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Application of digital computer to magnetic data interpretation using surface integral method

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APPLICATION OF DIGITAL COMPUTER TO MAGNETIC DATA INTERPRETATION USING SURFACE INTEGRAL METHOD

BY

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ABSTRACT

A simple method is developed for the calculation of the magnetic effect due to three-dimensional bodies. The method is based on the use of surface integration instead of volume integration. Thus, any three-dimensional body can be considered as having two surfaces, upper and lower, with magnetic pole distributions. Simple equations based on potential theory have been derived for the calculation of the vertical component and total intensity due to these surface distributions of poles. The anomalous field of the body can be obtained by subtracting the effect due to one of the surfaces from that of the other.

The method can be applied to the interpretation of magnetic anomalies arising mainly from structures or polarization contrasts in the magnetic basement rocks.

The calculations have been programmed in a fixed point system for the Royal McBee LGP-30 electronic digital computer. The programs may be used for either vertical magnetometer data or total intensity data. Application to some theoretical models establishes the relative accuracy of the method.

The technique has been presented as an application of the digital computer to magnetic interpretation where the time required to obtain computed results is an economic factor.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

LIST OF FLOW CHARTS

Flow Chart | Page

I. INTRODUCTION

A. GENERAL

The problem of magnetic interpretation is how to use the measured magnetic data to obtain information about the hidden geological subsurface. The measurements may be done at the surface mostly by a vertical magnetometer or above the surface of the earth by an airborne magnetometer. It is known that most, but not all, sedimentary rocks are practically non-magnetic, while crystalline rocks of igneous origin, such as granite, basalt, and gabbro, containing appreciable amounts of ferromagnetic minerals, are sufficiently magnetic to influence the earth's magnetic field at or above the surface of the earth. Due to this fact, it can be stated that in most areas the problem of magnetic interpretation is to deduce as much information as possible concerning the nature and structure or topography of and the depth to the igneous basement rocks.

The importance of the magnetic method is that it has been widely used in the mining field both directly to search for magnetic ores such as magnetic iron deposits, and indirectly to locate non-magnetic minerals or structures favorable to their occurrence if they were associated with magnetic materials, and can be outlined by magnetic means. Magnetic methods, in some cases, have been used successfully in petroleum prospecting, where oil-bearing structures in the sedimentary section are associated with topographic features in the underlying basement rocks. Many examples of applications of magnetic methods can be found in the geophysical case histories. (See Bibliography)

B. PURPOSE OF INVESTIGATION

In spite of its importance, magnetic interpretation is not simple. The results of a magnetic survey are more difficult to interpret, even, than those of a gravity survey which can be very similarly interpreted. This is due to the fact that more factors are involved in magnetic interpretation, such as the direction of the magnetizing vector. Accordingly, in the case of an aeromagnetic survey, where the variations of the total magnetic field are recorded, the difficulty is further increased than in the case dealing with only the magnetic vertical component.

Baranov (1957) stated that

> "In magnetism, the computation is much more complicated and a great number of variable factors must be taken into account, such as the inclination of the normal field, the orientation of the structure with respect to the magnetic meridian, and so on."

Several methods for magnetic interpretation have been described in the literature. Most of these are considered as standard methods which can be used successfully to yield the most probable interpretation. However, a lot of computations are involved requiring many man hours.

So, it was the purpose of this investigation to develop a simple method for magnetic interpretation with a minimum of calculations and to find a means for manipulating these calculations in a minimum of time. The increasing availability of the electronic digital computers at many places makes their use for the solution of these magnetic problems feasible. The principal advantages of using the computer are substitution of computer time for human time and strain, and increased accuracy of the results. Computer time ranges from hours or fraction of an hour needed by the smaller computers to minutes with the much faster computers.

C. METHOD OF INVESTIGATION

The magnetic anomaly of a three-dimensional body of arbitrary shape is calculated. Either the vertical or the total intensity anomaly, or both, can be computed according to the types of the surveyed magnetic map or maps to be considered. The method used in interpretation is the standard indirect method: a certain distribution of magnetic material is assumed, the field due to this assumed distribution is calculated and then the distribution has to be modified until the calculated field fits as closely as desired the observed data.

The theory involved is that, if a uniform polarization is assumed, the magnetic effect of a body can be approximated by surface integration rather than volume integration which is the basis of most other methods. The body is considered to have two surfaces; the effect due to the lower surface has to be subtracted from that due to the upper surface to obtain an approximation of the magnetic anomaly produced by the body.

Programs of the computations have been written in fixed point system for the Royal McBee LGP-30 electronic digital computer of the

Missouri School of Mines. Applications to some theoretical models establish the relative accuracy of the method.

D. PREVIOUS WORK

Various procedures have been developed in the literature for interpreting magnetic data. Some of these are direct or analytic; others are indirect or synthetic. Some are used for the treatment of vertical intensity anomalies; a few others are used for total intensity anomalies. Some can be applied to point or line sources; others can be applied to two-dimensional bodies. However, few methods are available for three-dimensional cases.

In the analytic method, the data are analyzed directly to yield the approximate size, shape and depth of a possible anomalous distribution. The contribution to this method due to Peters (1949) was outstanding. He described some analytical techniques for interpreting magnetic data in deep basement areas on a routine basis. One of these methods is the downward continuation of the observed vertical field to the source, and then by removal of the regional contours, the basement topography can be calculated from the residual anomalies. He described also a "slope" method for depth estimation using the maximum slope of the anomaly curve and a more general method which he called "error curve" method based on the idea that, if continuation of the observed magnetic intensity is carried downward to a certain depth and then back up again, fairly accurate results are obtained until the depth of burial is approached. Beyond this depth the error increases rapidly. Henderson and Zietz (1949) in a pair of papers have worked out grid systems for computing second derivative maps and also for upward continuation from total magnetic intensities.

Dean (1958) developed a linear filter theory for gravity and magnetic interpretation. He indicated that the operations of second derivative, analytic continuation, smoothing, the removing of residuals or regionals are analogous mathematically to the filtering action of electric circuits except that they must act on functions of two space variables (x and y). He showed that the frequency response of upward continuation is an exponential function decreasing with increasing frequency, while the downward continuation has a frequency response which is the reciprocal of that of upward continuation.. His method consists of matching frequency responses by coefficient sets. Henderson (1960) devised a comprehensive system of calculation of first and second vertical derivatives or downward continuation of magnetic and gravity fields for electronic digital computers.

The synthetic method, on the other hand, is an indirect one involving trial and error. It is more common and can be applied by using graphical aids or models. Nettleton (1942) computed several typical profiles for the theoretical variation of vertical magnetic intensity due to different simple geometrical forms. Profiles of the actual anomaly can be compared with these theoretical profiles and the depth to the center of the source can be deduced from relations between this depth and the half width of the anomaly curve. Henderson and Zietz (1948) have developed curves by which the depth of isolated poles or of a line of such poles can be calculated from the total intensity profile obtained over each kind of feature. Smellie (1956) modified this work by adding methods of point dipole and lines of dipoles. Hutchison (1958) has developed a method for depth-breadth determinations of magnetized dikes and other related two-dimensional classes by superimposing the observed magnetic profile plotted logarithmically over a family of logarithmic master-curves for dikes of different assumed shapes. Also Cook (1950) has computed anomalies for a large variety of model dikes: vertical, inclined, infinitely deep, of finite depth, striking north, striking east, etc. Henderson and Zietz (1957) showed that calculations of the total intensity anomaly for theoretical and practical three-dimensional bodies are greatly facilitated by the orthographic projection of a topographic map of the body onto a plane normal to the inducing field.

Using model experiments, Zietz and Henderson (1956) devised a rapid method for calculating magnetic anomalies of three-dimensional structures by determining the magnetic fields of certain models at different depths and for several magnetic inclinations. However, this method has been adequately treated in the work of Vacquier, et al (1951) who computed an album of total intensity anomalies due to models of prismoidal forms having different dimensions and having been set up for different inclinations and orientations with respect to the external field. Vacquier in this work suggests the use of the curvature, which is proportional to the second derivative, in conjunction with the prismatic models to estimate depths to the basement. The method is considered most reliable for sources due to lateral susceptibility contrasts in the basement and having dimensions which are large compared to depth of burial.

Other workers who contributed to the magnetic interpretation include Skeels and Watson (1949) who showed that magnetic and gravitational quantities can be calculated by surface integration of the vertical component if the latter is known over a horizontal plane surface of sufficient extent. Also Hughes and Pondrom (1947) developed a method to compute the vertical magnetic anomalies from total magnetic field measurements, while Affleck (1958) expressed the relationships between the various magnetic anomaly components. This was found to be useful in predicting anomaly shapes for any magnetic latitude and in simplifying calculations of aeromagnetic or other component intensity anomaly for rock masses. Baranov (1957) described a new method for interpretation of aeromagnetic maps based on transformation of the total magnetic intensity anomalies into simpler anomalies "pseudo-gravimetric anomalies" in which the distortion due to the obliquity of the normal magnetic field is eliminated.

Some other articles approaching the subject are those by Alldredge and Dichtel (1949), Fisher (1940), Gassman (1951), Pirson (1940), and others. (See Bibliography)

II. THEORETICAL ANALYSIS OF MAGNETIC DATA

A. METHODS OF ANALYSIS

The usual treatment of magnetic data is almost exclusively empirical. Deduction and inference regarding the subsurface structure are drawn in a qualitative manner from the configurations and sizes of the magnetic anomalies. However, this empirical treatment is based partly on a knowledge of the theoretical anomalies produced by certain inhomogeneities. Sometimes a theoretical type of analysis is applied to the problem.

The theoretical procedure for deducing subsurface structure from magnetic data can be summarized as follows:

1. Assume:
   - (a) A certain structure or configuration of the subsurface formations which must be geologically plausible. The size and shape of the magnetic anomalies might help in this starting step.
   - (b) Probable values of the susceptibilities. Informations from drill holes or other sources may be used for choosing the appropriate susceptibility.
2. Compute the theoretical magnetic effects which the assumed configuration and susceptibility would produce at the surface.
3. Compare the theoretical and observed results.

4. Modify the assumptions until a satisfactory agreement is obtained between the observed and theoretical data.

In calculating the theoretical magnetic anomalies, different methods can be used:

1. Effect due to a single pole. This can be used directly in case of bodies having small cross section relative to their length, provided their depth extent is large enough that the effect of the magnetic pole at the lower end can be neglected.
2. Effect due to a dipole (vertical, horizontal, or inclined). This can be used if the depth of the subsurface body is too small to permit neglecting the effect of the lower pole.
3. Effect due to uniformly magnetized bodies having geometrical shape like the sphere; horizontal and vertical cylinders, ellipsoids of revolution, etc.
4. Effect due to two- and three-dimensional bodies of other shapes like magnetized strata, structures in the basement rocks, etc. This can be calculated by making use of the three previous methods.

The calculation of the magnetic effects of three-dimensional bodies, especially structures in the basement, is emphasized in this investigation. To do this, we have to know the field due to a single pole.

B. CALCULATION OF THE FIELD DUE TO A SINGLE POLE

1. Coordinate System:

The coordinate system used in the mathematical development is a right-handed one. If we rotate the x-axis into the y-axis, a right-hand screw will advance along the positive z-axis (fig. 1). In other words, we are going to take the x-axis positive toward the north, the y-axis positive toward the east, and the z-axis positive vertically downward.

2. Mathematical Discussion:

In mathematics, a potential is often defined as a mathematical expression such that its derivative or rate of change in any particular direction is a force of some kind in that direction. The magnetic potential U referred to in this section is a function of space such that the negative of its partial derivative (or rate of change) in any direction is the magnetic force in that direction. (See Kellogg, 1929, P. 53) Thus, if ΔH_x, ΔH_y and ΔH_z represent the components of the magnetic force in the x, y, and z directions respectively, then:

$$\Delta H_x = -\frac{\partial U}{\partial x}\ ; \qquad \Delta H_y = -\frac{\partial U}{\partial y}\ ; \qquad \Delta H_z = -\frac{\partial U}{\partial z} \text{ ---(1)}$$

Physically, the magnetic potential at any point P due to a pole of strength m is defined as the work done on a unit magnetic pole in carrying it from infinity to the point under consideration. This can be expressed by the formula:

$$U = -\int_{\infty}^{r} \frac{m}{r^2}\, dr = \frac{m}{r} \text{ ---------------------(2)}$$

where r is the distance between the pole and the point P (fig. 1) and is given by the equation:

$$r^2 = (x' - x)^2 + (y' - y)^2 + (z' - z)^2$$

x, y, and z are the coordinates of the point P. x', y', and z' are the coordinates of the pole m.

Thus U is a function of the coordinates (x, y, z) of

P and has a definite value at every point P of space external to the magnetic pole m. Equation (2) can be re-written as:

$$U = \frac{m}{r} = \frac{m}{[(x'-x)^2 + (y'-y)^2 + (z'-z)^2]^{\frac{1}{2}}}$$

The components of the magnetic field at point P due to a magnetic pole of strength (-m) are given by the partial derivatives of this equation:

$$\Delta H_x = \frac{\partial U}{\partial x} = \frac{m(x'-x)}{r^3} \quad \text{---------------------} \quad (3a)$$

$$\Delta H_y = \frac{\partial U}{\partial y} = \frac{m(y'-y)}{r^3} \quad \text{---------------------} \quad (3b)$$

$$\Delta H_z = \frac{\partial U}{\partial z} = \frac{m(z'-z)}{r^3} \quad \text{---------------------} \quad (3c)$$

where ΔH_x and ΔH_y are the horizontal components of the magnetic field in the north and east direction respectively, ΔH_z is the vertical component.

C. CALCULATION OF THE FIELD DUE TO THREE-DIMENSIONAL BODIES

1. Types of Anomalies:

There are two general types of magnetic anomalies that can be found in any magnetic survey:

a. Broad anomalies covering large areas and having large amplitude, measured usually by hundreds of gammas. Their intensity depends largely on the depth of burial (fig. 2). These large anomalies are mostly due to lateral changes in susceptibility within the basement complex or, in other words, due to regions of major polarization contrast which

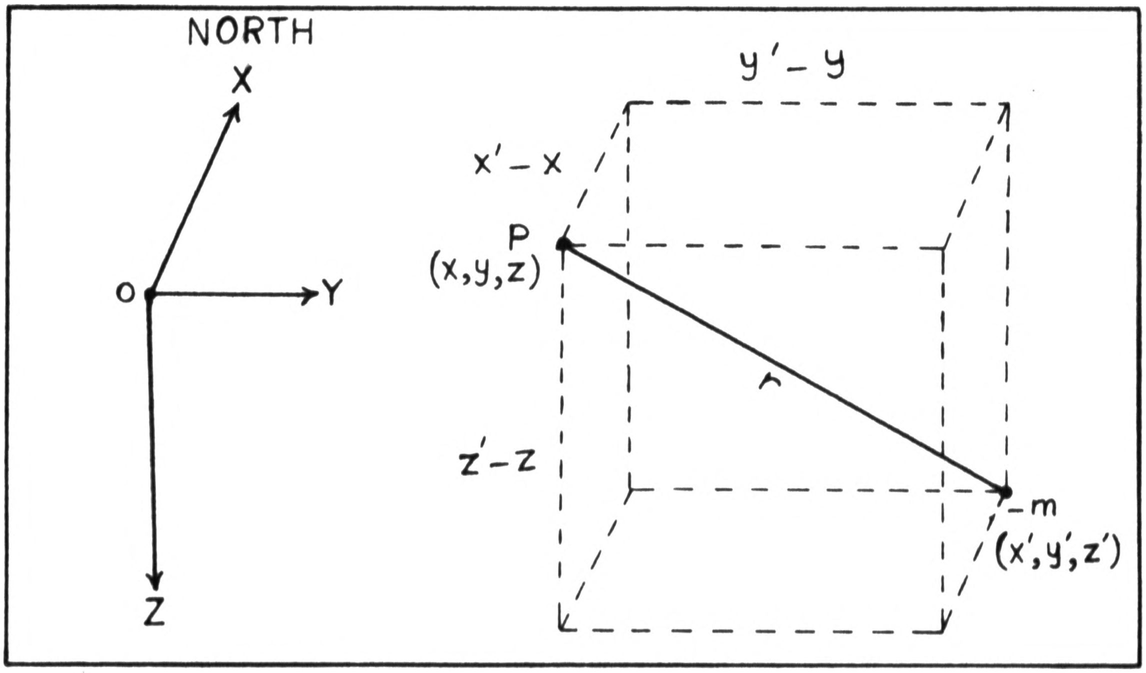


Fig. 1. Coordinate system used in calculating the magnetic fields due to pole (-m).

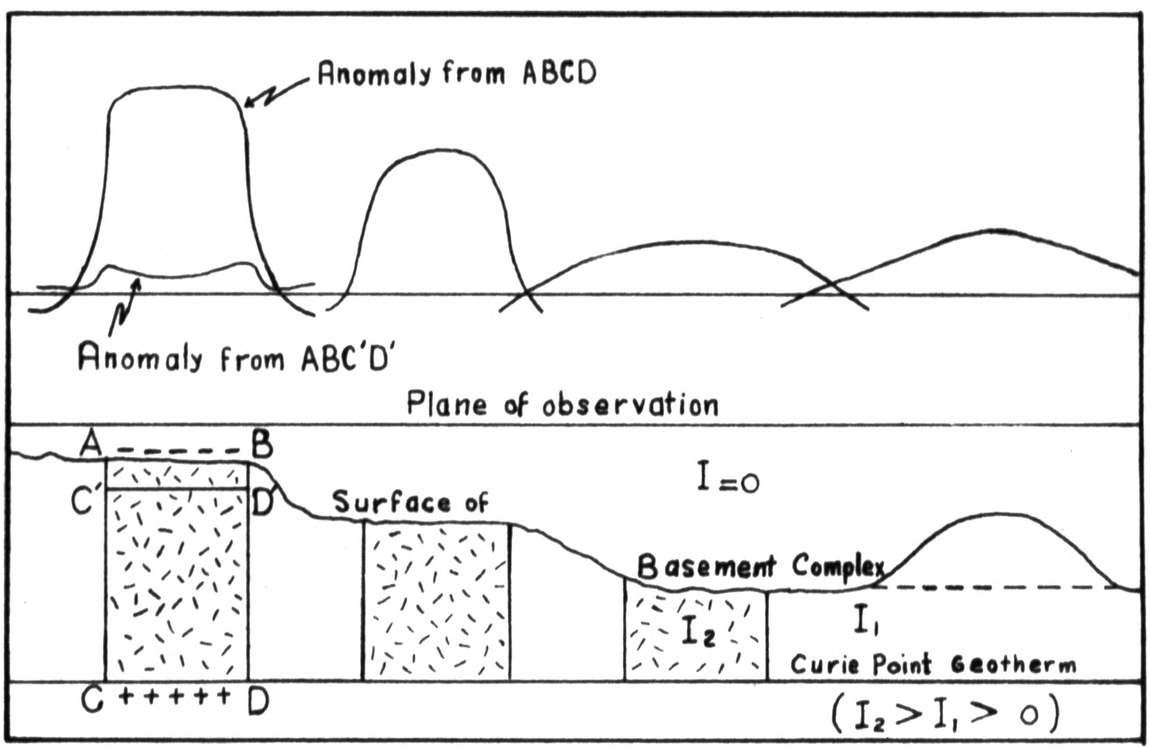


Fig. 2. Types of magnetic anomalies and variation of vertical magnetic intensity anomalies with depth of burial.

(Modified from Vacquier, 1951)

are bounded by approximately vertical surfaces that extend downward several miles from the top of the basement complex to the depth where the rocks cease to be magnetic (i.e., the curve point geotherm) (See fig. 2). The lateral extent of these rock masses is often 10 miles or more. These anomalies can be well-shown in airborne magnetic surveys (Vacquier, 1951). Their nature can be obtained by approximating these masses or regions by prismatic rectangular bodies with flat surfaces and vertical sides having infinite depth.

b. Small anomalies measured usually in tens or units of gamma. These are arising from either one or the other of two causes:

(i) Smaller (shallow and thin) polarization contrast within the basement as the case of a basalt flow. In this case the anomalies are relatively flat. Such a case can be approximated by a thin slab with horizontal top and bottom and having vertical sides, (as indicated by ABC'D' in fig. 2). Vacquier (1951) suggested that the computation of the magnetic effect of this prismatic block can be made by subtraction of the anomalies of two infinitely long prisms.

(ii) Structure or relief of the crystalline rock surface in which case the polarization contrast has sloping instead of vertical boundaries as the case of a buried mountain. The anomalies are relatively sharper. This effect of relief was neglected by Vacquier because the magnetic anomalies produced by relatively small masses (i.e., when the topographic relief is small with respect to depth of burial) would be comparatively small and are usually lost among the much larger anomalies arising from contacts between different rock types. The magnetic effect due to these topographical bodies can be computed directly or indirectly by subdividing it into thin slabs and adding the effects of each of these slabs.

The method developed in this investigation can be applied to each of these cases as will be shown later on.

2. Basic Principles:

To calculate the field due to a three-dimensional body of a given form and polarization, a useful approximation may be obtained by considering the volume magnetization of the body as replaced by magnetic poles on its surface. By Gauss's theorem, for effects at points outside a magnetized body, the volume magnetization within the body can be replaced by a surface distribution of magnetization. Thus, any simple body which is simply magnetized can be considered as having two surfaces: an upper surface with a distribution of negative poles, and an opposite lower surface with an equal distribution of positive poles. Due to this approximation, in calculating the magnetic effect of a body, we can now replace the volume integration throughout the magnetized body by surface integration over its surface.

If a structural or topographical relief in the crystalline basement is more magnetic than surrounding rocks it will have a distribution of negative poles on its upper surface. Thus, its magnetic effect is calculated by carrying the surface integration from minus infinity to plus infinity. However, to avoid this, one can assume a level surface with a similar distribution of negative poles whose effect is subtracted from that of the basement surface. By this subtraction the negative poles are changed to positive ones distributed throughout this level surface which represents the general basement level (indicated by the line z=h in fig. 3). In other words, the basement level is extended throughout the area to separate the local relief from the general topography.

In case of a basement high, e.g., a buried hill, this level will represent the lower surface of the structure with a distribution of positive magnetic poles. The basement surface will be the upper one with negative poles. Thus, in the surrounding area of the high where the basement is assumed to be constant in topography, the effects of the negative and positive poles cancel each other since both distributions coincide together. Accordingly, the effect due to the basement high is the only thing to account for (fig. 3a).

