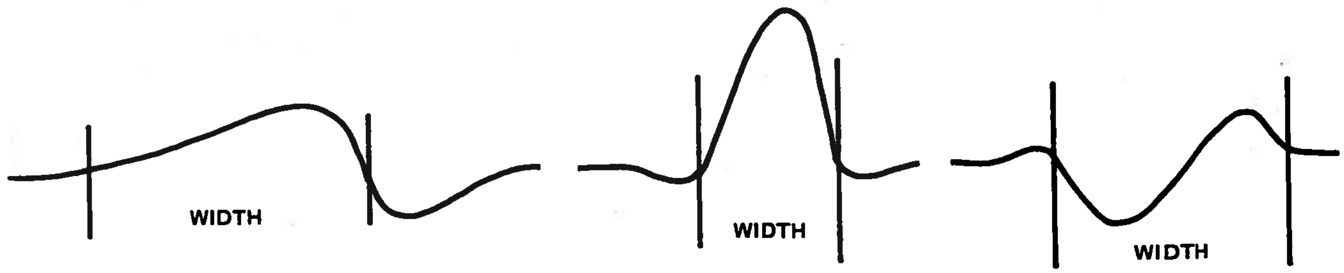


Figure 33. Anomaly 'Width'

tion, the slope of its surface and its discontinuities. The depth to various points on the surface of crystalline rock or magnetic basement allows one to map that surface and its topography and structures to depths exceeding 30,000 feet and to infer thickness of sediments or conformable sedimentary structures above it for exploration of petroleum, sedimentary ores, placer deposits or groundwater. Areas underlain by pediment or other sedimentary deposits may be ruled economic or noneconomic according to depth. The depth to ore deposits associated with pyrrhotite, magnetite or ilmenite may be estimated as an aid to a drilling program or even for estimation of total tonnage of magnetic iron ore deposits. Black sand deposits of rutile, zircon, monazite, diamonds, gold, platinum, etc. are often associated with other high density, very resistant yet magnetic minerals, namely, magnetite or ilmenite. The depth to objects of search whether buried iron or man-made structures is invaluable in guiding the subsequent excavation efforts.

Identification of Anomaly

The anomaly of interest must be identified and discriminated against the obscuring effects of others. Recognition of the anomaly itself is usually the most difficult aspect of depth determination because of the composite effects of multiple sources, sources at various depths and at various distances in any direction from the magnetometer. Only the net effect of all anomalies are measured by the magnetometer since it has no inherent discrimination ability at the disposal of the operator. The anomaly should be inspected to ascertain the probable source and, if complex, the possible combination of sources. For example, a wide, shallow dike will appear as two anomalies which may or may not coalesce depending upon the relative width and depth. A very broad anomaly or regional gradient (described in Chapter IV). is usually caused by anomalies which are extremely deep or distant or by the normal variation in the earth's magnetic field. If one wishes to remove this gradient, it can be done either by drawing a straight line through the non-anomalous portions of the profile (away from the anomaly of interest) or by drawing a very smooth but broad wavelength curve through the data of much longer wavelength than any anomalies of interest. This regional gradient or background is then subtracted from the anomaly and the remaining, or residual anomaly, replotted. It is this anomaly which is then interpreted for either depth or for amplitude or general configuration of sources as described in Chapter IV.

Fall-Off Rate

The variation of anomaly amplitude with distance, or fall-off rate, is important in the interpretation of anomalies for it relates the anomaly to depth, it describes in a general way the configuration of the source, and it assists in determining susceptibility and mass of the causative magnetite. Recall that the anomaly from a dipole varies as $\frac{1}{r^3}$ and that of a monopole as $\frac{1}{r^2}$. The fall-off rate, in actual practice, does not involve precisely such factors or exponents but, in fact, is typically $\frac{1}{r^{2.5}}$, $\frac{1}{r^{0.6}}$, etc., or even $\frac{1}{r^0}$ as described above. In other words, various configurations of dipoles, monopoles, lines and sheet-like distributions of these poles constitute a continuous series of fall-off rates even in the vicinity of a single anomaly as one is much closer or further away from the source.