In case of a depression in the basement, i.e., a basement low, the same principle can be applied, but here the general basement level with positive poles will be above the depressed basement surface having a distribution of negative poles. (fig. 3b)

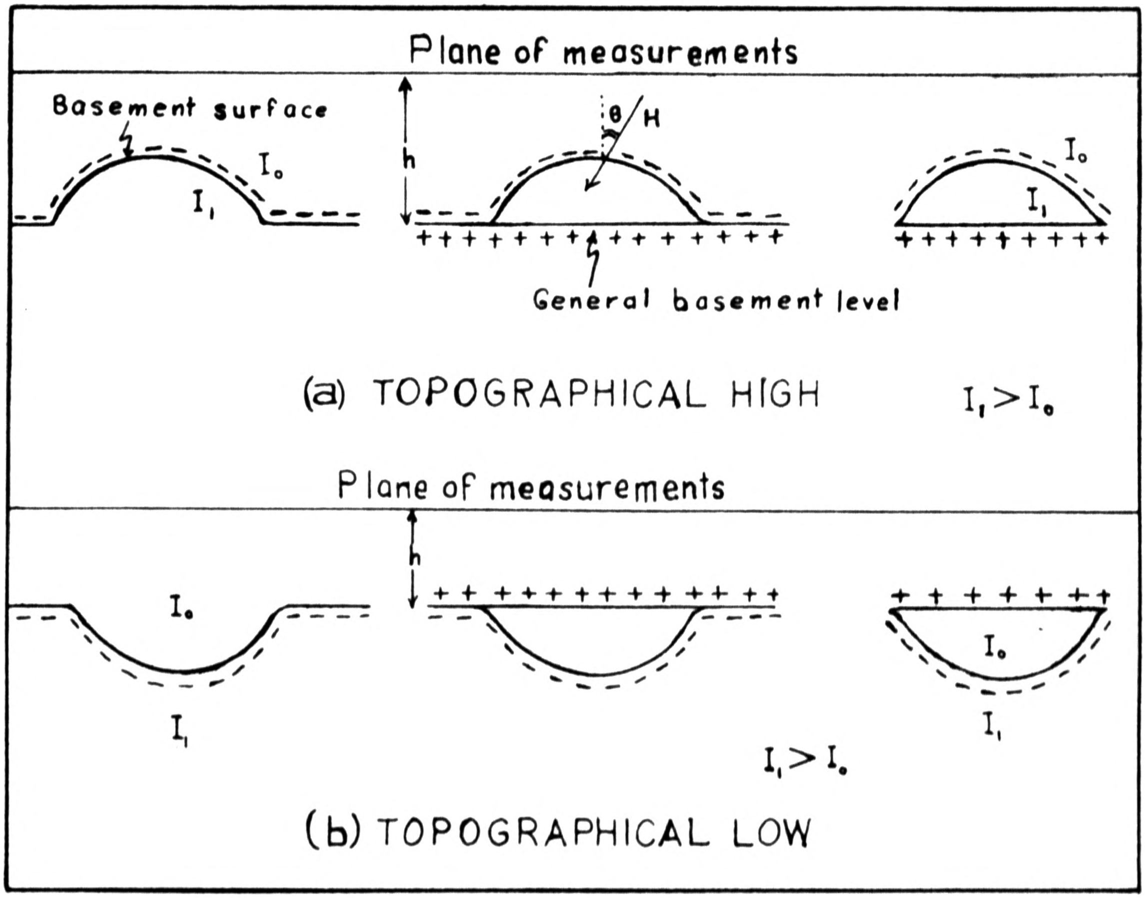


Fig. 3. Calculation of the magnetic field due to three-dimensional basement structure or relief.

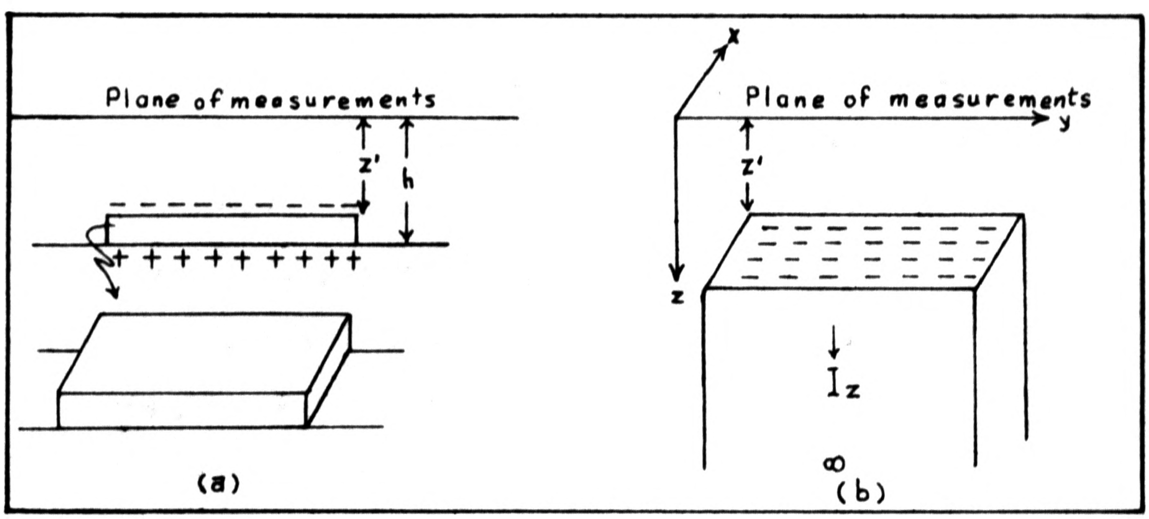


Fig. 4. Calculation of the magnetic field due to rectangular bodies.
(a.) thin slab (b.) infinite prism

By this procedure, we have separated the regional effect from local effects due to any relief in the basement whether elevation or depression.

Now, we can replace the surface integration by summation. This is done by dividing the subsurface structure into grid squares (or rectangles) and then calculate the magnetic effect due to each grid. By adding the effects of all grids of the surface with negative poles (basement surface) and subtracting the effects of those of the opposite surface with positive poles (general basement level), we obtain the magnetic anomalous field due to the structure. One must put into consideration that the grids of the basement surface lie at variable depth z' from the surface of measurements while all the grids of the basement level lie at a constant depth h.

In case of a thin slab or any rectangular block with finite depth, its magnetic effect can be calculated in a similar manner by adding the effects of the grids of the upper surface with negative poles and subtracting the effects of those of the lower surface with positive poles. In this case, the depth z' is the same for all grids of the upper surface (fig. 4a).

In case of a rectangular prism with infinite depth, the magnetic effect of its lower surface can be neglected and we have the effect due to the upper surface with negative poles and at a constant depth z' only (fig. 4b).

Another approach for approximating the magnetic effect of a three-dimensional structure which might be mentioned is similar in its results to the previous approximation. However it might be more effective and more accurate in case of an irregularly shaped body. The body is subdivided into thin prismatic rectangular slabs of constant thickness and varying horizontal dimensions (fig. 5). The magnetic field of each slab at its appropriate depth is calculated and then contoured as mentioned before by adding the effects of the upper surface and subtracting the effects of the bottom. The field due to the whole body could be obtained by superimposing these contoured maps and adding numerically the effects at each point.

By adding the magnetic effects of the tops of the slabs and subtracting the effects of the bottoms, it is evident that the contribution of areas common to the top and bottom of two slabs will be zero, so that the anomaly will consist of the effects due to the top of the uppermost slab and the bottom of the lowermost slab, and also due to the horizontal areas of the steps approximating the sloping boundary of the body.

If contoured magnetic fields of numerous slabs were made available, having the geometrical shape mentioned above, buried at different depths, and for several magnetic inclinations, then for an irregular magnetic mass distribution, the field could be obtained directly by superimposing the appropriate contoured maps and adding numerically the effects at each point. This approach has been used by Zietz and Henderson (1956) using experimental models.

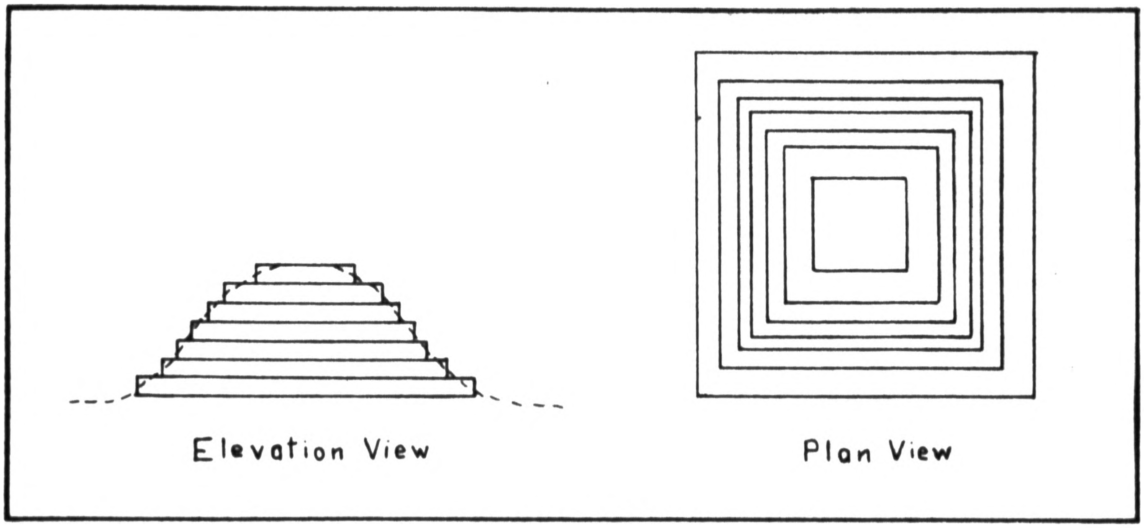


Fig. 5. Approximation of a three-dimensional structure by prismatic slabs. (After Zietz and Henderson, 1956).

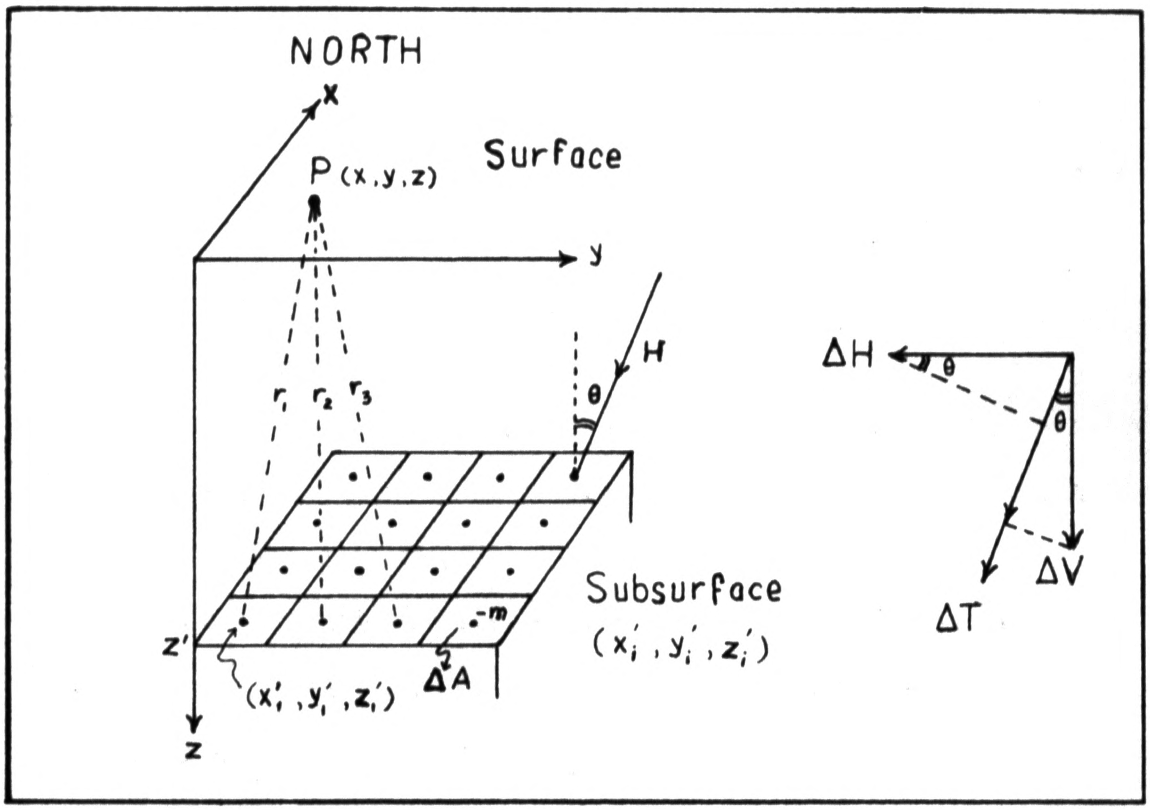


Fig. 6. (a) Calculation of the magnetic field due to surface distribution of poles.
(b) Calculation of the total anomalous field from North and vertical components.

3. Mathematical Discussion

The components of the magnetic field due to surface with a distribution of negative poles can be obtained by use of equations (3) for a single pole summing for all poles over the surface. Thus, the north component (ΔH) and vertical component (ΔV) due to the surface are given by:

$$\Delta H = m \sum_{i=1}^{n} \frac{(x'_i - x)}{r_i^3} \text{ ----------------(4a)}$$

$$\Delta V = m \sum_{i=1}^{n} \frac{(z'_i - z)}{r_i^3} \text{ ----------------(4b)}$$

where, as before, x, y, and z are the coordinates of the point at which the magnetic field is measured; x'_i, y'_i, and z'_i are the coordinates of the centers of the subsurface grids, i.e., the coordinates of the magnetic poles, r_i is the distance between the i^{th} magnetic pole and the point of measurements and is given by:

$$r_i^2 = (x'_i - x)^2 + (y'_i - y)^2 + (z'_i - z)^2 \text{ -------(5)}$$

The summation in equations (4a) and (4b) is carried over all the grids; n is the number of the grids.

m is the magnetic pole strength and in this case is given by:

$$m = I \Delta A \text{ -----------------------------------(6)}$$

where ΔA is the area of each grid square (or rectangle).

I is the polarization or intensity of magnetization which is defined as pole strength per unit area, and it can be expressed as:

$$I = k H_n$$

k is the magnetic susceptibility of the rocks

H_n is the component of the magnetic earth's field normal to the surface and in its turn, can be written as:

$$H_n = H \cos \theta$$

where H is the total earth's field, θ is the angle between the direction of this field and the normal to the surface. If the surface is horizontal, then θ will be the complement of the magnetic inclination which is constant throughout the area (fig. 6a). Thus, in case of any relief in the basement surface, the slope of the boundaries is assumed to be small so that the grids can be assumed as horizontals. Now we can express m given by equation (6) as:

$$m = H\, k\, \Delta A \cos \theta \text{ ------------------------- } (6a)$$

Substituting this value of m and that of r_i in equations (4a) and (4b) we can express the north and vertical components as:

$$\Delta H = H\, k\, \Delta A \cos \theta \sum_{i=1}^{n} \frac{(x'_i - x)}{[(x'_i - x)^2 + (y'_i - y)^2 + (z'_i - z)^2]^{3/2}} \text{ --- } (7a)$$

$$\Delta V = H\, k\, \Delta A \cos \theta \sum_{i=1}^{n} \frac{(z'_i - z)}{[(x'_i - x)^2 + (y'_i - y)^2 + (z'_i - z)^2]^{3/2}} \text{ --- } (7b)$$

The effect due to the opposite surface with positive poles is obtained from the same equations by replacing z'_i with h which is the constant depth of the basement level.

The total anomalous magnetic intensity measured by the airborne magnetometer is taken as the sum of the projections of the north and vertical components of the actual anomalous magnetic intensity on the direction of the total magnetic intensity (fig. 6b). The east (y) component of the magnetic intensity ΔHy is zero, since the x axis is directed north (Vacquier, 1951). Thus, if ΔT represents the total anomalous magnetic intensity, then:

$$\Delta T = \Delta H \sin \theta + \Delta V \cos \theta \qquad (8)$$

Equations (7a), (7b), and (8) were programmed for the Royal McBee LGP-30 electronic digital computer in fixed point system. The programs were discussed in Chapter III.

D. BASIC ASSUMPTIONS AND LIMITATIONS OF THE METHOD

In the development of this method and specially for airborne magnetometry, certain assumptions must be made for the simplification of the procedure. These have been mentioned above, but are summarized here:

1. The bodies to be dealt with are assumed to be homogeneous, i.e., have uniform properties and are uniformly polarized.
2. In airborne magnetometry the anomalous total field is assumed to be in the direction of the earth's normal field which is assumed to be uniform over the area. Hughes and Pondrom (1947) have shown that this assumption results in a negligible error for sufficiently small areas as in exploration work.
3. The magnetic polarization of the basement rocks is assumed to be in the same direction as the present direction of the earth's magnetic field. In other words, any remanent magnetization is assumed to be codirectional with the normal field;

otherwise the body is magnetized entirely by induction.

4. The polarization of the rocks is assumed to have no horizontal component, i.e., a vertical polarization is only considered. Thus, in calculating the magnetic effect of the prismatic bodies, the effect due to the vertical sides was neglected; only effects due to the horizontal surface were considered. In high magnetic latitudes this approximation would introduce negligible errors. Vacquier (1951) indicated in his model anomalies the progressive change of the magnetic expression of the same idealized bodies with decreasing magnetic latitude.

5. In calculating the total anomalous magnetic intensity, the east (y) component of the magnetic intensity is assumed to be zero, since the x axis is directed north. This will not affect the accuracy of the method, since the declination of the earth's field from the north is in the range of few degrees which can be neglected.

All these assumptions place limitations on the procedure. The accuracy of the method depends on the degree to which these simplifying assumptions are satisfied. However, for most cases discussed in the literature, these assumptions were found to be reasonable.

III. ELECTRONIC COMPUTER CALCULATIONS

A. CALCULATION PROCEDURE

The computation processes were programmed by the author for the Royal McBee LGP-30 electronic digital computer of Missouri School of Mines and Metallurgy. The system used in programming is the fixed point system which is more flexible and much faster than other systems. Four programs have been written for different cases encountered depending on whether the vertical or the total anomalous field, or both, are required to be calculated and whether the body to be dealt with has a finite depth or infinite depth. The general procedure for all these programs is almost the same. There is little difference between them, even one may be modified to do the function of the other. However they were written here separately for simplification and for increasing the speed of computation.

In general, the calculation procedure is summarized as follows: The magnetic effect due to the first subsurface grid is calculated for all the surface points by using the equations developed in Chapter II. The effect due to the next grid, is then calculated and added to the previous effect for each surface point and so on until the effects due to all the n subsurface grids are calculated and summed for each of the s surface points. Thus, the calculations will be carried (n x s) times.

By this procedure, the surface data (i.e., the coordinates of the surface points) have to be stored in the computer, while the subsurface data should be fed to the computer, one at a time.

B. SYMBOLS USED

x, y, z = coordinates of the points at which the magnetic field is measured at the surface or over the surface of the earth (simply called surface data).

$x', y', z',$ = coordinates of the subsurface points at which the magnetic poles are located (subsurface data).

h = the constant vertical depth from the surface of measurements to the basement level or in general depth to the lower surface of the body.

$\Delta x', \Delta y'$ = interval between the subsurface points (i.e., grid interval) in the x' and y' directions respectively.

x'_f = final or largest value of x' plus an increment (about half $\Delta x'$)

y'_f = final or largest value of y' plus an increment (about half $\Delta y'$)

r = distance between subsurface and surface points

S = number of surface points or stations at which measurements are made

$s = S - 1/2$

n = number of subsurface points (i.e., number of grids)

ΔA = grid area $= \Delta x' \cdot \Delta y'$

m = magnetic pole strength

k = susceptibility of the rocks

H = earth's total field

θ = angle between the direction of H and the vertical (i.e., the complement of the angle of inclination)

ΔH_-, ΔV_- = horizontal (north) and vertical components of the anomalous magnetic field due to the surface having a distribution of negative poles (Generally the upper surface)

ΔH_+, ΔV_+ = horizontal and vertical components due to the surface having a distribution of positive poles (generally the lower surface)

ΔH, ΔV = anomalous horizontal and vertical components due to both upper and lower surfaces or due to only the upper surface if the lower one is at infinite depth.

In the first case: $\Delta H = \Delta H_- - \Delta H_+$

$\Delta V = \Delta V_- - \Delta V_+$

In the second case: $\Delta H = \Delta H_-$, $\Delta V = \Delta V_-$

ΔT = total anomalous magnetic intensity

C. FUNCTIONS OF THE PROGRAMS

1. Program No. 1:

The purpose of this program is to compute only the vertical magnetic anomaly due to the upper surface only of a three-dimensional body whose lower surface is assumed to be at infinite depth e.g. an infinite rectangular prism.

The program will print out in sequence the values of x, y and corresponding values of ΔV.

2. Program No. 2:

The purpose of this program is to compute only the vertical magnetic anomaly due to both upper and lower surfaces of a three-dimensional body having a finite depth e.g. buried hill, basalt flow represented by thin slab or any feature represented by rectangular block. The program will print out x, y and ΔV in sequence as program No. 1.

3. Program No. 3:

The purpose of this program is to compute the vertical, horizontal and total magnetic intensity due to the upper surface only of a three-dimensional body having a lower surface at infinite depth. The program will print out in sequence the values of x, y and the corresponding values of ΔV and/or ΔT. This can be controlled by the transfer control button in the computer. If ΔV is required to be printed together with ΔT, the transfer control button is depressed. This is indicated by the appearance of light behind the button. However, if ΔT only is required, the transfer control button must be up, i.e., in its normal position (unlighted). In this case, the computer will not print ΔV.

4. Program No. 4:

The function of this program is to compute the vertical, horizontal and total magnetic intensity due to both upper and lower surfaces of a three-dimensional body having a finite depth. The sequence and mechanism of printing out is the same as those of program No. 3.

D. FLOW CHARTS

The flow charts of the four programs appear on pages 30 - 34.

These charts have been drawn mainly for a fixed point system. However, by slight modifications they can be used for other systems of the LGP-30 e.g. Act III compiler.

E. DESCRIPTION OF THE FLOW CHARTS

The description is referred to flow chart (4) of program No. 4, but it can be applied to the other charts except that some boxes are slightly modified and a few others are omitted according to the function of each program.

Box 1: Input data are stored in memory. These include initial values of x' and y', final values x'_f and y'_f, $\Delta x'$, $\Delta y'$, h, H, k, cos θ, sin θ, ΔA, s and the surface data x, y and z.

Box 2: m is calculated from equation (6a) and then stored.

Box 3: The computer is stopped in order to load the reader with the second data tape containing z' which will be input later (Box 8). This being done, the computer start button is pushed to start computing again.