Representing various geologic sources as simple prismatic bodies, one may assume the following fall-off rates: a dipole will be produced by a source all of whose dimensions are small (less than 1/10 compared to the distance between the source and magnetometer). Such a body is rarely seen in nature except as a very confined, usually magnetite-rich ore body. A monopole varying as $\frac{1}{r^2}$ will be produced by a long, thin, vertical prism, such as a narrow vertical intrusive in steeply dipping fields or a horizontal cylinder striking N-S in equatorial fields (e.g., a N-S anticlinal structure on the basement, one end of which is near the magnetometer). A line of dipoles is produced by a long, horizontal cylinder magnetized through its short dimension as in steeply dipping latitudes or striking E-W in equatorial regions. Such a cylinder will also vary as $\frac{1}{r^2}$. A line of monopoles would effectively be observed near one edge of a dike dipping in the direction of the field and would vary approximately as $\frac{1}{r}$. At a point above a horizontal semi-infinite sheet, the field would vary inversely as $\frac{1}{r^0} = 1$, which is another way of expressing the fact that the field does not vary at all with distance from a horizontal semi-infinite sheet of monopoles or dipoles. A wide vertical dike in a steep field or the edge of a fault might represent combinations between a line of dipoles or sheet-like distribution of monopoles and may thus vary as $\frac{1}{r^2}$ or $\frac{1}{r^{0.5}}$ or less. *Figure 34* indicates these variations.

Assumptions on Maximum Amplitude and Depth Estimates

Unless the remanent magnetization is actually measured, it is generally disregarded, and only the induced magnetization and susceptibility are utilized in these expressions. The magnetic anomaly calculated from these

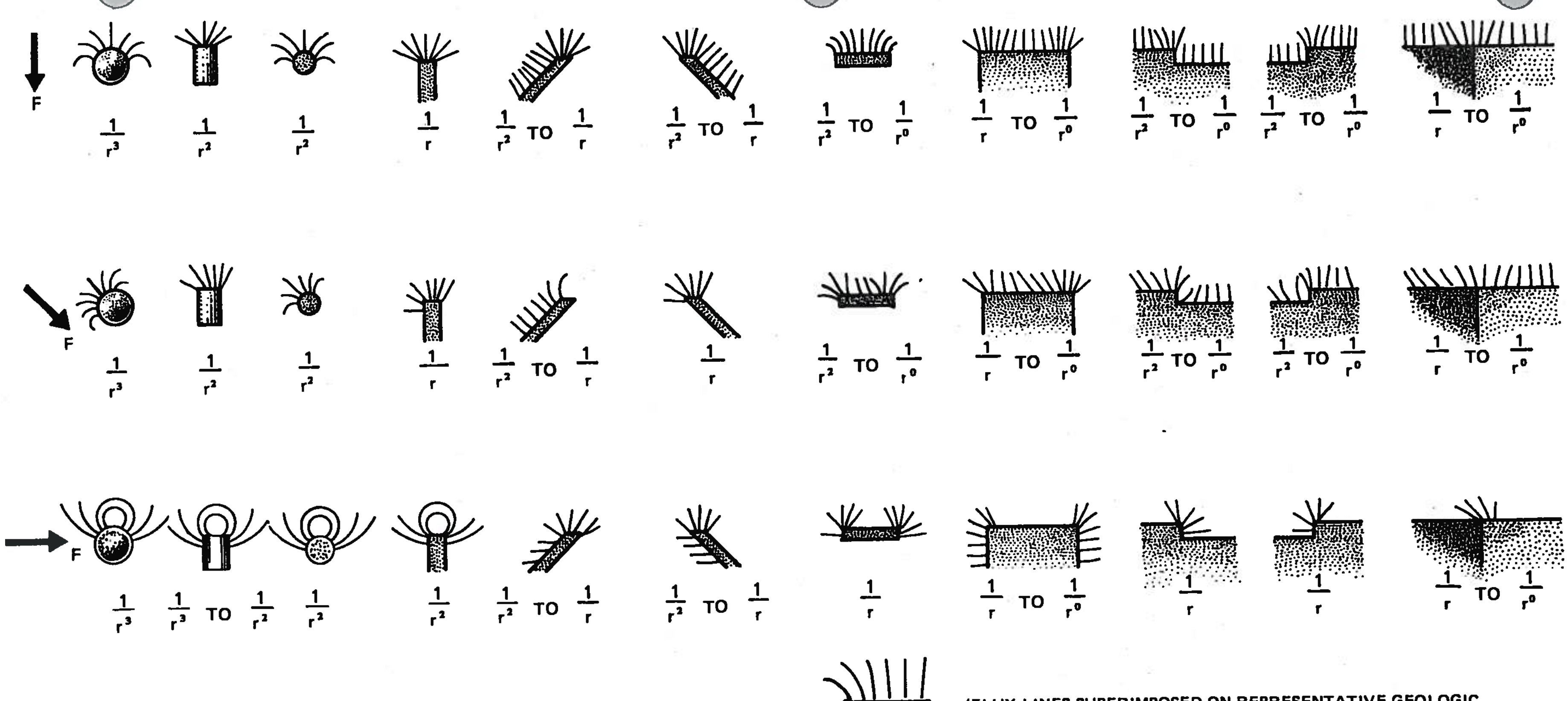
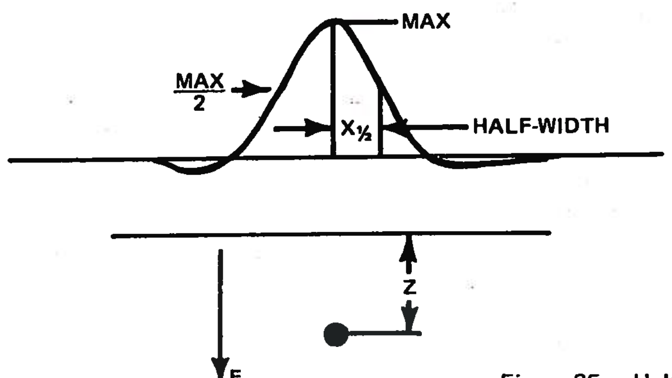