Box 4: Sum I and sum II are set to zero for storage of ΔV and ΔH respectively.

Box 5: s is decreased by one and replaces the previous value. If the new s is still positive proceed directly to Box 6. If s is negative transfer to Box 7.

Box 6: The addresses of sum I and sum II are modified to the next following addresses. This is done in fixed point system by adding 1 at q = 29 (or Z0001) to the address. The addresses being modified, unconditional transfer to Box 4. The process is repeated as long as s is positive until 2S locations are set to zero for the storage of the values of ΔV and ΔH at S surface points. This being done, s becomes negative and the procedure in Box 7 is followed.

Box 7: The value of s, which is modified in Box 5, is reset to its initial value.

Box 8: z' is read one at a time for a certain subsurface grid.

Box 9: The quantities indicated inside are calculated and stored.

Box 10: r^2 is calculated from equation (5), then r is obtained by taking the square root of r^2. r^2 and r are stored.

Box 11: ΔV_- due to the surface with negative poles is calculated using equation (7b), then sum I is added and result is stored in sum I.

Box 12: ΔH_- is calculated using equation (7a), then sum II is added and result is stored in sum II.

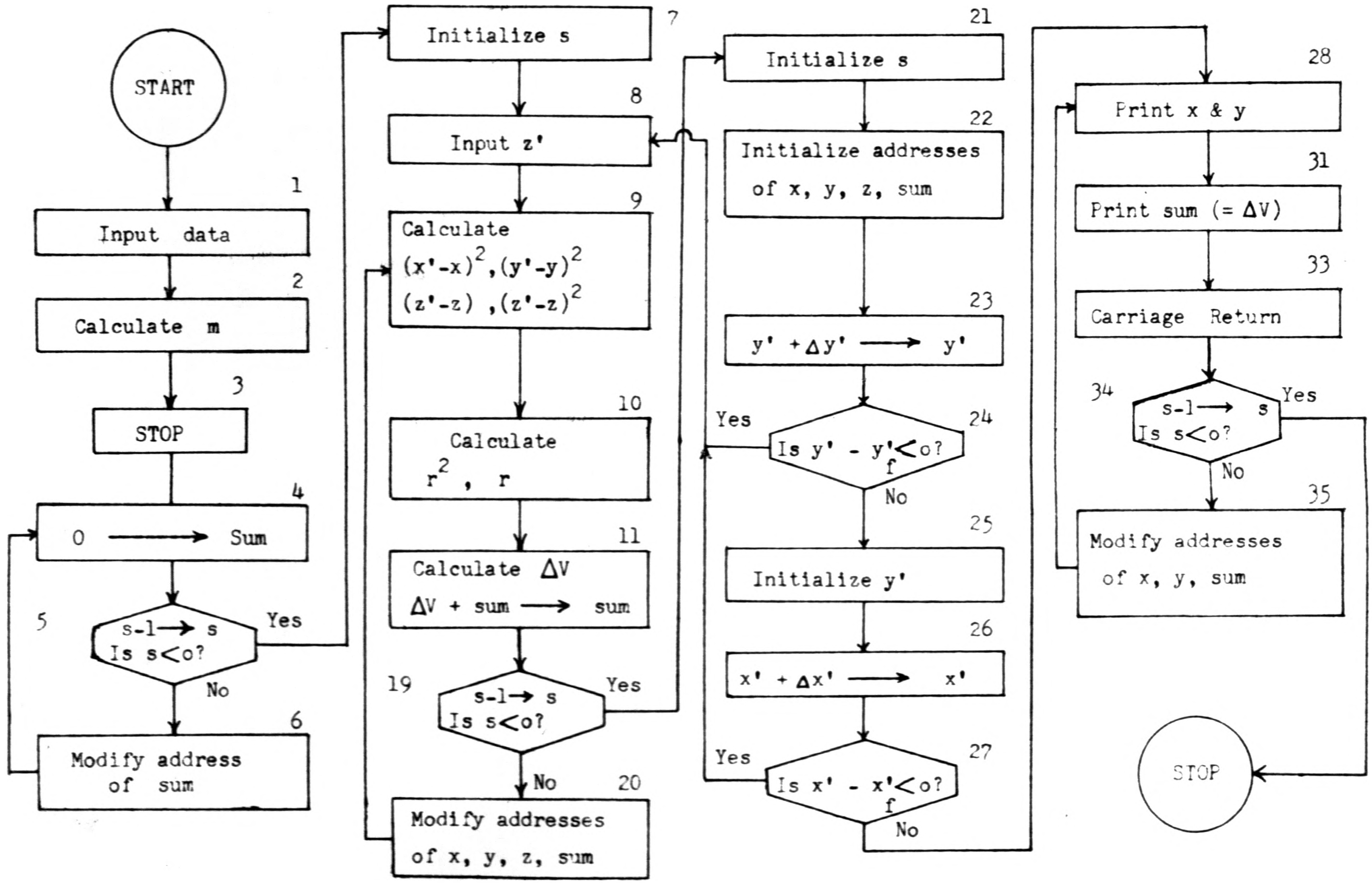
Box 13: Using h, the depth to the surface with positive poles, instead of z', the quantities (h-z) and $(h-z)^2$ are calculated and stored in the locations of (z'-z) and $(z'-z)^2$ respectively.

Box 14: The new values of r^2 and r are calculated.

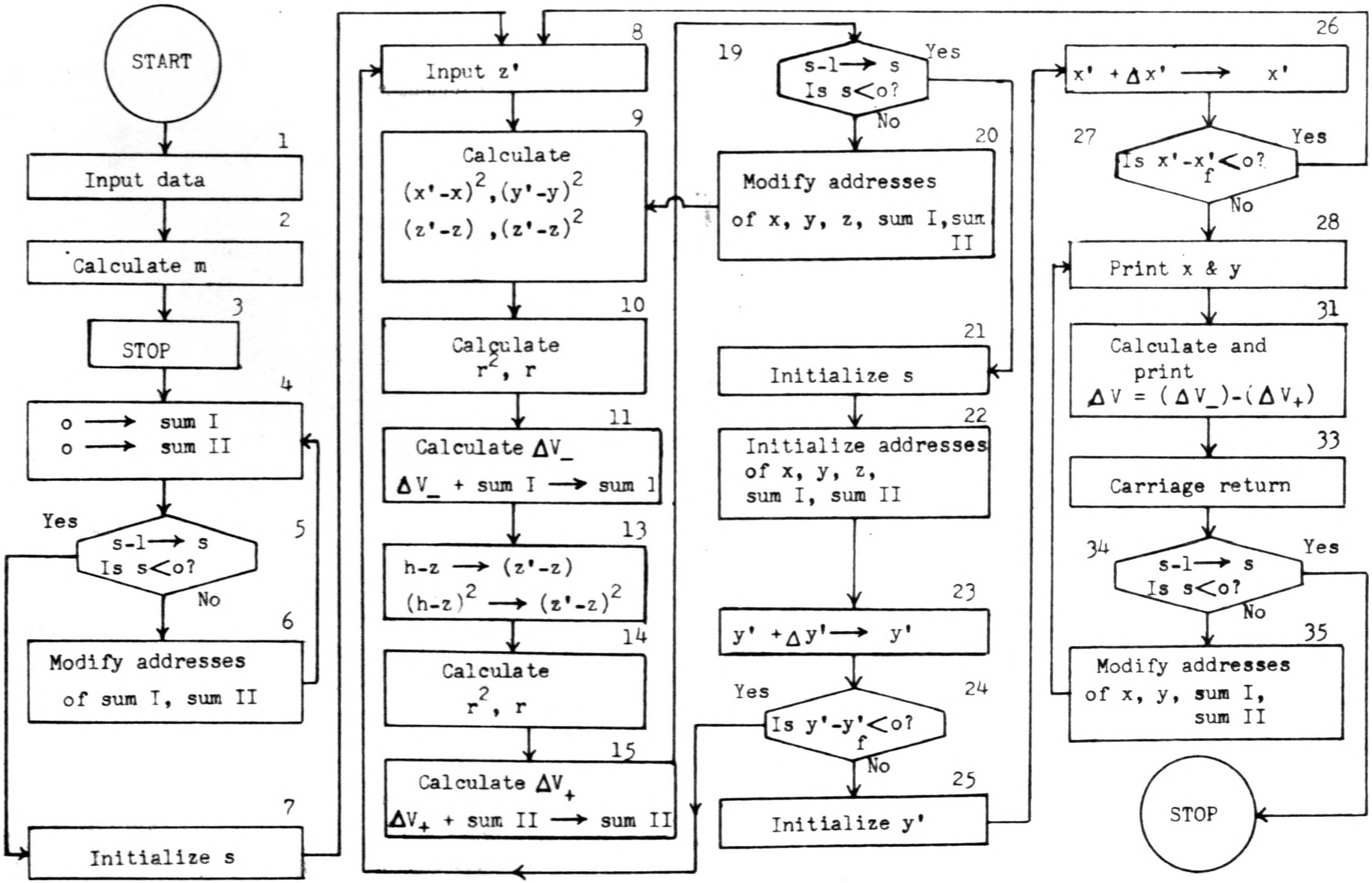
Box 15: ΔV_+ due to the surface with positive poles is calculated using equation (7b) and then stored.

Box 16: ΔV_+ is subtracted from sum I and result is stored in sum I.

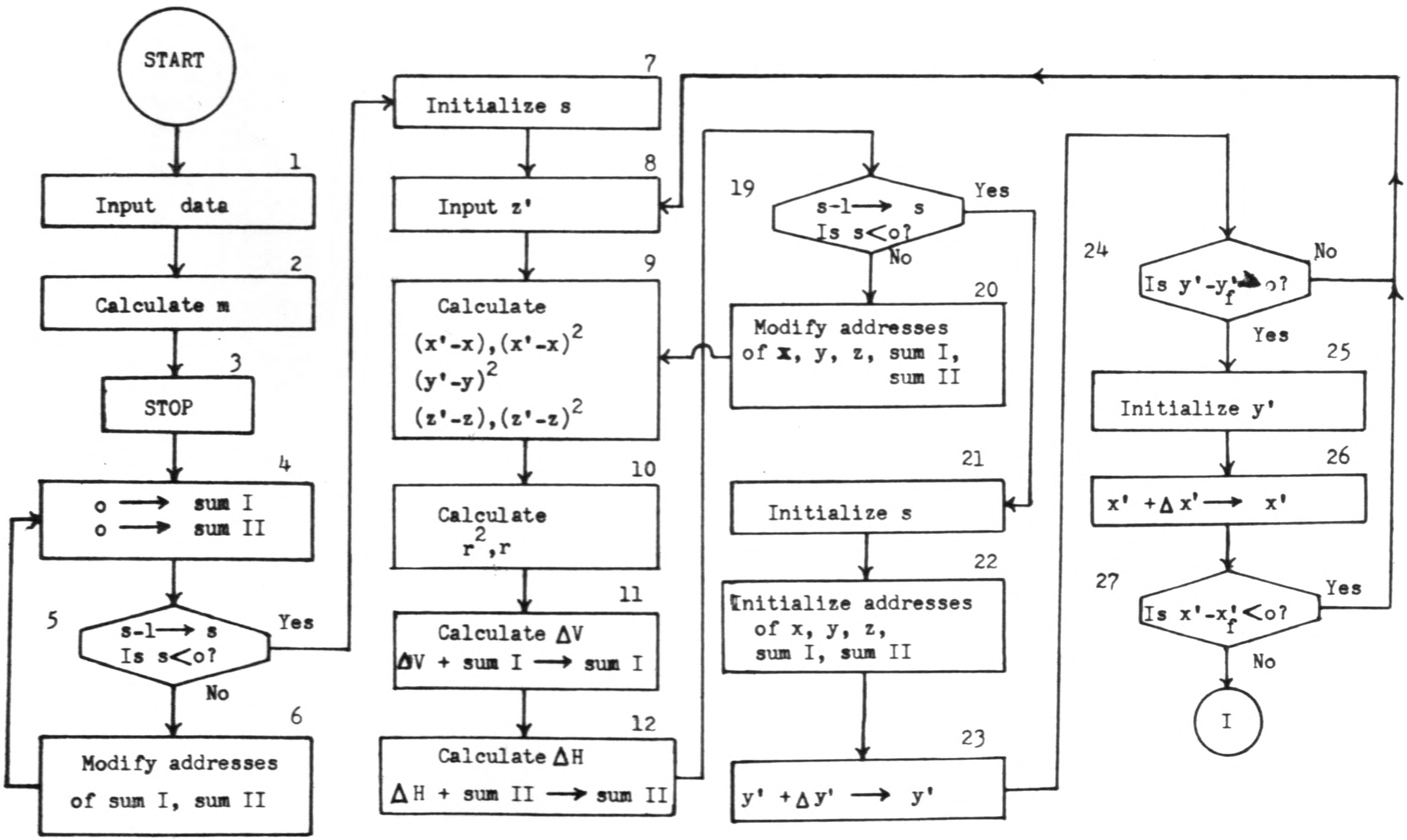
Box 17: ΔH_+ is calculated using equation (7a) and then stored.



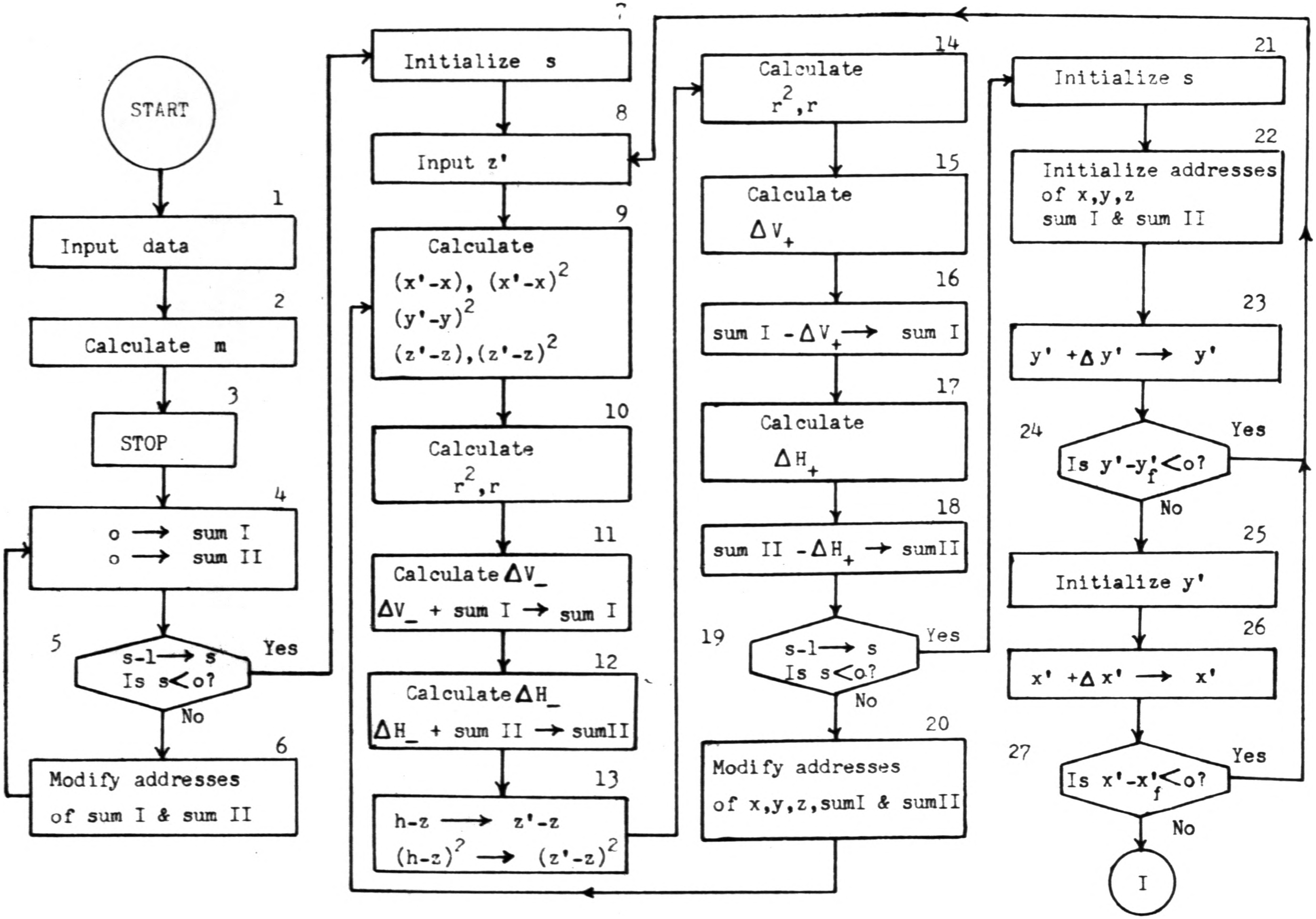
Flow Chart (1) - Program No. 1



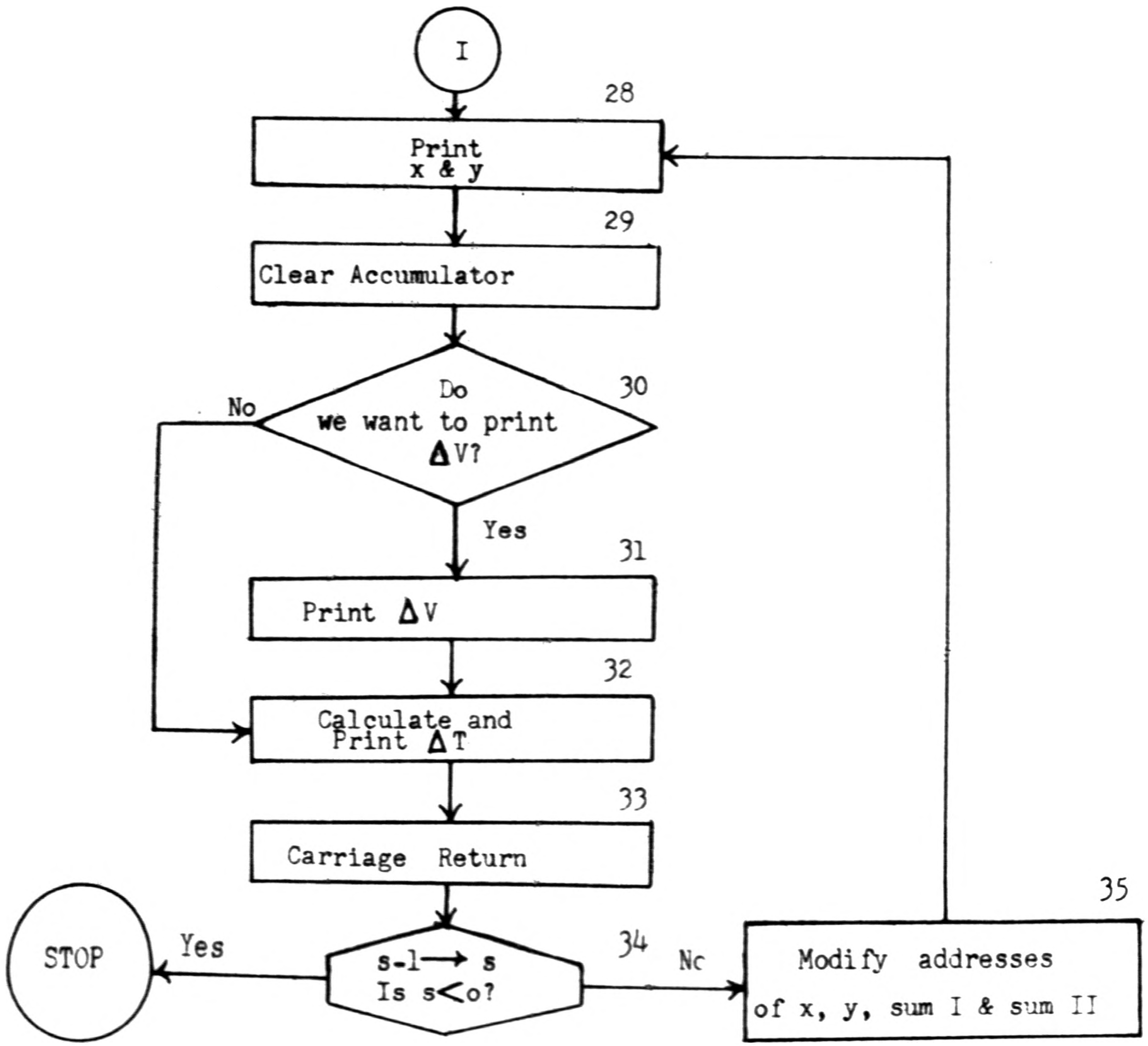
Flow Chart (2) - Program No. 2



Flow Chart (3) - Program No. 3



Flow Chart (4) - Program No. 4



Flow Chart (5) - Continuation of Flow Charts (3) and (4).

Box 18: ΔH_+ is subtracted from sum II and result is stored in sum II.

Box 19: Have ΔV and ΔH been calculated for all surface points? If not proceed directly to Box 20. Otherwise, transfer to Box 21.

Box 20: Addresses of x, y, z, sum I and sum II are modified to the next ones and by unconditional transfer to Box 9 the procedure is repeated for the calculation of ΔV and ΔH using new values of x, y, and z corresponding to the next surface station. This is carried on until ΔV and ΔH are calculated for all surface points. Hence, the procedure in Box 21 is followed.

Box 21: s is set at its initial value.

Box 22: Addresses of x, y, z, sum I and sum II which are modified in Box 20 are set at their initial values.

Box 23: The value of y' is increased by $\Delta y'$ and stored in the location for y' (to calculate the effect due to the next subsurface grid in the y' or east direction).

Box 24: Has end of row in the y' direction been reached? If not, i.e., if ΔV and ΔH due to all grids in a row have not been computed, transfer back to Box 8. Otherwise, the procedure in Box 25 is followed.

Box 25: y' is set at its initial value.

Box 26: The value of x' is increased by $\Delta x'$ and stored in the location for x' (to calculate the effect due to the next row of grids).

Box 27: Are there any more rows to compute? If yes, transfer back to Box 8. If no, which means that the final value of x' has been used in the computation, i.e., the effects due to all sub-surface grids have been computed, then the procedure in Box 28 is followed.

Box 28: The values of x and y are printed.

Box 29: The accumulator is set to zero (see Box 30).

Box 30: According to a criterion set up by the programmer, ΔV, is printed out if desired or, if not, the computation proceeds to Box 32 without printing ΔV. This has been done in fixed point system by using the instruction 800T XXXX which means that, if the accumulator is positive and the transfer control button is down, control is transferred to memory location XXXX (Box 31 in this case), while if the transfer control button is up, the instruction following T XXXX is executed next (this is an unconditional transfer to Box 32).

Box 31: ΔV is printed out.

Box 32: ΔT is calculated using equation (8) and then printed out.

Box 33: A carriage return is executed.

Box 34: If all values of x, y, ΔV and/or ΔT have not been printed out, procedure in Box 35 is followed. Otherwise, the computation is stopped.

Box 35: Addresses of x, y, ΔV (sum I) and ΔH (sum II) are replaced by the next following addresses and, by unconditional transfer to Box 28, new values of x, y, ΔV and/or ΔT are printed out.

F. SUBROUTINES

Three subroutines are used in each of the four programs.

1. Input Subroutine:

This is used to input and store data from the first data tape, and to feed in z' from the second data tape. The subroutine used in this investigation is the data input No. 5 subroutine - Program 11.4B.

2. Output Subroutine:

This is used to print the output data. The subroutine used is the data output No. 1 subroutine - Program 12.0B.

3. Square Root Subroutine:

This is used to obtain r by taking the square root of r^2. The subroutine used is the square root subroutine - Program 15.1.

For more information about these subroutines, refer to the LGP-30 subroutine manual.

G. MEMORY REQUIREMENTS

The storage required for the programs ranges, in general, from approximately 125 locations for program No. 1 to 200 locations for program No. 4 (exclusive of the subroutines). Storage required for miscellaneous data is 20 locations. Also 10 locations of temporary storage are needed to store some quantities during computations. The storage requirement for surface data (x, y, and z) is 3 S locations. For output data S locations are required in case of using program No. 1 and 2 S locations in using other programs.

Thus, the total requirement is of the order of:

(4S + 150) words or locations for program No. 1

(5S + 200) words or locations for programs No. 2 and No. 3

and (5S + 250) words or locations for program No. 4.

In this investigation, the programs are written such that four tracks are required for program No. 4 and data storage (three tracks only are required for each of the other programs), one track is required for square root subroutine and two tracks are required for each of x, y, z ΔV and ΔH so that any program can be used to calculate the magnetic field at a maximum of 128 surface stations.

H. ESTIMATION OF THE RUNNING TIME

The time taken by the square root subroutine 15.1 is a maximum of 510 milli-seconds. The input subroutine 11.4B can read 40 - 50 words per minute. Printing by the output subroutine 12.0B takes about 1.5 seconds per word including the tab if the output is taken through the high speed punch.

The time required for the computation of the magnetic field at one surface point depends on the number of subsurface grids. By using the programs in fixed point system, it was found that the machine time required for the computations (without printing) per a single subsurface grid at a single surface station is approximately 1.3 seconds for program No. 1, 1.6 seconds for program No. 2, 1.5 seconds for program No. 3, and 2.6 seconds for program No. 4. This estimated time would be reduced further if the programs were optimized.

I. SUMMARY OF THE OPERATION PROCEDURE OF THE COMPUTER

The steps to be followed in the operation of the computer are summarized in this section and must be carried out in the following order:

1. The subroutines are loaded in the computer.
2. The program tape is read and stored in the computer.
3. The first data tape containing all necessary data except z' is read. After all data has been stored, the computer will stop.
4. The second data tape containing z' is loaded in the reader.
5. The start button is depressed. z' will be fed one at a time during the computation.

After all the computations are completed, the output data are taken either through the flexowriter or through the high speed punch. In the latter case the break point 16 button must be down, if output subroutine 12.0B is used.

N.B. In case of using program No. 3 or No. 4, the transfer control button must be down if one wants to print the vertical magnetic component.

IV. APPLICATION OF THE METHOD TO THEORETICAL MODELS

The method discussed in the previous chapter has been applied to calculate the magnetic effect due to twelve theoretical models. This has been done mainly to check the relative accuracy of the method by comparing the results obtained herein with those obtained by Vacquier, et al (1951) who calculated the magnetic effects due to identical prismatic models.

A. GENERAL PROPERTIES OF MODELS

The prismatic models, which are considered similar to large lithologic units in crystalline rock, have the following common properties as described by Vacquier, ibid:

(1) Horizontal upper surface, one unit below the plane of the map.

(2) Vertical side walls that extend infinitely downward, except for two models whose vertical walls have finite length.

(3) Polarization in the direction of the earth's main magnetic field.

(4) A magnetic susceptibility, constant throughout the prism, and in contrast to the susceptibility of the rock surrounding the prism.

The prismatic models are rectangular in plane in order to facilitate the computation of their magnetic fields. The dimensions of the rectangle are in units of the depth of burial of the top of the prism. The dimensions are expressed herein as a x b where a is the dimension of the side that is parallel to magnetic north and b is the dimension of the other side in the east-west direction, a and b range from 1 to 8 in length. In case of the models with finite vertical length, the dimensions are expressed as a x b x c where c is the height of the model.

B. CONSTRUCTION OF THE MODEL CHARTS

The total and vertical intensity anomalies were calculated for each of the twelve models which have different dimensions and having been set up for different magnetic inclinations of 45°, 60°, 75°, and 90°. The dimensions of the models and the coordinates are measured in terms of the depth of burial of the top of the prism which is taken as unity. The center of the prism is taken as the origin of the coordinates. However, if the origin is taken at the corner of the prism, same results will be obtained.

The horizontal surface of the prism is divided into square grids. The side of the square is equal to the depth of burial in some prisms or half the depth of burial in others. In one of the prisms the grid interval is taken as equal to one quarter the depth of burial.

The polarization of the prisms was taken as unity ($k\ H = 1$) for most of the models so that the values of the calculated total intensity (in C. G. S. units) can be compared with those values (Δ T/I) obtained in the work of Vacquier, ibid. In a few models, H was given a value of 60,000 gammas and k was given a value of 0.003 C. G. S. units.

Program No. 1 has been used in computing the total intensity of the models where the magnetic inclination is 90° in which case the total intensity is equal to the vertical component. In case of the other inclinations, program No. 3 has been used to compute the total and vertical magnetic intensity due to infinitely long prisms, while program No. 4 has been used in case of models with finite vertical length. The results obtained from the programs for each model are given in appendix D.

The values of the total magnetic intensity are contoured on the right side of Figures 7 - 18 for each model. The left side has not been contoured since the anomaly will be symmetrical about the magnetic north axis.

C. DESCRIPTION OF THE MODEL CHARTS

The model charts shown in Figures 7 - 18 are maps of the total intensity anomaly produced by a prismatic model. These prismatic models are given numbers from 1 - 12. In the following description each model is indicated by its dimensions, magnetic inclination, grid interval and polarization:

Model No. 1: (Fig. 7) 6 x 2, inclination 45°, grid interval = 1/2 depth of burial, Hk = 1.

Model No. 2: (Fig. 8) 6 x 1, inclination 60°, grid interval = depth of burial, H = 60,000 gammas, k = 0.003.

Model No. 3: (Fig. 9) 4 x 6, inclination 60°, grid interval = depth of burial, H = 60,000 gammas, k = 0.003.

Model No. 4: (Fig. 10) 1 x 1, inclination 60°, grid interval = 1/4 depth of burial, Hk = 1.

Model No. 5: (Fig. 11) 8 x 8 x 7, inclination 60°, grid interval = depth of burial, H = 60,000 gammas, k = 0.003.

Model No. 6: (Fig. 12) 8 x 8 x 1, inclination 60°, grid interval = depth of burial, H = 60,000 gammas, k = 0.003.

Model No. 7: (Fig. 13) 6 x 1, inclination 75°, grid interval = 1/2 depth of burial, H = 60,000, k = 0.003.

Model No. 8: (Fig. 14) 6 x 2, inclination 75°, grid interval = 1/2 depth of burial, Hk = 1.

Model No. 9: (Fig. 15) 2 x 6, inclination 75°, grid interval = 1/2 depth of burial, Hk = 1.

Model No. 10: (Fig. 16) 6 x 1, inclination 90°, grid interval = 1/2 depth of burial, Hk = 1.

Model No. 11: (Fig. 17) 1 x 6, inclination 90°, grid interval = 1/2 depth of burial, Hk = 1.

Model No. 12: (Fig. 18) 8 x 6, inclination 90°, grid interval = depth of burial, Hk = 1.

D. ACCURACY OF THE METHOD

The accuracy of the program calculations has been checked by calculating a small-scale sample problem on a desk calculator. The results from both computer and desk calculator were accurate within three decimal places. However in preparing Figures 7 through 18, the computer values were rounded to two decimal places in those cases using C. G. S. units and to whole integers where gammas were used. Thus the accuracy of the points used in preparing the contour maps is $\pm$ 0.005 C. G. S. units or $\pm$ 0.5 gammas.

The model charts shown in figures 7 through 18 have been compared with the equivalent charts shown in the work of Vacquier. The comparison showed that there is a similarity between the general shape of the anomalies in both works. However, as far as the absolute values of the total intensity are concerned, there is an excellent agreement between both results when the inclination of the magnetic field is 90°. This can be shown by comparing Figures 16, 17, and 18 with Vacquier's Figures A77, A80, and A83 respectively. In the cases where the inclination of the magnetic field is 75° to 45°, the magnetic contours calculated in this thesis are shifted northward compared to Vacquier's work up to 20% of the length of a north-south prism.

Figures 19 and 20 are photographs of Vacquier's Figures A83 and A45, given here for comparison with figures 18 and 1 of this thesis respectively. The similarity between both results when the inclination is 90° can be shown by figures 18 and 19, while the relative discrepancy when the inclination is 45° is indicated in Figures 1 and 20.