Figure 34. Field Lines and Fall-Off Rates of Various Geologic Models

(FLUX LINES SUPERIMPOSED ON REPRESENTATIVE GEOLOGIC MODELS FOR VARIOUS ORIENTATIONS OF INDUCING FIELD. ANOMALY AMPLITUDE PROPORTIONAL TO INDICATED TERM OF $1/r^n$.)



SPHERE (DIPOLE)	$Z = 2X_{1/2}$
VERTICAL CYLINDER (MONOPOLE)	$Z = 1.3X_{1/2}$
EDGE OF NARROW DIKE (LINE OF MONOPOLES)	$Z = X_{1/2}$
HORIZONTAL CYLINDER (LINE OF DIPOLES)	$Z = 2X_{1/2}$

Figure 35. Half-width Rules – Vertical Field

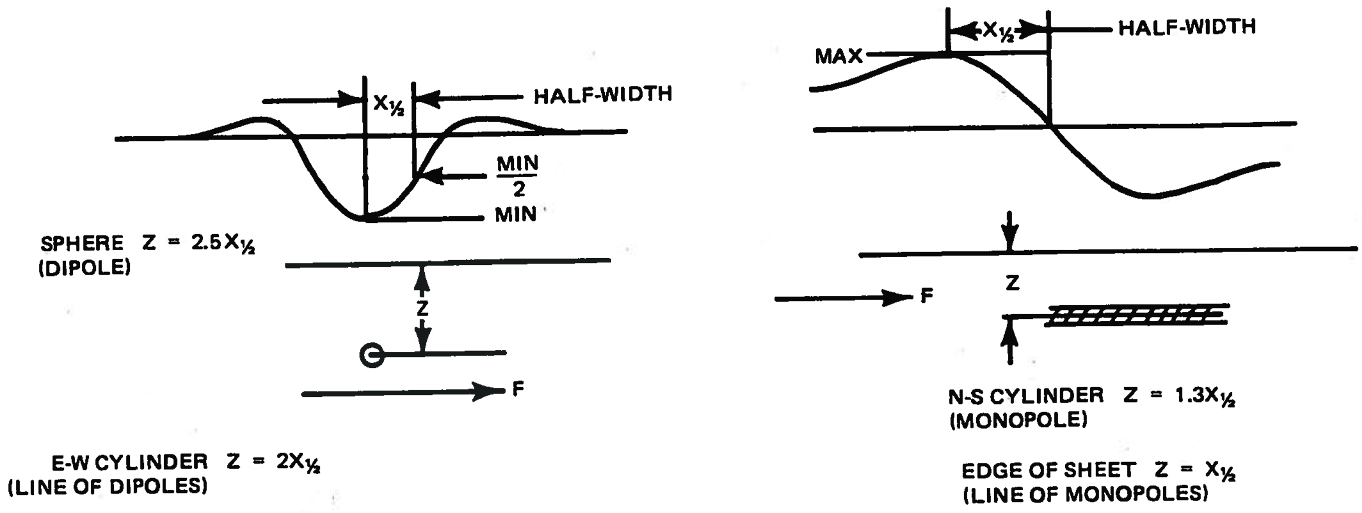


Figure 36. Half-width Rules – Horizontal Field (Equatorial)

highly simplified expressions represents the maximum amplitude from the local zero, non-anomalous field to the positive peak value in the northern and sourthern latitudes and to the minimum negative value in equatorial regions. It does not represent the peak-to-peak value which includes both positive and negative portions of the anomaly signature. The depth estimates derived from any of the techniques described are seldom more accurate than 10% of the actual depth and sometimes as poor as 50%. By theory most of the estimates are maximum estimates so that the actual source will actually be at a shallower depth. Moreover, the 'poles' or source described frequently throughout their chapter are within the geologic body or object of search and not simply on the surface; therefore, such depths are again maximum depths.