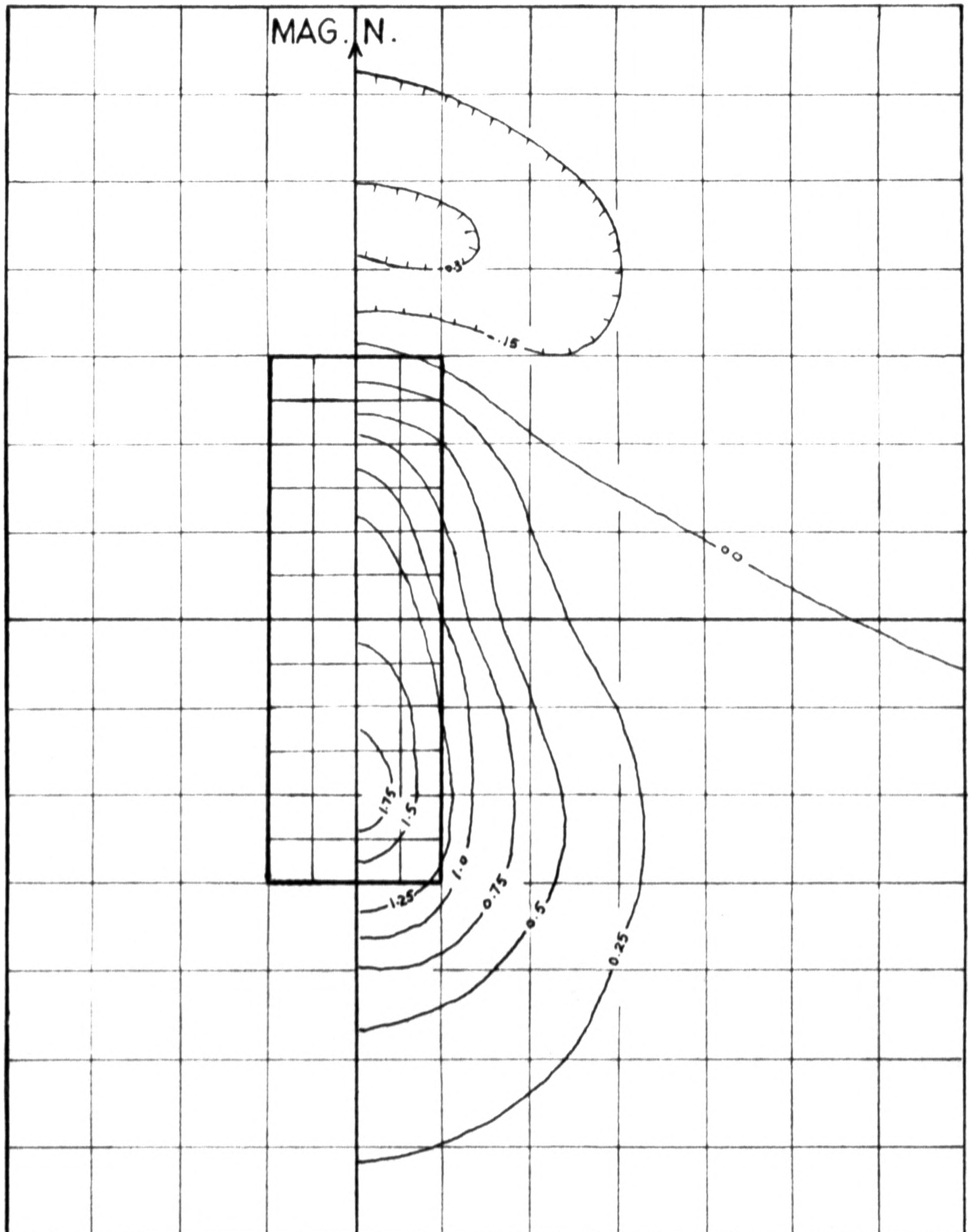


Fig. 7. Total intensity (C.G.S.) - Model No. 1

Inclination 45°

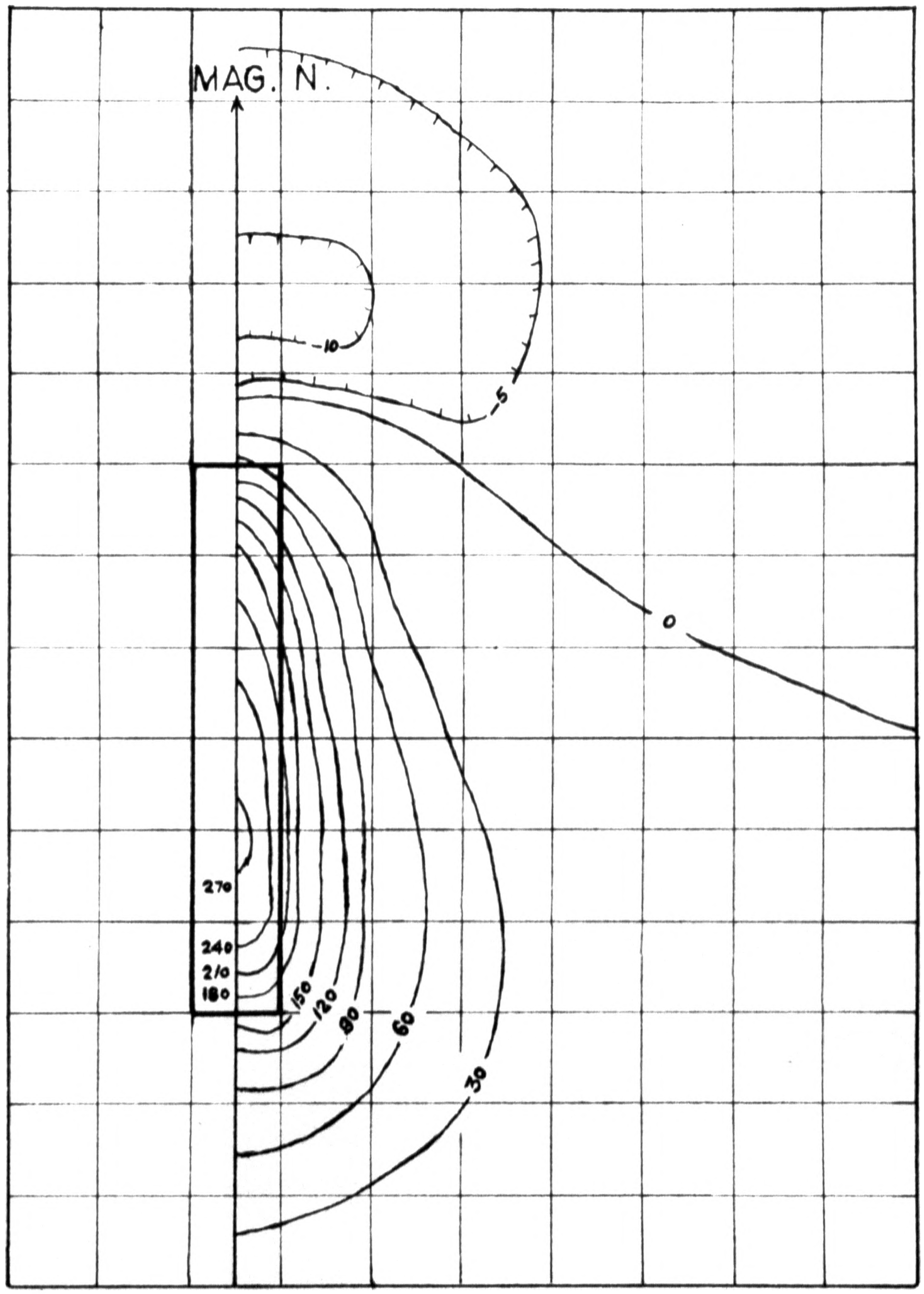


Fig. 8. Total intensity (Gammas) - Model No. 2

Inclination 60°

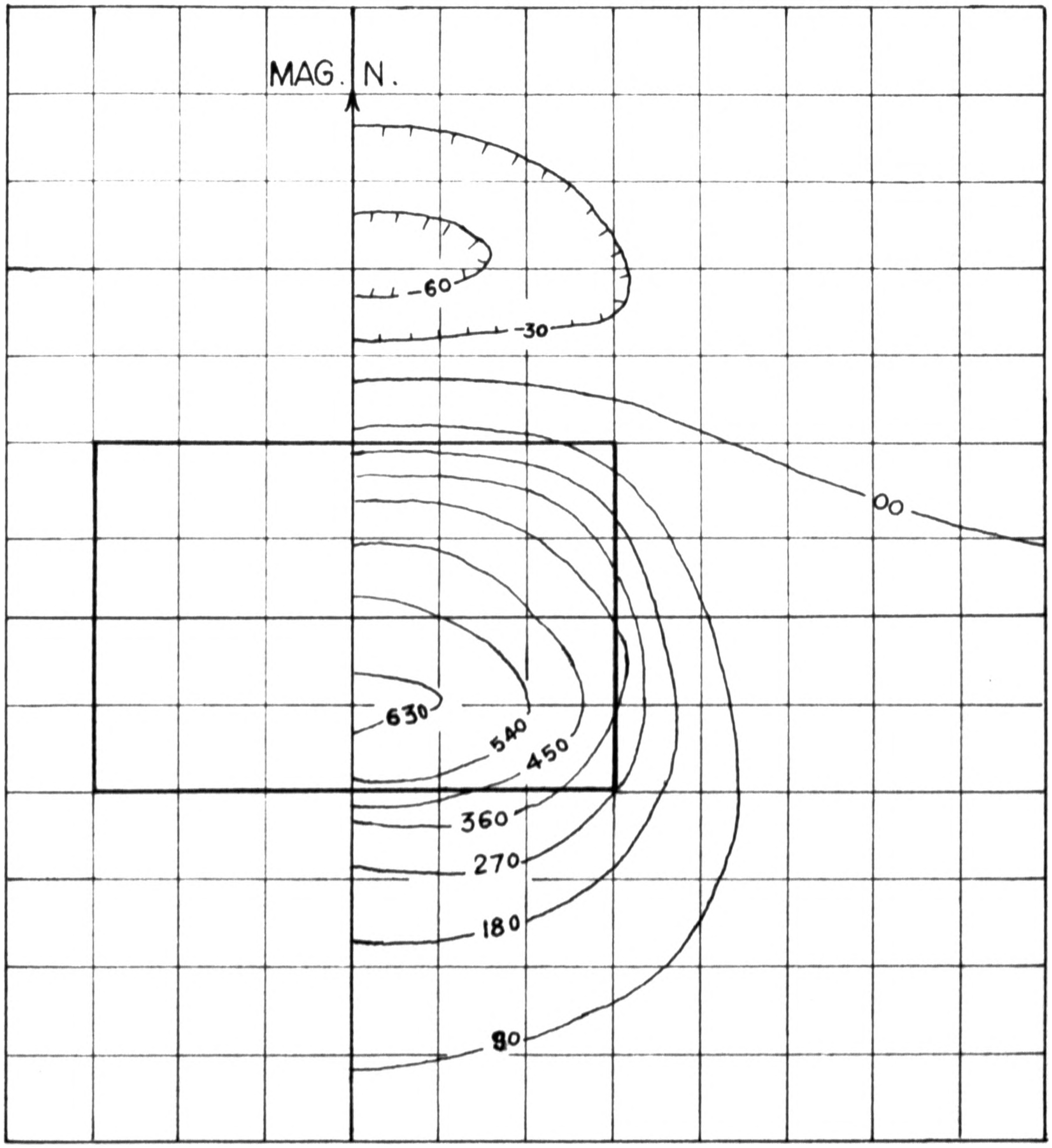


Fig. 9. Total intensity (Gammas) - Model No. 3

Inclination 60°

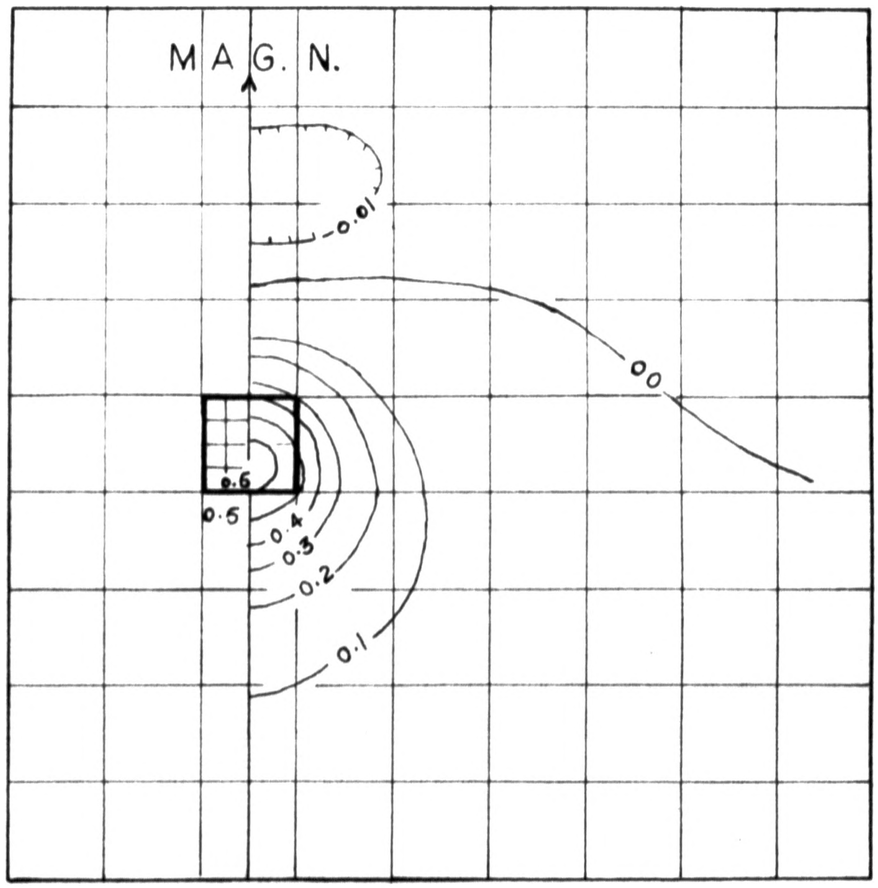


Fig. 10. Total intensity (C.G.S.) - Model No. 4

Inclination 60°

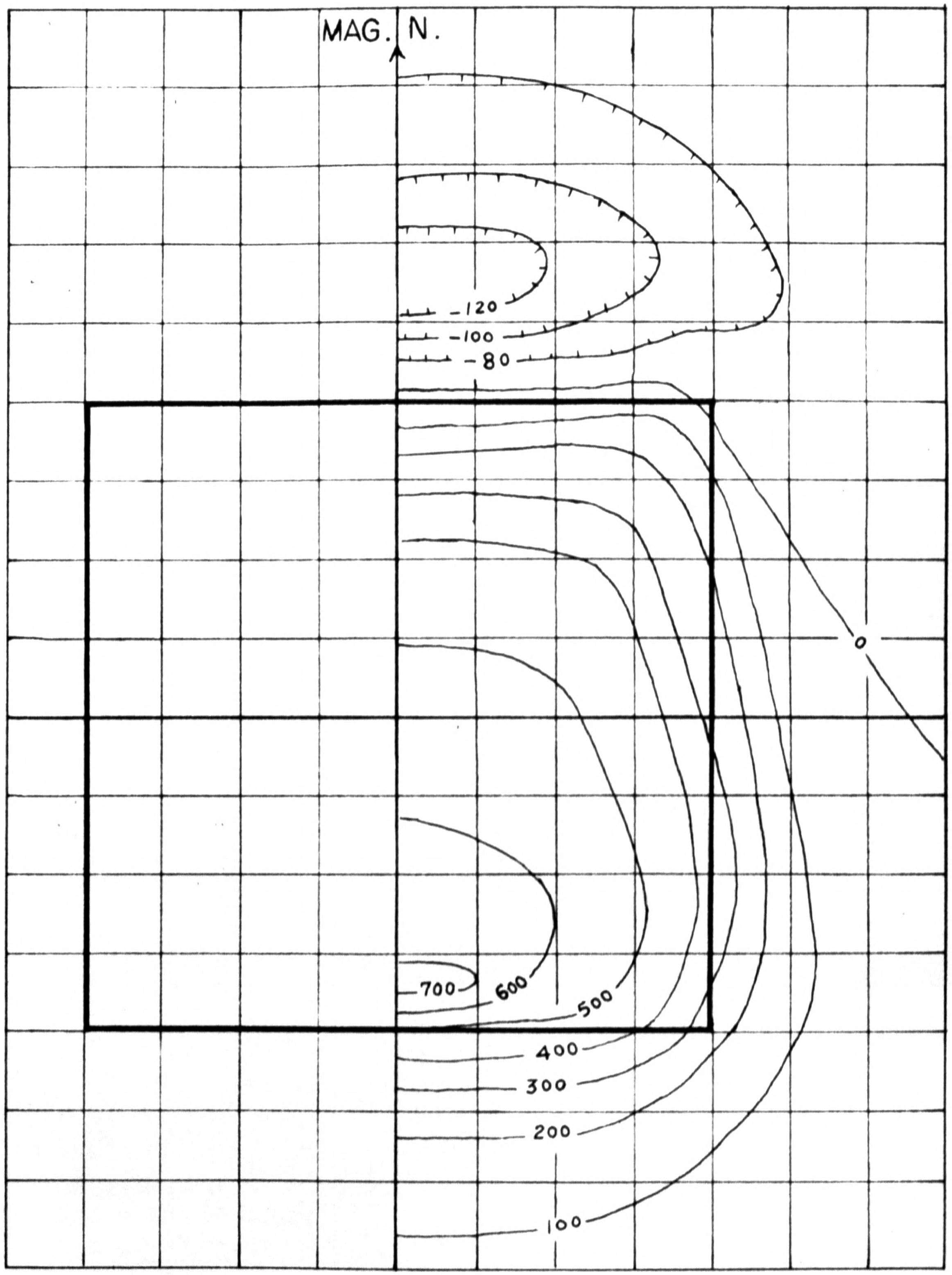


Fig. 11. Total intensity (Gammas) - Model No. 5, 8 X 8 X 7

Inclination 60°

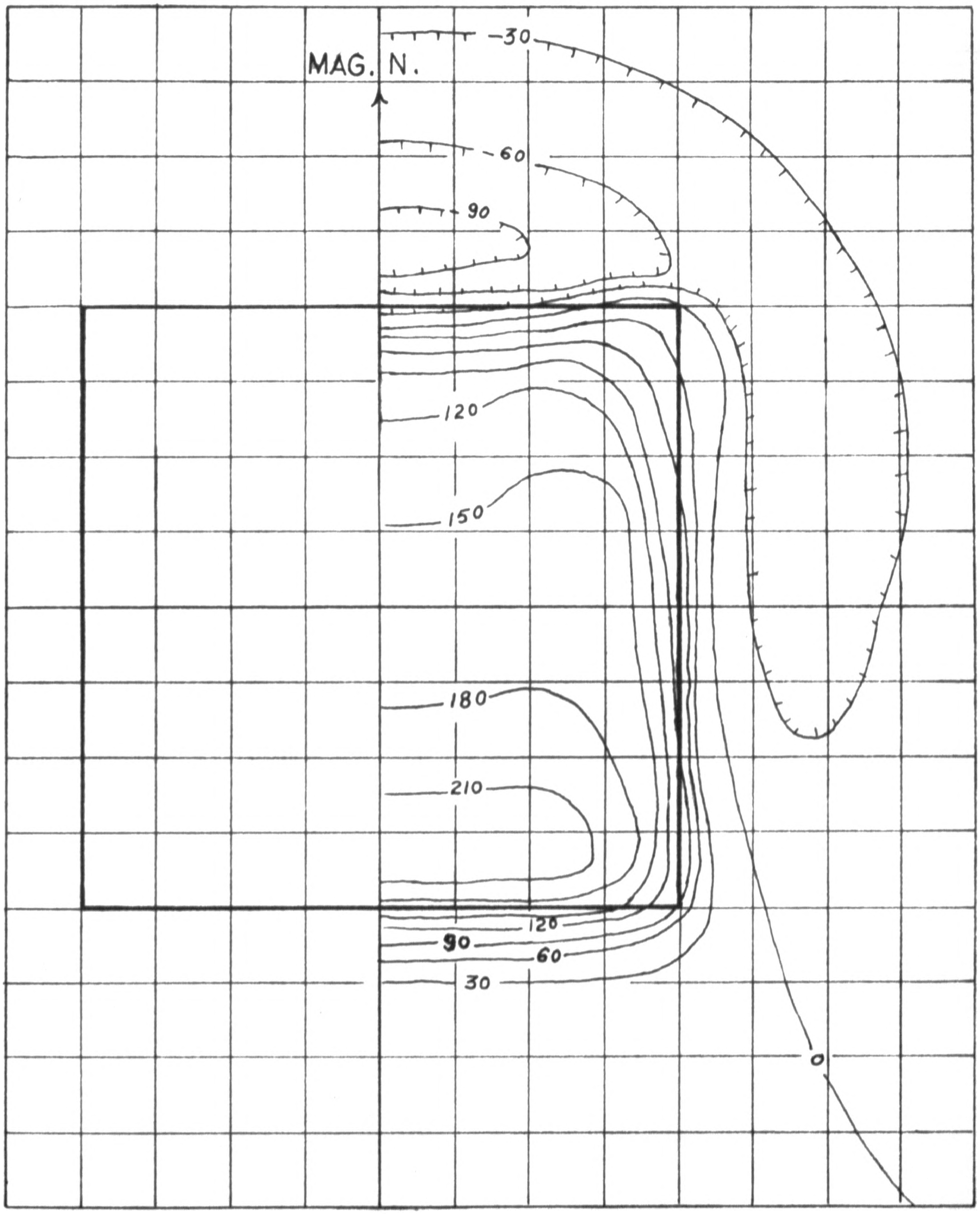


Fig. 12. Total intensity (Gammas) - Model No. 6, 8 X 8 X 1

Inclination 60°

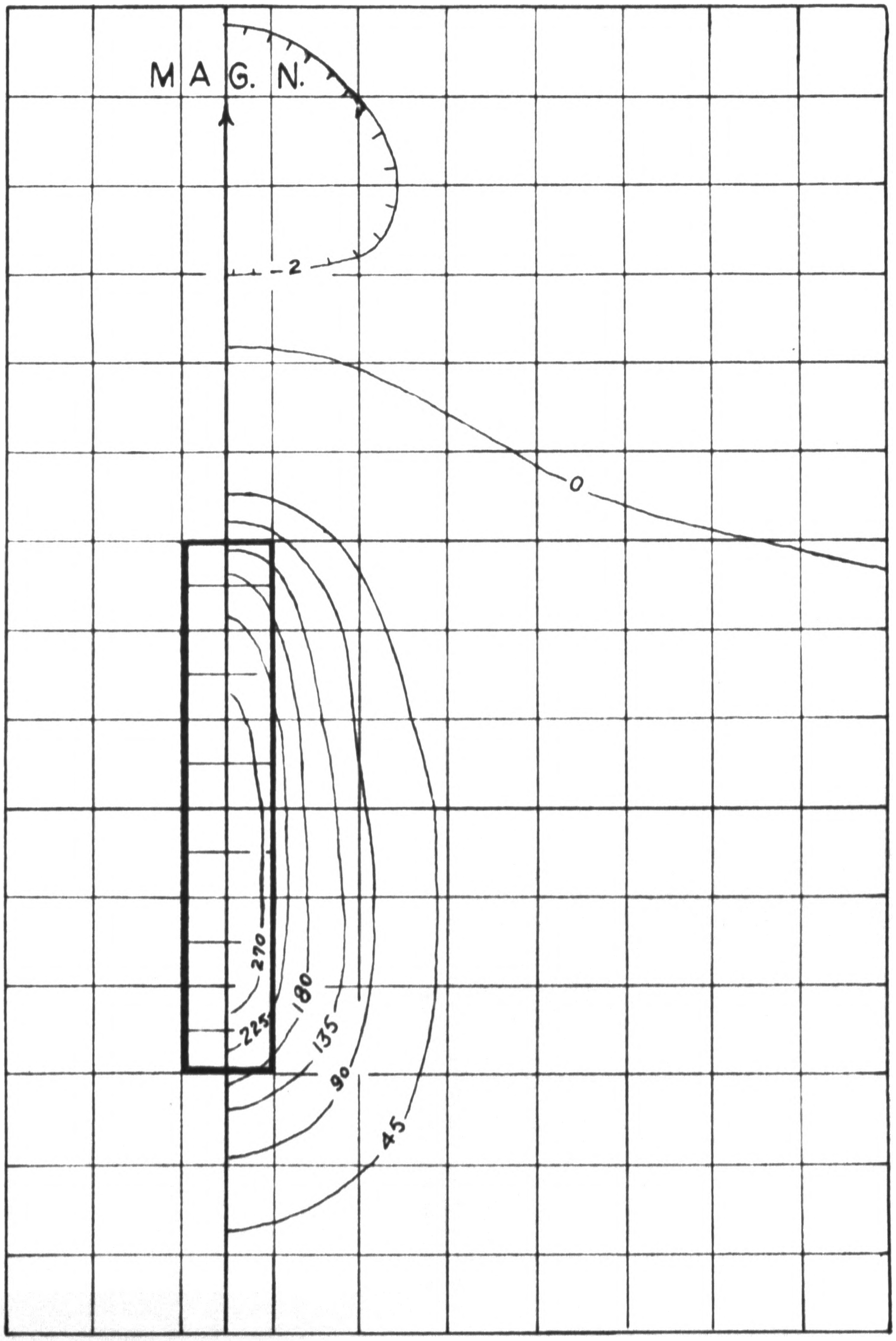


Fig. 13. Total intensity (Gammas) - Model No. 7

Inclination 75°

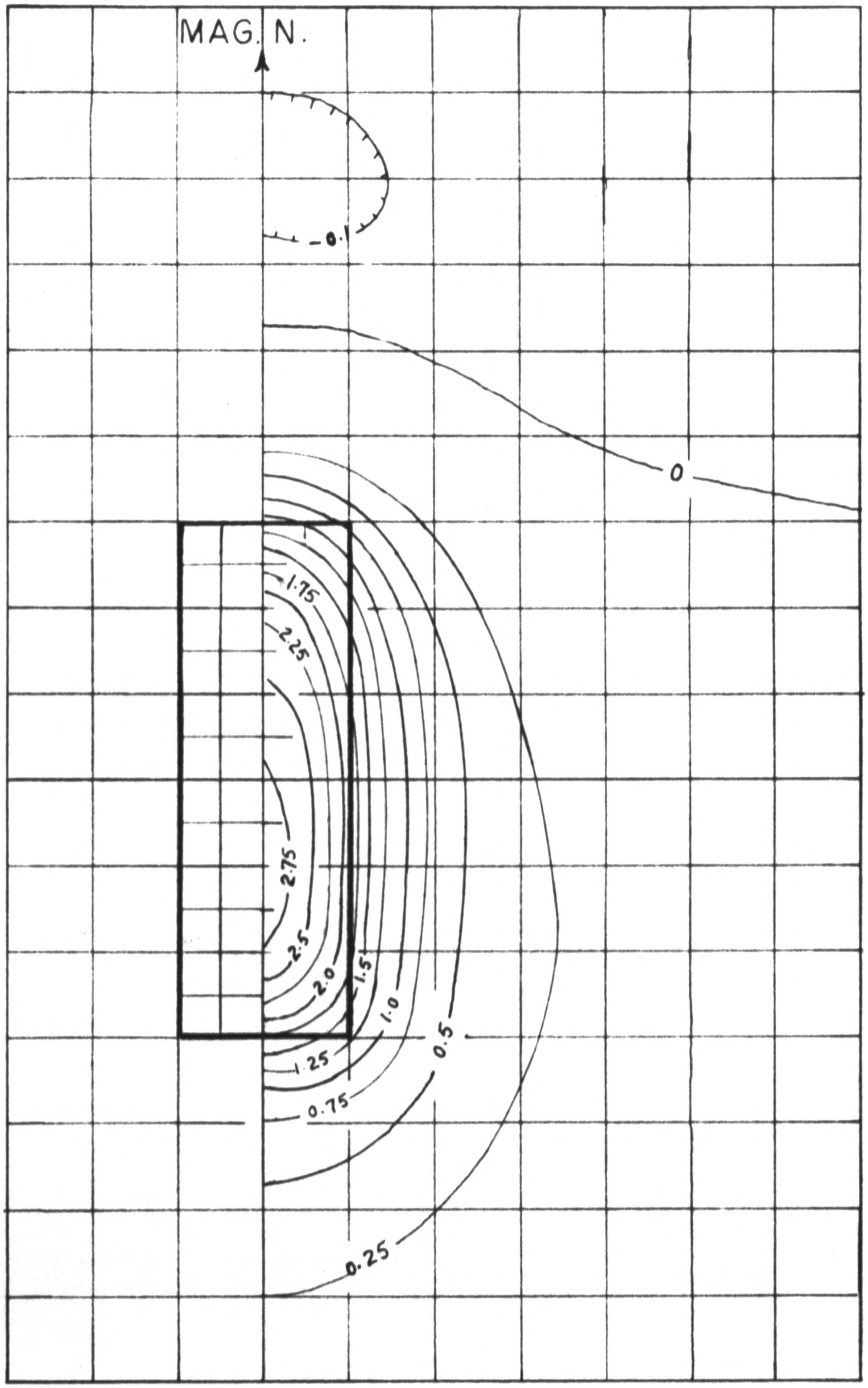


Fig. 14. Total intensity (C.G.S.) - Model No. 8

Inclination 75°

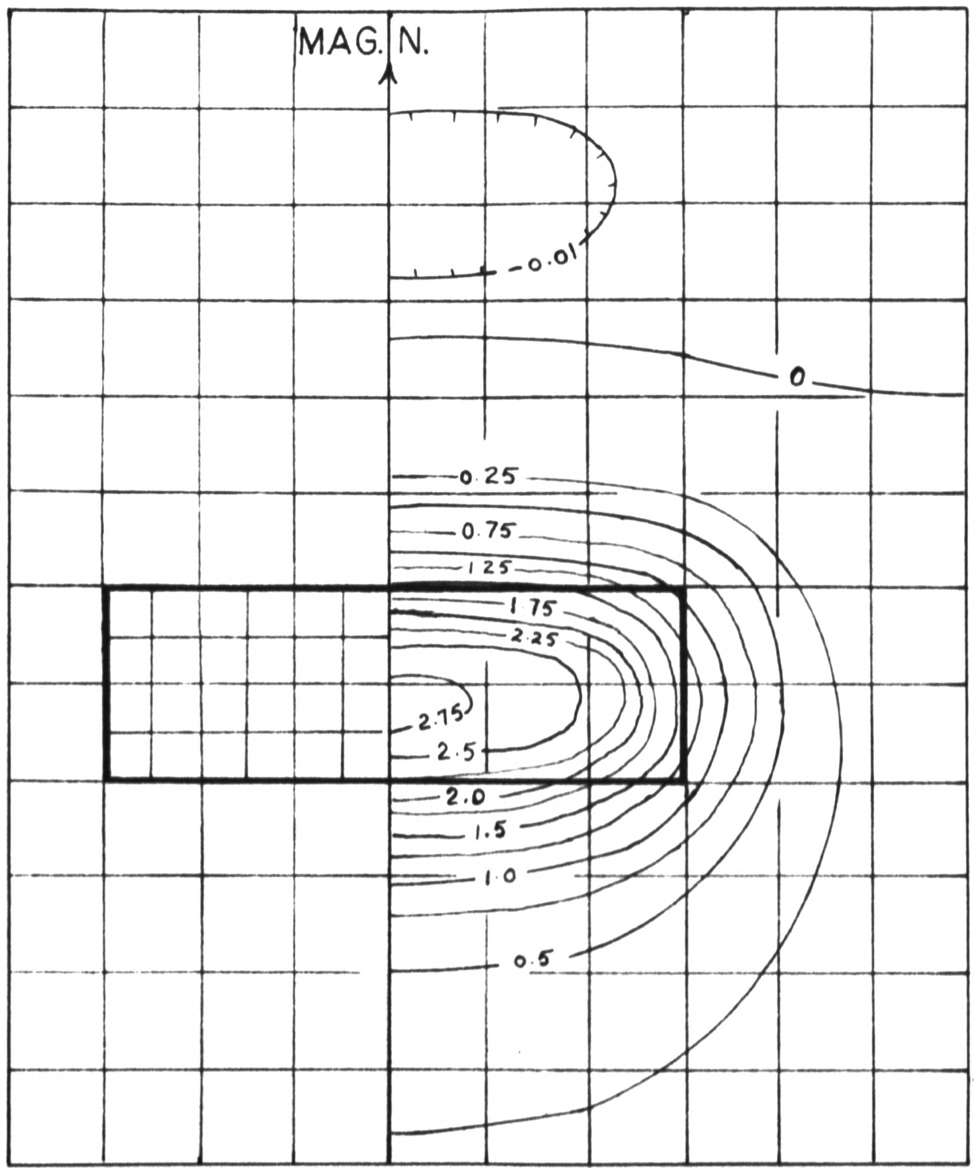


Fig. 15. Total intensity (C.G.S.) - Model No. 9

Inclination 75°

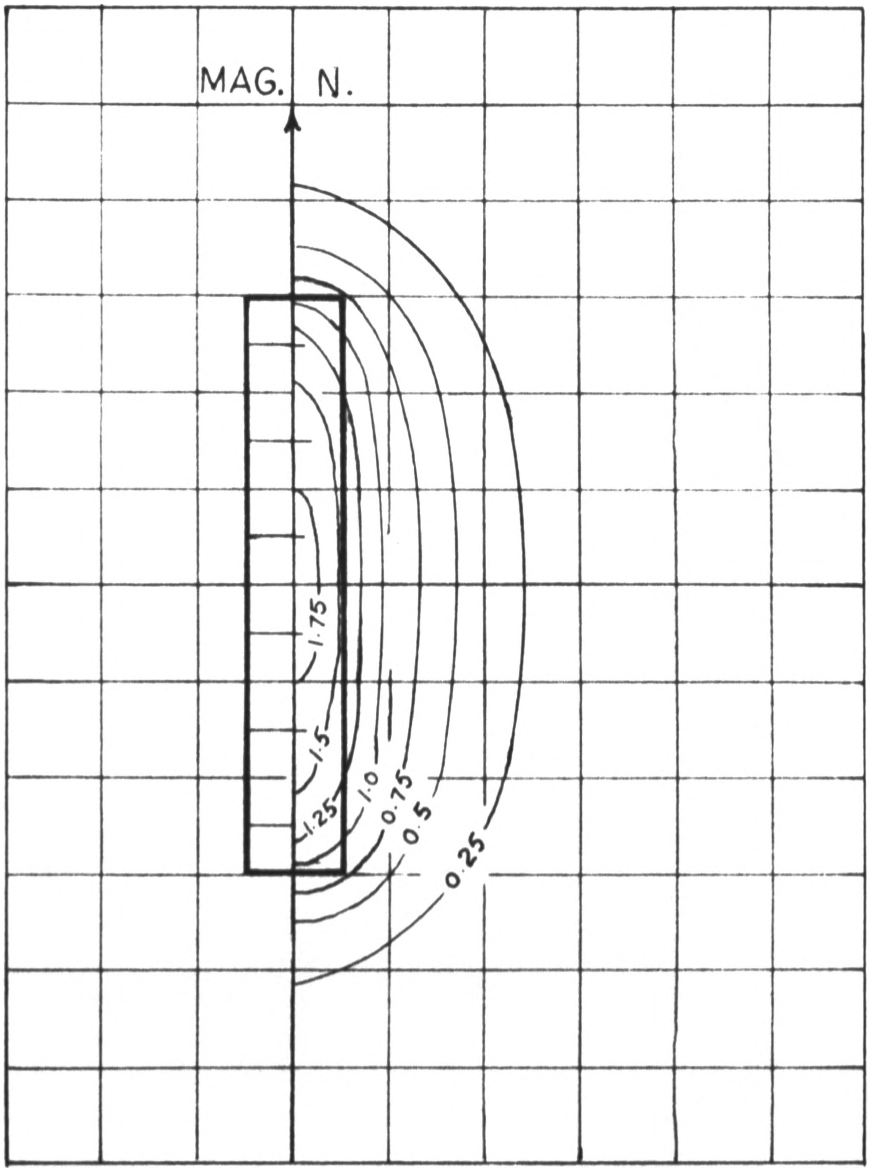


Fig. 16. Total intensity (C.G.S.) - Model No. 10

Inclination 90°

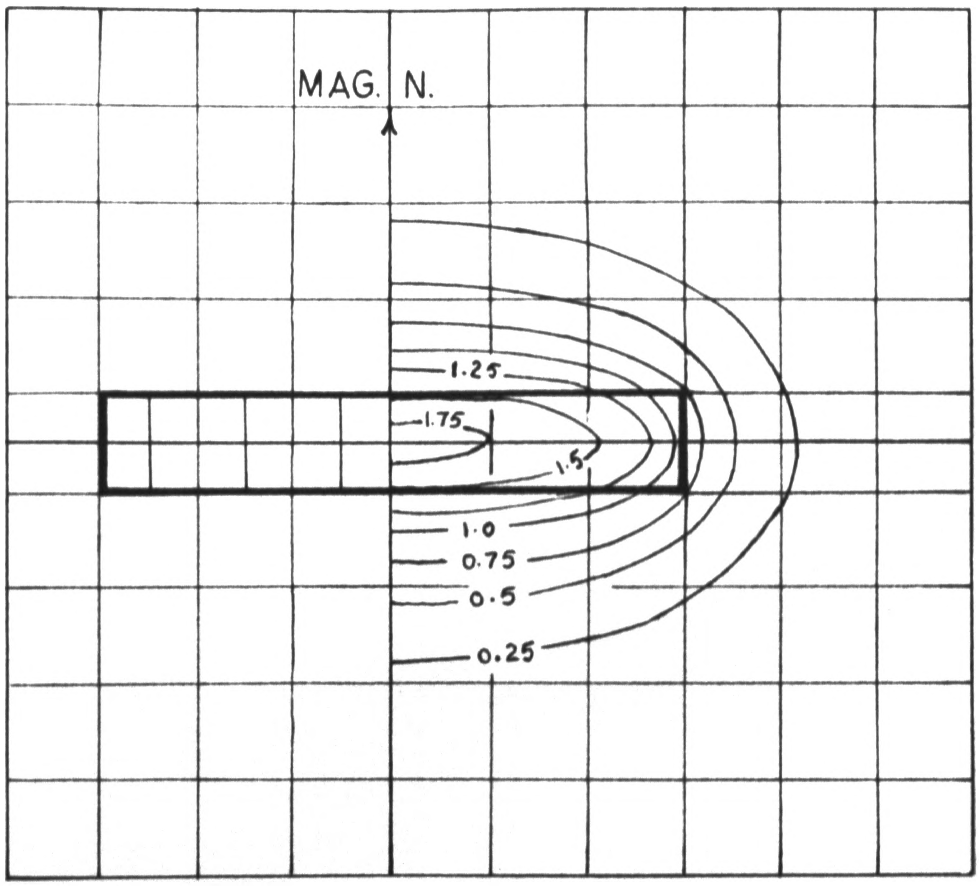


Fig. 17. Total intensity (C.G.S.) - Model No. 11

Inclination 90°

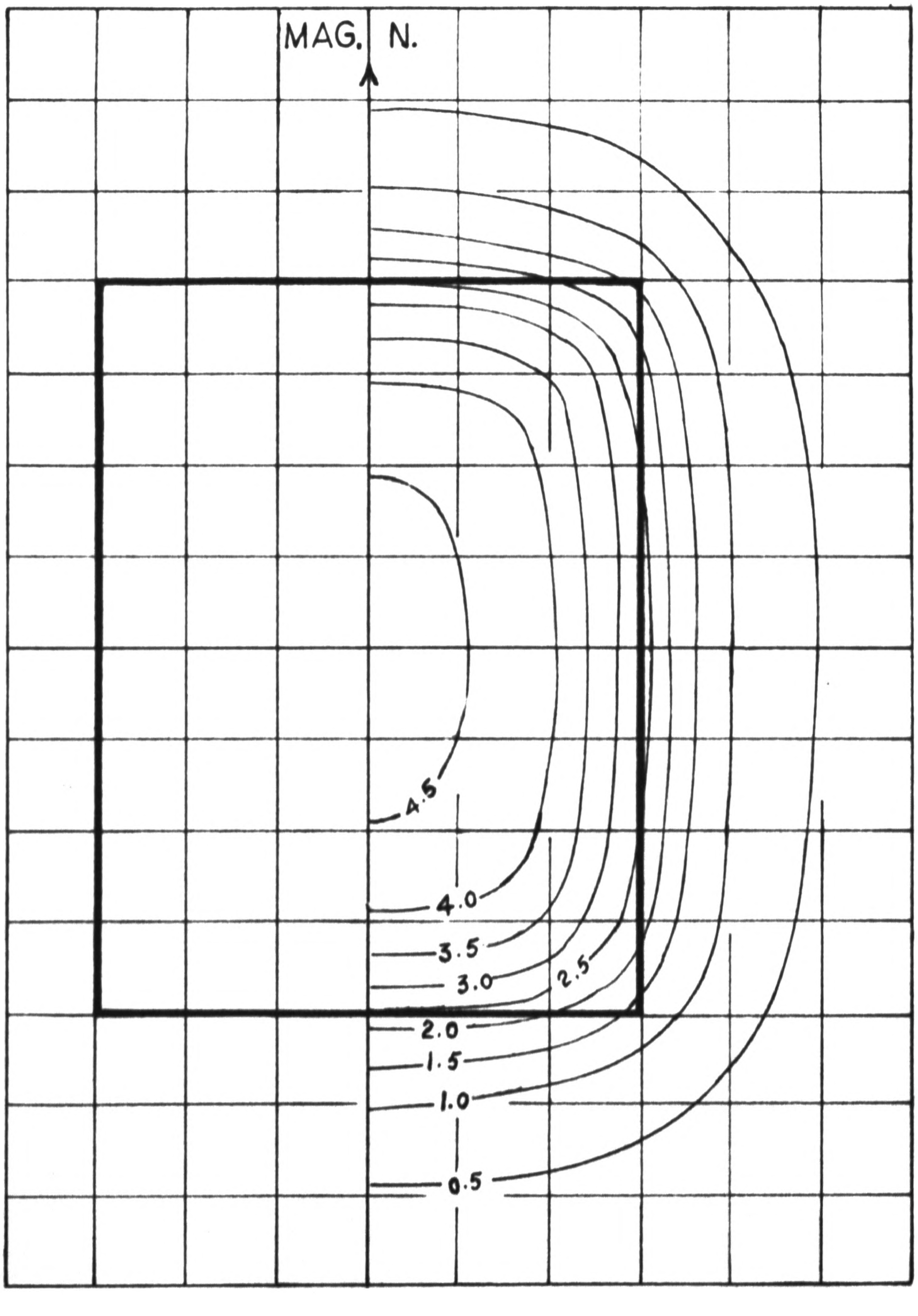


Fig. 18. Total intensity (C.G.S.) - Model No. 12

Inclination 90°

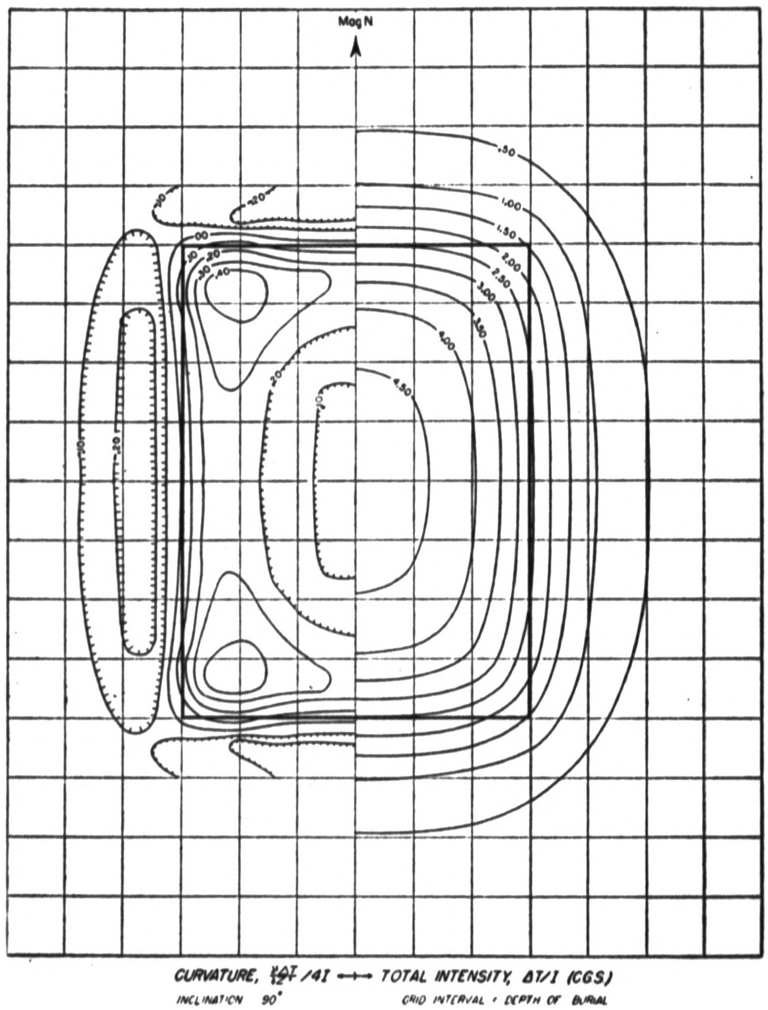


Figure 19. Model 8 x 6, inclination 90° (Vacquier's figure A83) to be compared with Figure 18.

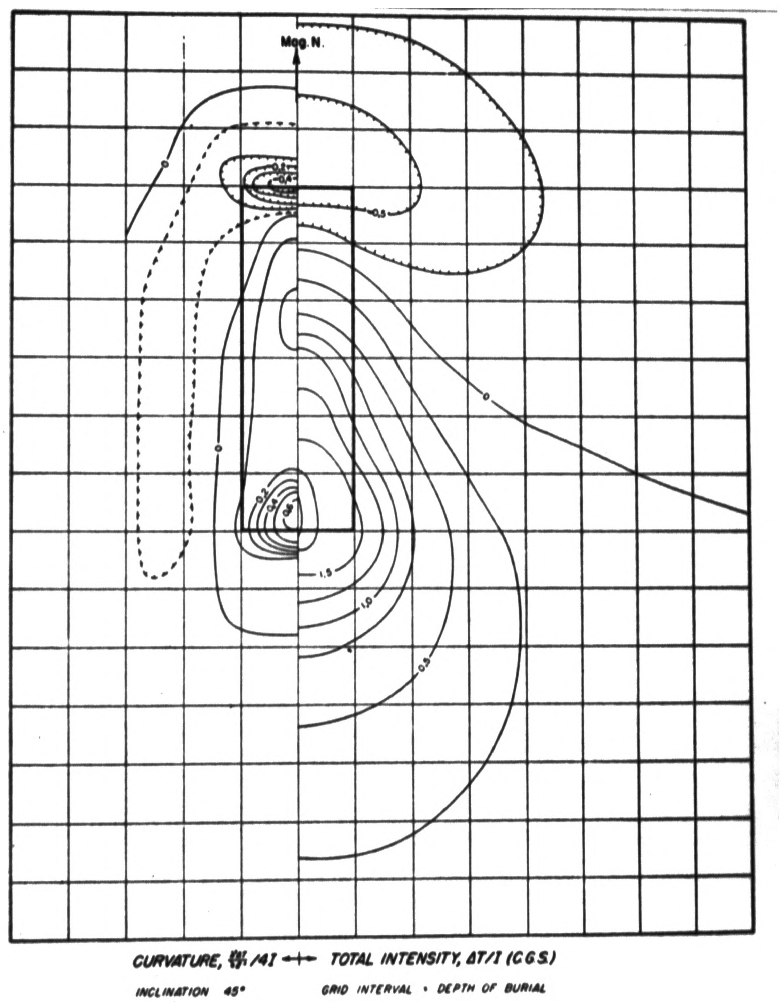


Figure 20. Model 6 x 2, inclination 45° (Vacquier's figure A45) to be compared with Figure 7.

V. SUMMARY AND CONCLUSIONS

The summary and conclusions of this study are as follows:

1. Magnetic anomalies due to three-dimensional bodies can be calculated in a minimum of time with an accuracy adequate for most purposes. If the inclination of the magnetic field is less than 60^{o} the error can be expected to increase as the inclination decreases.

2. The method can be applied to the interpretation of magnetic data specially those due to magnetic distribution in the basement rocks, whether these data are obtained by a vertical magnetometer or they are total intensity data.

3. The magnetic distribution may be due to lateral polarization contrast within the basement rocks or due to topographical relief of the basement surface. The latter is of special importance in oil exploration, since many geologic deformations or structures that form traps for oil accumulation are underlain by basement uplifts. Also, the estimation of the basement depths, even if it is rough, may be very valuable for indicating the available thickness of sedimentary section in which oil accumulation may occur.

4. The method of interpretation is summarized as follows:

   (i) Assume a certain distribution of magnetic material having a certain susceptibility, certain shape and located at a certain depth.

(ii) By incorporating these three parameters into a computer program, compute the magnetic effect (total or vertical intensity, or both) due to the assumed distribution at the surface or any plane above the surface.

(iii) Plot the values of the magnetic intensity obtained from the computer on a contour map or on a profile.

(iv) Compare the theoretical map or profile with the actual one.

(v) If the comparison is not satisfactory, modify the assumptions and re-run the program using the new data until a reasonable fit is obtained.

5. Model studies can be applied as an effective method for magnetic interpretations specially aeromagnetics involving three-dimensional structures. A complete album of model fields can be made available by this method and can be used as a reference for interpretations. Thus, the anomalous field of a three-dimensional structure can be readily calculated by replacing the body by the proper array of prismatic blocks and by comparing this field with the actual field, the distribution of the blocks may be altered until a proper fit is obtained.

6. It must be emphasized that any interpretation of observed magnetic data should be made cautiously because, in general, the solution is not unique. Only the magnitude of the anomaly and the earth's field at the point in question are known.

The unknown susceptibility, depth of burial, and shape and size of the structure all enter as parameters and the observed field may always be approximated by several combinations of these parameters. However, when two of these quantities are known, the third may be reliably determined. Therefore, the interpreter must resort to other aids besides direct theory. The three most effective aids are

(a) Adequate geologic or subsurface control (this is the most important).

(b) Magnetic studies over known geologic conditions in the immediate area.

(c) Model experiments.

Thus, with a clue to the probable shape of the structure, and an idea of the magnetic properties of the rocks, it is possible to compute the theoretical anomalies for a series of structures which would give the results obtained from the field measurements, and to select from this series the structure that seemed most likely from the geological standpoint.

7. The method developed in this investigation still needs more study and development so that it can be applied to all cases without any restriction. However, it has the advantage of being simple and of allowing rapid calculations.

In conclusion, the author believes that digital computers have great versatility in treating geophysical problems where the time required to obtain computed results is an economic factor. He presents this technique of application of a digital computer to magnetic interpretations as one approach to this idea.

VI. BIBLIOGRAPHY

AFFLECK, J. (1958) Interrelationships between magnetic anomaly components. Geophysics, vol. 23, pp. 738-748.