Half-Width Rules

In vertical or horizontal fields, it can be shown, from the previous expressions for dipoles and monopoles, that for simple forms of anomaly sources, the depth to their centers is related to the half-width of the anomaly. The half-width is the horizontal distance between the principal maximum (or minimum) of the anomaly (assumed to be over the center of the source) and the point where the value is exactly one-half the maximum value *(see Figure 35)*. This rule is only valid for simple-shaped forms such as a sphere (dipole), vertical cylinder (monopole), and the edge of a narrow, nearly vertical dike (line of monopoles) in the polar regions. At the magnetic equator, the half-width rules are somewhat different with the sphere remaining unchanged, an E-W horizontal cylinder being a line of dipoles, a N-S cylinder being a monopole, and the edge of an E-W striking horizontal sheet representing a line of monopoles. The rules presented in *Figure 36* apply according to the corresponding array of poles and in the case of the latter two, the half width being the horizontal distance between the point of maximum (or minimum) and zero anomaly. The half width rules are derived from formulae given above in "Dipole and Monopole Signatures in Vertical and Horizontal Fields".

Slope Techniques

Perhaps the most commonly used set of methods for estimating depth are those which utilize criteria involving the measurement of the horizontal gradient or slope at the inflection points of the anomaly. Based upon empirical observations utilizing computed models, these slopes are measured according to the horizontal extent of the 'straight' portion of the slope *(see Figure 37)* or the horizontal extent determined by different combinations of the tangent or slope at the inflection point, maximum of the anomaly and half slopes, etc. Each of these horizontal distance measurements when multiplied by an empirically-determined factor equals the depth to the top of the anomaly source. (The straight-slope, for example, is multiplied by a factor between 0.5 and 1.5). Detailed explanations of these methods are available in the references cited.

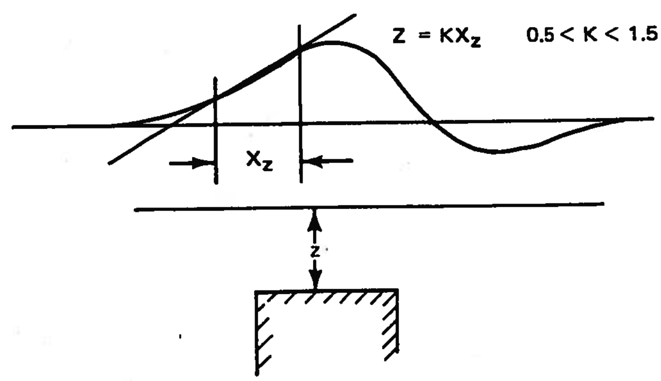


Figure 37.

Other Depth Estimating Methods

Modeling techniques require that one examine the observed anomaly for its likely source configuration. A model is assumed, the anomaly calculated, compared with the observed and repeatedly altered until a satisfactory fit to the observed data is finally achieved, with such work usually performed on a computer. Other computer-oriented depth estimating methods include programs utilizing Fourier and Hilbert transforms, convolution and other semi-automated programs which are usually applied to large volumes of data. Gradiometer measurements made with sensors at two points usually vertically arranged can also be used for depth estimates (see Chapter VIII).

Interpretation Summary

Interpretation is facilitated if one can thoroughly familiarize himself with how and why a given source produces an anomaly in the earth's field, the nature of total field measurements and the general behavior of an anomaly signature with increasing depth. What at first may have appeared complex in the interpretation of field profiles and maps is more readily understood when the above phenomena are examined one at a time.

The first procedure that should be followed in the interpretation of a given profile is to focus on the anomaly width and shape and attempt to construct at least a mental image of the source in realistic geologic terms (or object in the case of search) and its depth. Use the eye to discriminate against noise and the regional gradient or filter by one of the suggested techniques. Anomalous horizontal gradients should then be used, for lack of any other specific criteria, as an indicator of the edge of subsurface structures producing a magnetization contrast. Most anomalies on any given profile or map represent a simple contrast in magnetization or lithology, i.e., the edge of a body. Attempt to correlate such features on adjacent lines or interpret them as contacts on a total intensity contour map. The cessation, displacement or interruption of otherwise long or continuous features may also represent significant geologic structural information. However, one must realize also that a magnetic survey is only able to map a contact where there is a magnetization contrast so that, for example, different lithologies on either side of a long continuous fault will be mapped only in segments where such contrasts occur.

Changes in the character of the short wavelength anomalies (noise) may also represent mappable information if one is careful to evaluate their typical depth so as not to be mapping irrelevant soil anomalies. Negative anomalies arising from features of locally lower magnetization are as important geologically as the more common positive anomalies. Furthermore, the *most geologically significant anomalies on a given map are probably the more subtle ones and not necessarily the largest, most prominent anomalies.* Lastly, the total intensity profiles and maps are not an end in themselves, but are rendered usable only when expressed in terms of geology (or objects of a search). The more geological information one has (or size, magnetic or depth information for an object of search) the more valuable the total intensity data becomes and vice-versa.

SITE INVESTIGATION REPORT

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CHEMICAL SPECIALTIES

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