ALLDREDGE, L. R., and DICHTEL, J. J. (1949) Interpretation of Bikini magnetic data. Am. Geophys. Union Trans., vol. 30, pp. 831-836.

BARANOV, V. (1957) A new method for interpretation of aeromagnetic maps: Pseudo-gravimetric anomalies. Geophysics, vol. 22, pp. 359-383.

BULLARD, E. C., and COOPER, R. I. B. (1948) The determination of the masses necessary to produce a given gravitational field. Proc. Royal Soc. of London, vol. 194A, pp. 332-347.

COOK, K. L. (1950) Quantitative interpretation of magnetic anomalies over veins. Geophysics, vol. 15, pp. 667-686.

DEAN, W. C. (1958) Frequency analysis for gravity and magnetic interpretation. Geophysics, vol. 23, pp. 97-127.

DOBRIN, M. B. (1960) Introduction to geophysical prospecting, 2nd ed. McGraw-Hill, New York, pp. 263-338.

ELKINS, T. A. (1951) The second derivative method of gravity interpretation. Geophysics, vol. 16, pp. 29-50.

EVE, A. S. (1932) A magnetic method for estimating the height of some buried magnetic bodies. Geophysical Prospecting 1932, Trans. Am. Inst. Mining Met. Engrs., pp. 200-215.

EVJEN, H. M. (1937) The place of the vertical gradient in gravity interpretation. Geophysics, vol. 1, no. 1, pp. 127-136.

FISHER, J. W. (1940) An experimental device for computing magnetic and gravitational anomalies. Geophysics, vol. 5, pp. 22-30.

GARLAND, G. D. (1951) Combined analysis of gravity and magnetic anomalies. Geophysics, vol. 16, pp. 51-62.

GASSMANN, F. (1951) Graphical evaluation of the anomalies of gravity and of the magnetic field, caused by three-dimensional bodies. Third World Petroleum Congress Proc., Sec. I., pp. 613-621.

GRANT, F. S. (1952) Three-dimensional interpretation of gravitational anomalies, Part I. Geophysics, vol. 17, pp. 344-365.

____________ (1952) Three-dimensional interpretation of gravitational anomalies, Part II. Geophysics, vol. 17, pp. 756-780.

HEILAND, C. A. (1940) Geophysical exploration. New York, Prentice-Hall, Inc.

HENDERSON, R. G. (1960) A comprehensive system of automatic computation in magnetic and gravity interpretation. Geophysics, vol. 25, no. 3, pp. 569-585.

________________, and Zietz, I. (1948) Analysis of total magnetic intensity anomalies produced by point and line sources. Geophysics, vol. 13, pp. 428-436.

________________ (1949) The computation of second vertical derivatives of geomagnetic fields. Geophysics, vol. 14, pp. 508-516.

________________ (1949) The upward continuation of anomalies in total magnetic intensity fields. Geophysics, vol. 14, pp. 517-534.

________________ (1957) Graphical calculation of total intensity anomalies of three-dimensional bodies. Geophysics, vol. 22, pp. 887-904.

HOWE, H. H. (1940) Height of magnetic anomalies. Am. Geophys. Union Trans. of 1940, pp. 309-311.

HUGHES, D. S. (1942) The analytic basis of gravity interpretation. Geophysics, vol. 7, pp. 169-178.

_____________, and PONDROM, W. L. (1947) Computation of vertical magnetic anomalies from total magnetic field measurements. Am. Geophys. Union Trans., vol. 28, no. 2, pp. 193-197.

HUTCHISON, R. D. (1958) Magnetic analysis by logarithmic curves. Geophysics, vol. 23, pp. 749-769.

JACOBSEN, P. Jr. (1961) An evaluation of basement depth determinations from airborne magnetometer data. Geophysics, vol. 26, no. 3, pp. 309-317.

JAKOSKY, J. J. (1960) Exploration Geophysics, 2nd ed., Trija Publishing Company, Calif., pp. 61-246.

KELLOGG, O. D. (1929) Foundations of potential theory. New York, Dover Publications, Inc., . 384 pp.

LGP-30 Operation and subroutine manuals, Royal McBee Corporation.

MUFFLY, G. (1946) The airborne magnetometer. Geophysics, vol. 11, pp. 321-334.

NAGATA, T. (1938) Magnetic anomalies and the corresponding subterranean mass distribution. Bul. of the Earthquake Research Institute, Tokyo Imperial University, vol. 16, pp. 550-577.

_________ (1938) Magnetic anomalies and corresponding subterranean structure. Proc. of the Imperial Academy of Tokyo, vol. 14, pp. 176-181.

NETTLETON, L. L. (1940) Geophysical prospecting for oil. McGraw-Hill, New York, pp. 155-228.

_______________ (1942) Gravity and magnetic calculation. Geophysics, vol. 7, pp. 293-310.

_______________ (1954) Regionals, residuals and structures. Geophysics, vol. 19, pp. 1-22.

_______________, and ELKINS, T. A. (1944) Association of magnetic and density contrasts with igneous rock classifications. Geophysics, vol. 9, pp. 60-78.

PETERS, J. W. (1949) The role of the magnetometer in petroleum exploration. Mines Mag., vol. 39, no. 7, pp. 11-15.

PETERS, L. J. (1949) The direct approach to magnetic interpretation and its practical application. Geophysics, vol. 14, pp. 290-320.

PIRSON, S. J. (1940) Polar charts for interpreting magnetic anomalies. A. I. M. E. Trans. vol. 138, pp. 173-192.

RUMBAUGH, L. H., and ALLDREDGE, L. R. (1949) Airborne equipment for geomagnetic measurements. Am. Geophys. Union Trans., vol. 30, pp. 836-849.

SKEELS, D. C. (1947) Ambiguity in gravity interpretation. Geophysics, vol. 12, no. 1, pp. 43-56.

____________, and WATSON, R. J. (1949) Derivation of magnetic and gravitational quantities by surface integration. Geophysics, vol. 14, pp. 133-150.

SMELLIE, D. W. (1956) Elementary approximations in airomagnetic interpretation. Geophysics, vol. 21, pp. 1021-1040.

STEENLAND, N. C., and BROD, R. J. (1960) Basement mapping with aeromagnetic data - Blind River Basin. Geophysics, vol. 25, no. 3, pp. 586-601.

SWARTZ, C. A. (1954) Some geometrical properties of regional maps. Geophysics, vol. 19, pp. 46-70.

VACQUIER, V., STEENLAND, N. C., HENDERSON, R. G., and ZIETZ, I. (1951) Interpretation of aeromagnetic maps. Geol. Soc. Am. Mem. 47, 151 p.

VESTINE, E. H. (1941) On the analysis of surface magnetic fields by integrals, Part I. Terr. Magnetism and Atm. Electricity, vol. 46, pp. 27-41.

_____________, and DAVIES, N. (1945) Analysis and interpretation of geomagnetic anomalies. Terr. Magnetism and Atm. Electricity, vol. 50, pp. 1-36.

WYCKOFF, R. D. (1948) The gulf airborne magnetometer. Geophysics, vol. 13, pp. 182-208.

ZIETZ, I., and HENDERSON, R. G. (1956) A preliminary report on model studies of magnetic anomalies of three-dimensional bodies. Geophysics, vol. 21, pp. 794-814.

VII. APPENDICES

APPENDIX A

MEMORY LOCATIONS AND THEIR CONTENTS

APPENDIX A

MEMORY LOCATIONS AND THEIR CONTENTS

The following is a general memory map for all programs showing the locations used, their contents, and the q point:

Memory Location	Contents	q
5135	z'	5
36	Initial x' ω	5
37	Δ x'	5
38	x'_f	5
39	Initial y' ω	5
40	Δ y'	5
41	y'_f	5
42	Initial x'	5
43	Initial y' storage	5
44	h	5
45	H	16
46	k	1
47	Cos θ	1
48	Sin θ	1
49	1	1
50	Δ A	2
51	s working	9
52	s storage	9
53	1	9
54	1	4

Temporary Storage:

Memory Location	Contents	q
5155	$m = Hk \Delta A \cos \theta$ ω	20
56	$x' - x$ ω	5
57	$(x' - x)^2$ ω	10
58	$(y' - y)^2$ ω	10
59	$z' - z$ ω	5
60	r^2 ω	10
61	r ω	5
62	$\Delta H \sin \theta$ ω	15

(for programs No. 4 and No. 5)

In general, the memory map for each program, showing the location of program, data, and square root subroutine, is as follows:

Programs No. 1, No. 2, and No. 3:

Location	Contents	q
Track 48	Square root subroutine 15.1	
49 50 51	Program No. 1, No. 2, or No. 3 and data indicated in general memory map starting in location 5135	
52 53	x	5
54 55	y	5
56 57	z	5
58 59	ΔV_-	14
60 61	ΔV_+ (for Program No. 2) or ΔH_- (for Program No. 3)	14

Program No. 4:

Location	Contents	q
Track 47	Square root subroutine 15.1	
48 49 50 51	Program No. 4 and data indicated in general memory map starting in location 5135	
52 53	x	5
54 55	y	5
56 57	z	5
58 59	Δ V	14
60 61	Δ H	14

APPENDIX B

PROGRAMS NO. 1-4 AS WRITTEN FOR THE LGP-30 COMPUTER

APPENDIX B

PROGRAMS No. 1 - 4 AS WRITTEN FOR THE LGP-30 COMPUTER

Program No. 1

```
;0004900'/0000000'
r6308'u4000'b5145'm5146'm5150'm5147'h5155'z0000'
c5800'c5800'b5151's5153'h5151't4919'b4908'a5062'
y4908'y4909'u4908'b5152'h5151'r6308'u4000'b5136'
s5200'h5156'm5156'h5157'b5139's5400'h5158'm5158'
h5158'b5135's5600'h5159'm5159'a5158'a5157'h5160'
r4850'u4800'h5161'b5155'd5160'm5159'd5161'm5154'
a5800'h5800'b5151's5153'h5151't5004'b4924'a5062'
y4924'b4929'a5062'y4929'b4934'a5062'y4934'b4948'
a5062'y4948'y4949'u4923'b5152'h5151'b5200'b5006'
y4924'b5400'b5009'y4929'b5600'b5012'y4934'b5800'
b5015'y4948'y4949'b5139'a5140'h5139's5141't4921'
b5143'h5139'b5136'a5137'h5136's5138't4921'b5200'
m5153'r5061'u5058'b5400'm5153'r5061'u5058'b5800'
r5061'u5058'p1600'z0000'b5151's5153'h5151't5062'
b5031'a5062'y5031'b5035'a5062'y5035'b5039'a5062'
y5039'u5031'r6312'u4400'z0004'u0000'z0001'
.0004900'
```

Program No. 2

```
;0004900'/0004900'
xr6308'xu4000'b0245'm0246'm0250'm0247'h0255'xz0000'
c0900'c0900'c1100' 0251's0253'h0251't0023'b0008'
a0233'y0008'y0009'b0010'a0233'y0010'u0008'b0252'
h0251'xr6308'xu4000'b0236's0300'h0256'm0256'h0257'
b0239's0500'h0258'm0258'h0258'b0235's0700'h0259'
m0259'a0258'a0257'h0260'xr4850'xu4800'h0261'b0255'
d0260'm0259'd0261'm0254'a0900'h0900'b0244's0700'
h0259'm0259'a0258'a0257'h0260'xr4850'xu4800'h0261'
b0255'd0260'm0259'd0261'm0254'a1100'h1100'b0251'
s0253'h0251't0130'b0028'a0233'y0028'b0033'a0233'
y0033'b0038'a0233'y0038'y0055'b0052'a0233'y0052'
y0053'b0105'a0233'y0105'y0106'u0027'b0252'h0251'
b0300'b0132'y0028'b0500'b0135'y0033'b0700'b0138'
y0038'y0055'b0900'b0142'y0052'y0053'b1100'b0146'
y0105'y0106'b0239'a0240'h0239's0241't0025'b0243'
h0239'b0236'a0237'h0236's0238't0025'b0300'm0253'
r0232'u0229'b0500'm0253'r0232'u0229'b0900's1100'
r0232'u0229'xp1600'xz0000'b0251's0253'h0251't0233'
b0162'a0233'y0162'b0202'a0233'y0202'b0206'a0233'
y0206'b0207'a0233'y0207'u0162'xr6312'xu4400'xz0004'
xu0000'xz0001'
.0004900'
```

Program No.3

```
;0004900'/0004900'
xr6308'xu4000'b0245'm0246'm0250'm0247'h0255'xz0000'
c0900'c0900'c1100'b0251's0253'h0251't0023'b0008'
a0233'y0008'y0009'b0010'a0233'y0010'u0008'b0252'
h0251'xr6308'xu4000'b0236's0300'h0256'm0256'h0257'
b0239's0500'h0258'm0258'h0258'b0235's0700'h0259'
m0259'a0258'a0257'h0260'xr4850'xu4800'h0261'b0255'
d0260'm0259'd0261'm0254'a0900'h0900'b0255'd0260'
m0256'd0261'm0254'a1100'h1100'b0251's0253'h0251'
t0119'b0028'a0233'y0028'b0033'a0233'y0033'b0038'
a0233'y0038'b0052'a0233'y0052'y0053'b0059'a0233'
y0059'y0060'u0027'b0252'h0251'b0300'b0121'y0028'
b0500'b0124'y0033'b0700'b0127'y0038'b0900'b0130'
y0052'y0053'b1100'b0134'y0059'y0060'b0239'a0240'
h0239's0241't0025'b0243'h0239'b0236'a0237'h0236'
s0238't0025'b0300'm0253'r0232'u0229'b0500'm0253'
r0232'u0229'c0263'800t0161'u0200'b0900'r0232'u0229'
b1100'm0248'h0262'b0900'm0247'a0262'd0249'r0232'
u0229'xp1600'xz0000'b0251's0253'h0251't0233'b0150'
a0233'y0150'b0154'a0233'y0154'b0203'a0233'y0203'
y0161'b0200'a0233'y0200'u0150'xr6312'xu4400'xz0004'
xu0000'xz0001'
.0004900'
```

Program No. 4

```
;0004800'/0004800'
xr6308'xu4000'b0345'm0346'm0350'm0347'h0355'xz0000'
c1000'c1000'c1200'b0351's0353'h0351't0023'b0008'
a0307'y0008'y0009'b0010'a0307'y0010'u0008'b0352'
h0351'xr6308'xu4000'b0336's0400'h0356'm0356'h0357'
b0339's0600'h0358'm0358'h0358'b0335's0800'h0359'
m0359'a0358'a0357'h0360'xr4750'xu4700'h0361'b0355'
d0360'm0359'd0361'm0354'a1000'h1000'b0355'd0360'
m0356'd0361'm0354'a1200'h1200'b0344's0800'h0359'
m0359'a0358'a0357'h0360'xr4750'xu4700'h0361'b0355'
d0360'm0359'd0361'm0354'h0362'b1000's0362'h1000'
b0355'd0360'm0356'd0361'm0354'h0362'b1200's0362'
h1200'b0351's0353'h0351't0152'b0028'a0307'y0028'
b0033'a0307'y0033'b0038'a0307'y0038'y0062'b0052'
a0307'y0052'y0053'y0113'y0115'b0059'a0307'y0059'
y0060'y0122'y0124'u0027'b0352'h0351'b0400'b0154'
y0028'b0600'b0157'y0033'b0800'b0160'y0038'y0062'
b1000'b0200'y0052'y0053'y0113'y0115'b1200'b0206'
y0059'y0060'y0122'y0124'b0339'a0340'h0339's0341'
t0025'b0343'h0339'b0336'a0337'h0336's0338't0025'
b0400'm0353'r0306'u0303'b0600'm0353'r0306'u0303'
c0363'800t0235'u0238'b1000'r0306'u0303'b1200'm0348'
h0362'b1000'm0347'a0362'd0349'r0306'u0303'xp1600'
xz0000'b0351's0353'h0351't0307'b0224'a0307'y0224'
b0228'a0307'y0228'b0241'a0307'y0241'y0235'b0238'
a0307'y0238'u0224'xr6312'xu4400'xz0004'xu0000'xz0001'
.0004800'
```

APPENDIX C

LGP-30 CODING SHEETS OF PROGRAM NO. 4

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 Page 1 Of 7

Program Input Codes	Stop	Location	Instruction: Operation	Instruction: Address	Stop	Contents of Address	Notes
;00004800	'						
/00004800	'	X					
		0000	xr	6308	'		input 11.B
		01	xu	4000	'		input 11.B
		02	b	0345	'	H at 16	
		03	m	0346	'	k at 1	
		04	m	0350	'	ΔA at 2	
		05	m	0347	'	cos θ at 1	
		06	h	0355	'		m at 20
		07	xz	0000	'	X	stop
		08	c	1000	'		set Σ Δ V=0
		09	c	1000	'		" "
		10	c	1200	'		set Σ Δ H = 0
		11	b	0351	'	s at 9	
		12	s	0353	'	1 at 9	
		13	h	0351	'		
		14	t	0023	'		
		15	b	0008	'	X address	of ΔV
		16	a	0307	'	1 at 29	
		17	y	0008	'		
		18	y	0009	'		
		19	b	0010	'	address	of ΔH
		20	a	0307	'	1 at 29	
		21	y	0010	'		
		22	u	0008	'		
		23	b	0352	'	X initial s	
		24	h	0351	'		initialize s
		25	xr	6308	'		input 11.B
		26	xu	4000	'		input 11.B
		27	b	0336	'	x' at 5	
		28	s	0400	'	x at 5	
		29	h	0356	'		x'-x at 5
		30	m	0356	'	x'-x at 5	
		31	h	0357	'	X	$(x'-x)^2$ at 10

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 — Page 2 Of 7

Program Input Codes	Stop	Location	Instruction: Operation	Instruction: Address	Stop	Contents of Address	Notes
	'						
	'	☒					
		0032	b	0339	'	y' at 5	
		33	s	0600	'	y at 5	
		34	h	0358	'		y'-y at 5
		35	m	0358	'	y'-y at 5	
		36	h	0358	'		$(y'-y)^2$ at 10
		37	b	0335	'	z' at 5	
		38	s	0800	'	z at 5	
		39	h	0359	'	☒	z'-z at 5
		40	m	0359	'	z'-z at 5	
		41	a	0358	'	$(y'-y)^2$	at 10
		42	a	0357	'	$(x'-x)^2$	at 10
		43	h	0360	'		r^2 at 10
		44	xr	4750	'		sqrt 15.1
		45	xu	4700	'		sqrt 15.1
		46	h	0361	'		r at 5
		47	b	0355	'	☒ m at 20	
		48	d	0360	'	r^2 at 10	
		49	m	0359	'	z'-z at 5	
		50	d	0361	'	r at 5	
		51	m	0354	'	1 at 4	
		52	a	1000	'	$\Sigma \Delta V$	
		53	h	1000	'		ΔV at 14
		54	b	0355	'	m at 20	
		55	d	0360	'	☒ r^2 at 10	
		56	m	0356	'	x'-x at 5	
		57	d	0361	'	r at 5	
		58	m	0354	'	1 at 4	
		59	a	1200	'	$\Sigma \Delta H$	
		60	h	1200	'		ΔH at 14
		61	b	0344	'	h at 5	
		62	s	0800	'	z at 5	
		63	h	0359	'	☒	h - z at 5

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 Page 3 Of 7

Program Input Codes	Stop	Location	Instruction Operation	Instruction Address	Stop	Contents of Address	Notes
	'						
	'	☒					
		0100	m	0359	'	h-z at 5	
		01	a	0358	'	$(y'-y)^2$	at 10
		02	a	0357	'	$(x'-x)^2$	at 10
		03	h	0360	'		r^2 at 10
		04	xr	4750	'		sqrt 15.1
		05	xu	4700	'		sqrt 15.1
		06	h	0361	'		r at 5
		07	b	0355	'	☒ m at 20	
		08	d	0360	'	r^2 at 10	
		09	m	0359	'	h-z at 5	
		10	d	0361	'	r at 5	
		11	m	0354	'	1 at 4	
		12	h	0362	'		ΔV_+ at 14
		13	b	1000	'	$\Sigma \Delta V$ at 14	
		14	s	0362	'	ΔV_+ at 14	
		15	h	1000	'	☒	
		16	b	0355	'	m at 20	
		17	d	0360	'	r^2 at 10	
		18	m	0356	'	x'-x at 5	
		19	d	0361	'	r at 5	
		20	m	0354	'	1 at 4	
		21	h	0362	'		ΔH_+ at 14
		22	b	1200	'	$\Sigma \Delta H$ at 14	
		23	s	0362	'	☒ ΔH_+ at 14	
		24	h	1200	'		
		25	b	0351	'	s at 9	set counter to
		26	s	0353	'	1 at 9	loop
		27	h	0351	'		
		28	t	0152	'		
		29	b	0028	'	address	of x
		30	a	0307	'	1 at 29	
		31	y	0028	'	☒	

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 — Page 4 Of 7

Program Input Codes	Stop	Location	Instruction Operation	Instruction Address	Stop	Contents of Address	Notes
	'						
	'	☒					
		0132	b	0033	'	address	of y
		33	a	0307	'	1 at 29	
		34	y	0033	'		
		35	b	0038	'	address	of z
		36	a	0307	'	1 at 29	
		37	y	0038	'		
		38	y	0062	'		
		39	b	0052	'	☒ address	of ΔV
		40	a	0307	'	1 at 29	
		41	y	0052	'		
		42	y	0053	'		
		43	y	0113	'		
		44	y	0115	'		
		45	b	0059	'	address	of Δ H
		46	a	0307	'	1 at 29	
		47	y	0059	'	☒	
		48	y	0060	'		
		49	y	0122	'		
		50	y	0124	'		
		51	u	0027	'		
		52	b	0352	'	initial s	
		53	h	0351	'		initialize s
		54	b	0400	'	initial x	
		55	b	0154	'	☒ address	of x
		56	y	0028	'		
		57	b	06C0	'	initial y	
		58	b	0157	'	address	of y
		59	y	0033	'		
		60	b	0800	'	initial z	
		61	b	0160	'	address	of z
		62	y	0038	'		
		63	y	0062	'	☒	

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 Page 5 Of 7

Program Input Codes	Stop	Location	Instruction: Operation	Instruction: Address	Stop	Contents of Address	Notes
		X					
		0200	b	1000		ΔV	
		01	b	0200		address	of ΔV
		02	y	0052			
		03	y	0053			
		04	y	0113			
		05	y	0115			
		06	b	1200		Δ H	
		07	b	0206		X address	of Δ H
		08	y	0059			
		09	y	0060			
		10	y	0122			
		11	y	0124			
		12	b	0339		y' at 5	
		13	a	0340		Δy' at 5	increment y'
		14	h	0339			
		15	s	0341		X y'_f at 5	
		16	t	0025			
		17	b	0343		initial y'	
		18	h	0339			initialize y'
		19	b	0336		x' at 5	
		20	a	0337		Δx' at 5	increment x'
		21	h	0336			
		22	s	0338		x'_f at 5	
		23	t	0025		X	
		24	b	0400		x at 5	
		25	m	0353		1 at 9	x at 14
		26	r	0306			print x
		27	u	0303			
		28	b	0600		y at 5	
		29	m	0353		1 at 9	y at 14
		30	r	0306			print y
		31	u	0303		X	

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 Page 6 Of 7

Program Input Codes	Stop	Location	Instruction: Operation	Instruction: Address	Stop	Contents of Address	Notes
	☒						
		0232	c	0363			clear accumulator
		33	800t	0235			
		34	u	0238			
		35	b	1000		ΔV at 14	
		36	r	0306			print ΔV
		37	u	0303			
		38	b	1200		Δ H at 14	
		39	m	0348	☒	sin θ	at 1
		40	h	0362			Δ H sin θ at 15
		41	b	1000		ΔV at 14	
		42	m	0347		cos θ at 1	ΔV cos θ at 15
		43	a	0362		ΔH sin θ	ΔT at 15
		44	d	0349		1 at 1	ΔT at 14
		45	r	0306			print ΔT
		46	u	0303			
		47	xp	1600	☒		carriage return
		48	xz	0000			
		49	b	0351		s at 9	set counter to
		50	s	0353		1 at 9	loop
		51	h	0351			
		52	t	0307			stop if neg.
		53	b	0224		address	of x
		54	a	0307		1 at 29	
		55	y	0224	☒		
		56	b	0228		address	of y
		57	a	0307		1 at 29	
		58	y	0228			
		59	b	0241		address	of ΔV
		60	a	0307		1 at 29	
		61	y	0241			
		62	y	0235			
		63	b	0238	☒	address	of ΔH

CALCULATION OF VERTICAL AND TOTAL MAGNETIC INTENSITY

PROGRAM NO. 4 Page 7 Of 7

Program Input Codes	Stop	Location	Instruction Operation	Instruction Address	Stop	Contents of Address	Notes
		☒					
		0300	a	0307		1 at 29	
		01	y	0238			
		02	u	0224			
		03	xr	6312			output 12.0B
		04	xu	4400			
		05	xz	0004			
		06	xu	0000			
		07	xz	0001	☒	1 at 29	or stop
.00004800		08					
		09					
		10					
		11					
		12					
		13					
		14					
		15			☒		
		16					
		17					
		18					
		19					
		20					
		21					
		22					
		23			☒		
		24					
		25					
		26					
		27					
		28					
		29					
		30					
		31			☒		

APPENDIX D

OUTPUT DATA OBTAINED FROM THE LGP-30 COMPUTER FOR MODELS NO. 1-12

APPENDIX D

OUTPUT DATA OBTAINED FROM THE LGP-30 COMPUTER FOR MODELS NO.1-12

Output Data Obtained For Model No. 1 Using Program No. 3

x	y	ΔV	ΔT
.00000	.00000	2.09405	1.48016
.99999	.00000	2.05230	1.25763
1.99999	.00000	1.84183	.83731
2.49999	.00000	1.56164	.47122
3.00000	.00000	1.09823	.04675
4.00000	.00000	.35156	-.27026
.00000	.99999	1.43484	1.01404
.49999	.99999	1.42706	.92745
.99999	.99999	1.40099	.82190
1.49999	.99999	1.34735	.68472
1.99999	.99999	1.24517	.49789
2.49999	.99999	1.05738	.24707
3.50000	.99999	.47120	-.19281
5.00000	.99999	.11513	-.19821
5.99999	.99999	.05717	-.14843
.00000	1.49999	.89556	.63272
.99999	1.49999	.86915	.47057
.49999	1.99999	.53230	.31774
1.49999	1.99999	.49069	.16860
2.49999	1.99999	.38459	-.01474
4.00000	1.99999	.16290	-.16827
5.99999	1.99999	.04710	-.12600
.49999	3.50000	.14742	.07431
3.00000	3.00000	.13686	-.08169
3.00000	5.00000	.04292	-.04141
.00000	4.50000	.07717	.05420
3.00000	5.49999	.03401	-.03494
-.99999	.49999	1.88019	1.51528
-.99999	.75000	1.66979	1.35864
-.99999	.99999	1.40099	1.15835

x	y	Δ V	Δ T
-.99999	1.49999	.86915	.75756
-.99999	2.49999	.32061	.31994
-.99999	6.49999	.02711	03487
-1.99999	.25000	1.80268	1.73296
-1.99999	.75000	1.49208	1.47002
-1.99999	.99999	1.24517	1.26202
-1.99999	1.49999	.76019	.84375
-1.99999	3.00000	.18117	.26696
-1.99999	4.50000	.06658	.11422
-3.00000	.49999	1.01002	1.39898
-3.00000	.75000	.90230	1.27035
-3.00000	.99999	.76465	1.10635
-3.00000	1.49999	.49069	.77178
-3.00000	1.99999	.30633	.52892
-3.00000	3.00000	.13686	.27453
-3.50000	.49999	.58962	1.03903
-4.00000	.49999	.33213	.72964
-4.00000	1.99999	.16290	.39782
-4.00000	3.00000	.09075	.24191
-4.00000	4.50000	.04266	.12527
-5.00000	.00000	.13000	.40094
-5.00000	1.49999	.10017	.31881
-5.00000	4.50000	.03150	.11453
-6.99999	1.49999	.03073	.14962
1.49999	-.99999	1.34735	.68472
2.49999	-1.99999	.38459	-.01474
-3.00000	-.99999	.76465	1.10635
-.99999	-1.49999	.86915	.75756
-1.99999	-3.00000	.18117	.26696
-4.00000	-1.99999	.16290	.39782
-8.50000	.00000	.01684	.10287
-6.99999	3.50000	.02102	.10580
-6.49999	.00000	.04501	.19814
-5.99999	3.00000	.03596	.15053
-1.99999	5.99999	.03128	.05801
-.99999	4.00000	.10151	.11733

Output Data Obtained For Model No. 2

Using Program No. 3

x	y	Δ V	Δ T
.00000	.00000	292.26671	253.11166
.99999	.00000	287.51337	233.35726
1.99999	.00000	262.49879	188.15890
2.49999	.00000	233.27038	145.73776
3.00000	.00000	151.84909	61.99353
4.00000	.00000	40.85510	-8.02627
.00000	.99999	141.11657	122.21111
.49999	.99999	140.59965	115.35424
.99999	.99999	137.43601	105.72930
1.49999	.99999	132.03429	93.24725
1.99999	.99999	121.12949	74.92163
2.49999	.99999	103.14535	50.45077
3.50000	.99999	48.69721	1.30065
5.00000	.99999	12.69293	-11.02057
5.99999	.99999	6.35813	-9.31912
.00000	1.49999	82.43182	71.38837
.99999	1.49999	79.66256	57.86501
.49999	1.99999	49.67878	38.55948
1.49999	1.99999	45.52513	25.94906
2.49999	1.99999	35.86720	9.91000
4.00000	1.99999	16.74573	-6.83099
5.99999	1.99999	5.18392	-7.88607
.49999	3.50000	14.86467	10.64525
3.00000	3.00000	13.79840	-1.32537
3.00000	5.00000	4.57242	-1.45697
.00000	4.50000	8.02590	6.95061
3.00000	5.49999	3.65283	-1.29721
-.99999	.49999	228.05154	212.48595
-.99999	.75000	179.82282	169.96942
-.99999	.99999	137.43601	132.31799
-.99999	1.49999	79.66256	80.11517
-.99999	2.49999	30.77940	33.75222
-.99999	6.49999	2.92709	3.75420
-1.99999	.25000	245.87408	251.36182
-1.99999	.75000	160.41244	172.30779
-1.99999	.99999	121.12949	134.88180
-1.99999	1.49999	68.94556	82.97677
-1.99999	3.00000	17.93821	25.94384
-1.99999	4.50000	6.96365	11.12701
-3.00000	.49999	121.83723	165.51257

x	y	Δ V	Δ T
-3.00000	.75000	97.39802	136.09536
-3.00000	.99999	75.79258	109.50637
-3.00000	1.49999	45.94272	71.21822
-3.00000	1.99999	29.22457	48.32238
-3.00000	3.00000	13.79840	25.22497
-3.50000	.49999	67.91762	111.30313
-4.00000	.49999	37.52768	73.05063
-4.00000	1.99999	16.74573	35.83547
-4.00000	3.00000	9.46087	21.62237
-4.00000	4.50000	4.56618	11.21185
-5.00000	.00000	14.60904	37.45480
-5.00000	1.49999	10.89810	28.77722
-5.00000	4.50000	3.42628	10.05521
-6.99999	1.49999	3.42988	13.01330
1.49999	-.99999	132.03429	93.24725
2.49999	-1.99999	35.86720	9.91000
-3.00000	-.99999	75.79258	109.50637
-.99999	-1.49999	79.66256	80.11517
-1.99999	-3.00000	17.93821	25.94384
-4.00000	-1.99999	16.74573	35.83547

Output Data Obtained For Model No. 3

Using Program No. 3

x	y	Δ V	Δ T
.00000	.00000	629.86029	545.47769
.25000	.49999	634.17329	526.53357
.75000	.49999	610.33247	451.40875
.99999	.49999	582.75241	403.60330
1.25000	.49999	553.17991	354.00030
1.49999	.49999	510.51441	290.17831
1.75000	.49999	443.92657	209.46029
1.99999	.49999	363.03108	128.65823
2.25000	.49999	285.91227	63.97760
2.49999	.49999	222.30939	19.14010
3.00000	.49999	136.40109	-26.86474
3.50000	.49999	87.75792	-42.20632
5.00000	.49999	30.49523	-40.10000
.25000	1.49999	600.53755	499.49450
.75000	1.49999	578.39187	429.89877
.99999	1.49999	552.30601	385.26647
1.49999	1.49999	484.27658	278.59195
1.75000	1.49999	420.28838	201.17757
2.25000	1.49999	267.88051	61.34002
3.00000	1.49999	125.78734	-24.72107

x	y	Δ V	ΔT
5.00000	1.49999	28.35887	-37.46789
.00000	2.49999	475.35351	411.67019
.49999	2.49999	475.42829	375.86776
.99999	2.49999	439.76710	307.52872
1.49999	2.49999	388.27195	224.83142
2.49999	2.49999	163.45741	13.22342
4.50000	2.49999	32.60873	-34.65298
.00000	3.50000	201.69674	174.67525
.49999	3.50000	197.99090	148.94760
1.49999	3.50000	160.85284	75.09747
2.49999	3.50000	89.41047	-.04568
3.50000	3.50000	44.84583	-24.62298
.00000	5.49999	34.70614	30.05639
2.49999	5.49999	23.99092	-4.73889
-.49999	.49999	629.80503	595.10879
-1.25000	.49999	553.17991	604.14010
-1.99999	.49999	363.03108	500.13296
-2.49999	.49999	222.30939	365.91278
-3.00000	.49999	136.40109	263.11926
-3.50000	.49999	87.75792	194.20795
-4.50000	.49999	41.78985	115.85171
-5.99999	.49999	17.63113	63.26766
-7.99999	.49999	7.40579	34.41946
-.49999	1.49999	596.80186	562.37335
-1.49999	1.49999	484.27658	560.20388
-2.49999	1.49999	206.99279	339.91668
-3.50000	1.49999	80.63070	178.64681
-5.00000	1.49999	28.35887	86.58691
-6.99999	1.49999	10.55490	43.55120
-.49999	2.49999	475.42829	447.60229
-.99999	2.49999	439.76710	454.17395
-1.49999	2.49999	388.27195	447.67864
-2.49999	2.49999	163.45741	269.89428
-3.50000	2.49999	65.30114	145.78821
-4.50000	2.49999	32.60873	91.13290
-6.49999	2.49999	11.80170	45.70138
-.49999	3.50000	197.99090	193.98419
-1.49999	3.50000	160.85284	203.50903
-1.49999	3.00000	270.66465	322.22222
-2.49999	3.50000	89.41047	154.90964
-3.50000	3.50000	44.84583	102.29834
-5.49999	3.50000	15.39149	51.74783
-.99999	4.50000	69.55607	83.98895
-1.99999	4.50000	53.46272	86.22265
-4.00000	4.50000	22.41943	58.50509
-5.99999	4.50000	9.97068	36.41033
.00000	5.49999	34.70614	30.05639
-.49999	6.99999	14.26727	15.53164
1.99999	5.99999	20.49498	.07199
-5.00000	6.99999	6.76831	21.78106

Output Data Obtained For Model No. 4

Using Program No. 3

x	y	Δ V	Δ T
.00000	.00000	.69848	.60470
.09998	.00000	.69204	.57079
.20000	.00000	.67306	.52737
.29998	.00000	.64273	.47665
.39999	.00000	.60290	.42126
.49999	.00000	.55624	.36413
.70000	.00000	.45315	.25521
.99999	.00000	.30883	.12921
1.29998	.00000	.20297	.05428
1.99999	.00000	.08019	-.00741
3.00000	.00000	.02779	-.01702
-.30000	.00000	.64273	.63619
-.49999	.00000	.55624	.59893
-.70000	.00000	.45315	.52932
-.99999	.00000	.30883	.40539
-1.40001	.00000	.17632	.26690
-1.70000	.00000	.11728	.19558
-2.20001	.00000	.06326	.12176
-3.50000	.00000	.01806	.04690
-4.50000	.00000	.00872	.02727
-2.49999	.49999	.04319	.08981
-1.49999	.70000	.12483	.19604
-1.30000	.49999	.17873	.26208
-.99999	.49999	.26347	.34686
-.49999	.49999	.45143	.48766
-.30000	.49999	.51525	.51129
.00000	.49999	.55624	48154
.20000	.49999	.53752	42019
.39999	.49999	.48592	.33794
.70000	.49999	.37427	.20923
.99999	.49999	.26347	.10913
1.29998	.49999	.17873	.04718
3.00000	.49999	.02677	-.01641
-.49999	.29998	.51525	55542
.00000	.79998	.40191	.34790
.00000	1.19999	.23364	20218
.00000	1.49999	.15356	.13284
-.49999	.79998	.33540	.36401
-.49999	.99999	.26347	.28698
-.49999	1.29998	.17873	.19565
-.49999	1.79998	.09454	.10412
-1.49999	1.99999	.04555	.07247
-1.49999	1.29998	.08196	.12954
-.99999	.99999	.17417	.23105
-.99999	1.49999	.10306	.13781

x	y	Δ V	Δ T
-2.80000	1.49999	.02373	.05318
-3.50000	2.49999	.00996	.02605
29998	.79998	.37599	.27642
.49999	1.49999	.13778	.08709
49999	2 49999	.04319	.02679
.00000	4.50000	.00872	.00745
.99999	1.49999	.10306	.04043
1.99999	.99999	.06083	.00610
-1.49999	4.50000	.00750	.01208
1.49999	2.49999	.03007	.00381

Output Data Obtained For Model No. 5

Using Program No. 4

x	y	Δ V	Δ T
.00000	.00000	633.13043	548.30978
.49999	.00000	637.95565	530.08447
.99999	.00000	627.12674	497 23397
1.49999	.00000	624.42102	469.21453
1.99999	.00000	602.42886	421.04699
2.49999	.00000	581.31155	368.94631
3.00000	.00000	526.76483	282.68249
3.50000	.00000	446.76892	172.68233
4.00000	.00000	300.77138	21.58913
4.50000	.00000	161.12246	-79.98358
5.00000	.00000	75.20840	-119.11444
5.99999	00000	.65328	-122.91372
6.99999	00000	-22.92824	-103.55844
-.99999	.00000	627.12674	588.98691
-1.99999	.00000	602.42886	622.39568
-3.00000	.00000	526.76483	629.70553
-4.00000	.00000	300.77138	499.36471
-4.50000	.00000	161.12246	359.05716
-5.00000	.00000	75.20840	249.37976
-5.99999	.00000	.65328	124.04520
-7.49999	.00000	-27.40670	45.78203
.49999	.99999	631.98889	525.47531
1.49999	.99999	618.77174	466.03255
2.49999	.99999	576.39076	367.54852
3.19999	.99999	496.05862	244.56313
4.00000	.99999	297.74161	22.82519
5.00000	.99999	73.52673	-117.02007
6.49999	.99999	-14.87387	-111.96368

x	y	Δ V	Δ T
7.99999	.99999	-29.39228	-82.28316
-.49999	.99999	631.98889	569.16717
-1.99999	.99999	597.08559	615.46918
-3.00000	.99999	522.38607	622.56005
-4.50000	.99999	158.79695	353.24301
-5.99999	99999	-.06135	120.69147
-7.99999	.99999	-29.39228	31.37390
2.49999	1.99999	555.65989	358.91217
3.69999	1.99999	377.07295	113.89648
5.70000	1.99999	10.44331	-117 69088
6.99999	1.99999	-23.73561	-96.68127
-1.49999	1.99999	595.28880	580.04940
-3.50000	1.99999	427.37661	568.08111
-5.00000	1.99999	67.11944	227.07858
-6.99999	2.79998	-24.64155	47.61517
7.99999	4.00000	-28.60384	-65.00189
5.99999	4.00000	-15.47782	-89.94256
4.00000	4.00000	134.13630	-18.44219
2.49999	4.00000	274.65753	159.20666
.99999	4.00000	297.74161	229.95633
-.99999	4.00000	297.74161	285.74988
-3.00000	4.00000	247.29203	313.95898
-4.50000	4.00000	64.29354	181.04806
-6.30000	4.00000	-20.31796	51.57724
4.50000	3.50000	99.34860	-67.54632
3.19999	3.00000	421.88186	216.54717
1.49999	2.69999	558.89650	425.55737
.00000	3.00000	526.76483	456.19405
-1.99999	3.59999	403.87884	417.22524
-2.49999	3.00000	488.88634	528.05618
-4.00000	3.00000	247.29203	407.16262
-5.49999	3.00000	12.83394	129.70904
-4.00000	3 74999	173 82995	303.33993
6.99999	5.99999	-27 83598	-55.87304
5.49999	5.00000	-17 16822	-77.41571
3.00000	5.00000	51.34510	-18.18466
.75000	5.00000	74.29863	49.29693
-3.00000	5.00000	51.34510	107.11734
-5.00000	5.00000	-8.15995	62.36944
-.99999	5.99999	-.06135	13.64480
1.99999	5.99999	-2.58331	-29.26187
-6.99999	5.99999	-27.83598	7 65939

Output Data Obtained For Model No.6

Using Program No.4

x	y	Δ V	Δ T
.00000	.00000	179.04516	155.05841
1.25000	.00000	186.81338	149.95403
2.25000	.00000	193.95489	136.17388
2.74999	.00000	192.33426	114.22893
3.00000	.00000	183.55392	97.01946
3.24999	.00000	174.80920	78.23571
3.50000	.00000	156.83855	47.53958
3.79999	.00000	111.59460	-6.77337
4.50000	.00000	-4.17114	-92.42361
5.49999	.00000	-43.46371	-80.59149
5.99999	.00000	-40.67440	-64.65060
6.99999	.00000	-29.74548	-40.45465
7.99999	.00000	-20.81954	-26.04611
-.99999	.00000	182.08093	167.90960
-1.49999	.00000	191.80673	183.33850
-2.25000	.00000	193.95489	199.76749
-2.80000	.00000	190.60583	219.43154
-3.50000	.00000	156.83855	224.11404
-4.10000	.00000	54.34896	151.79065
-4.30000	.00000	21.16891	116.66427
-4.50000	.00000	-4.17114	85.19882
-4.79999	.00000	-28.03622	48.69226
-5.20001	.00000	-41.30624	18.35308
-5.49999	.00000	-43.46371	5.30960
-6.49999	.00000	-35.26580	-9.98394
-7.99999	.00000	-20.81954	-10.01461
.99999	.99999	185.03072	150.26364
2.19999	.99999	195.40646	139.33657
3.00000	.99999	185.85594	99.85073
3.50000	.99999	158.91111	50.27868
4.50000	.99999	-2.58046	-90.09091
5.39999	.99999	-42.05328	-82.05459
6.09999	.99999	-38.80093	-60.38250
.00000	1.99999	189.45510	164.07373
1.59999	1.99999	201.55132	156.47577
2.79998	1.99999	198.61282	121.37481
3.39999	1.99999	173.18273	72.62109
3.79999	1.99999	118.27885	3.93508
5.29998	1.99999	-37.89111	-79.24383
5.99999	1.99999	-37.08844	-58.93548
6.99999	1.99999	-27.44311	-37.01068
-.99999	.99999	185.03072	170.22054
-1.49999	1.99999	201.45825	190.03271
-2.20001	1.99999	201.61320	202.37002
-3.00000	.99999	185.85594	222.06280
-4.20001	1.99999	43.05791	134.42480
-4.50000	1.99999	1.63169	85.47744

x	y	Δ V	Δ T
-5.20001	1.99999	-36.50560	18.66961
-6.20000	1.99999	-35.32543	-7.50225
.00000	3.00000	183.55392	158.96313
1.49999	3.00000	194.68885	155.51351
2.39999	3.00000	197.83331	142.79339
3.24999	3.00000	175.84298	93.15399
3.69999	3.00000	132.21229	31.30382
4.50000	3.24999	2.21912	-66.46108
5.79998	3.00000	-34.26470	-56.13998
-1.80000	3.00000	192.37094	185.45181
-2.70001	3.00000	194.53538	208.36034
-4.00000	3.00000	78.06242	156.64947
-5.00000	3.00000	-27.55989	26.60208
-5.99999	3.00000	-33.10194	-5.97317
-6.99999	3.00000	-24.77369	-10.14761
1.49999	4.00000	80.23149	59.94748
2.69999	4.00000	82.76997	45.02148
3.50000	4.00000	65.56028	10.81246
4.50000	4.00000	-13.07996	-57.66448
6.59999	4.00000	-24.28161	-32.10846
5.00000	4.50000	-29.46724	-49.34332
.00000	3.79999	111.59460	96.64422
-1.49999	4.00000	80.23149	79.01818
-1.99999	3.50000	163.89968	159.84106
-2.49999	4.00000	84.18925	94.99093
-3.00000	3.50000	158.75307	179.63333
-4.00000	3.50000	65.56028	133.32919
-4.00000	3.79999	43.48238	101.98205
-4.50000	3.50000	-.94172	61.46914
-4.30000	4.00000	-.79150	50.41107
-5.00000	4.00000	-28.37331	8.82809
-5.29999	4.29999	-30.09353	-3.42199
-6.99999	5.00000	-17.95388	-9.48950
.00000	4.50000	-4.17114	-3.61230
.99999	4.50000	-2.58046	-6.91989
3.00000	4.50000	3.69879	-19.92569
4.00000	4.79998	-24.43937	-46.30000
1.99999	4.79998	-22.64579	-29.33260
-.49999	5.00000	-36.30432	-29.65765
-3.00000	5.00000	-27.55989	-8.22973
-4.00000	4.79998	-24.43937	4.01061
-3.00000	4.50000	3.69879	26.33218
-1.99999	4.79998	-22.64579	-9.89132
-.99999	4.29999	22.85649	24.89379
6.99999	5.99999	-14.59613	-16.59722
5.49999	5.99999	-21.23746	-25.07778
3.00000	5.99999	-33.10194	-35.80578
.00000	5.99999	-40.67440	-35.22531
-1.60000	5.59998	-40.62050	-30.59783
.00000	6.79998	-31.89654	-27.62335
-6.99999	6.49999	-13.07270	-8.15310
5.99999	-1.99999	-37.08844	-58.93548

Output Data Obtained For Model No. 7

Using Program No. 3

(Grid interval = 1/2 depth of burial)

x	y	Δ V	Δ T
.00000	.00000	309.61156	299.06296
.99999	.00000	304.11584	284.69269
1.99999	.00000	275.09521	243.27380
2.49999	.00000	233.69588	194.36721
3.00000	.00000	161.27706	119.05264
4.00000	.00000	47.07030	20.56707
.00000	.99999	162.65670	157.11487
.49999	.99999	161.67428	152.44833
.99999	.99999	158.40580	145.29916
1.49999	.99999	151.74156	134.34646
1.99999	.99999	139.39695	117.32299
2.49999	.99999	118.03607	91.70575
3.50000	.99999	56.37601	30.99136
5.00000	.99999	14.44835	1.20013
5.99999	.99999	7.18157	-1.64831
.00000	1.49999	95.44817	92.19616
.99999	1.49999	92.25687	82.66045
.49999	1.99999	57.19543	52.65786
1.49999	1.99999	52.41398	42.81249
2.49999	1.99999	41.23979	27.58102
4.00000	1.99999	19.11738	6.10293
5.99999	1.99999	5.84446	-1.51925
.49999	3.50000	16.85095	14.98617
3.00000	3.00000	15.66865	7.44408
3.00000	5.00000	5.14195	1.83267
.00000	4.50000	9.05102	8.74255
3.00000	5.49999	4.10287	1.38284
-.99999	.49999	252.42478	252.51132
-.99999	.75000	204.31741	205.61084
-.99999	.99999	158.40580	160.71844
-.99999	1.49999	92.25687	95.56665
-.99999	2.49999	35.21047	38.12500
-.99999	6.49999	3.28365	3.87679
-1.99999	.25000	261.78424	274.90790
-1.99999	.75000	181.69494	194.75298
-1.99999	.99999	139.39695	151.97213
-1.99999	1.49999	79.81003	90.57058
-1.99999	3.00000	20.40226	25.73852
-1.99999	4.50000	7.84900	10.53124
-3.00000	.49999	135.10821	163.32635
-3.00000	.75000	110.68042	135.87542
-3.00000	.99999	87.25006	109.22683
-3.00000	1.49999	53.06693	69.39084

x	y	Δ V	Δ T
-3.00000	1.99999	33.55384	45.73575
-3.00000	3.00000	15.66865	22.82534
-3.50000	.49999	78.03617	105.03216
-4.00000	.49999	43.29160	65.14757
-4.00000	1.99999	19.11738	30.82897
-4.00000	3.00000	10.71232	18.12569
-4.00000	4.50000	5.13698	9.16128
-5.00000	.00000	16.65646	30.45565
-5.00000	1.49999	12.38034	23.16540
-5.00000	4.50000	3.84950	7.81860
-6.99999	1.49999	3.85624	9.53567
1.49999	-.99999	151.74156	134.34646
2.49999	-1.99999	41.23979	27.58102
-3.00000	-.99999	87.25006	109.22683
-.99999	-1.49999	92.25687	95.56665
-1.99999	-3.00000	20.40226	25.73852
-4.00000	-1.99999	19.11738	30.82897

Output Data Obtained For Model No. 7

Using Program No. 3

(Grid interval = depth of burial)

.00000	.00000	325.98177	314.87555
.99999	.00000	320.68011	300.72592
1.99999	.00000	292.77992	260.18829
2.49999	.00000	260.17979	218.82122
3.00000	.00000	169.36595	123.46246
4.00000	.00000	45.56799	18.95370
.00000	.99999	157.39538	152.03286
.49999	.99999	156.81881	147.77554
.99999	.99999	153.29026	140.39209
1.49999	.99999	147.26536	130.74218
1.99999	.99999	135.10266	113.19055
2.49999	.99999	115.04390	88.67901
3.50000	.99999	54.31480	28.86636
5.00000	.99999	14.15714	.96551
5.99999	.99999	7.09160	-1.70953
.00000	1.49999	91.94097	88.80849
.99999	1.49999	88.85226	79.40191
.49999	1.99999	55.40960	50.94458
1.49999	1.99999	50.77679	41.26580
2.49999	1.99999	40.00474	26.42953
4.00000	1.99999	18.67744	5.72424
5.99999	1.99999	5.78193	-1.56008
.49999	3.50000	16.57942	14.72824

x	y	△ V	△ T
3.00000	3.00000	15.39012	7.20126
3.00000	5.00000	5.09988	1.79870
.00000	4.50000	8.95175	8.64672
3.00000	5.49999	4.07419	1.85058
-.99999	.49999	254.35897	254.34546
-.99999	.75000	200.56663	201.95334
-.99999	.99999	153.29026	155.74316
-.99999	1.49999	88.85226	92.24810
-.99999	2.49999	34.33004	37.25750
-.99999	6.49999	3.26471	3.85742
-1.99999	.25000	274.23741	287.08037
-1.99999	.75000	178.91711	192.09680
-1.99999	.99999	135.10266	147.80878
-1.99999	1.49999	76.89896	87.71279
-1.99999	3.00000	20.00749	25.33539
-1.99999	4.50000	7.76695	10.44467
-3.00000	.49999	135.89207	165.90218
-3.00000	.75000	108.63354	134.80795
-3.00000	.99999	84.53579	106.98282
-3.00000	1.49999	51.24255	67.64318
-3.00000	1.99999	32.59580	44.77190
-3.00000	3.00000	15.39012	22.53018
-3.50000	.49999	75.75240	103.47359
-4.00000	.49999	41.85679	63.84271
-4.00000	1.99999	18.67744	30.35784
-4.00000	3.00000	10.55222	17.94595
-4.00000	4.50000	5.09288	9.10943
-5.00000	.00000	16.29425	30.05917
-5.00000	1.49999	12.15524	22.90661
-5.00000	4.50000	3.82151	7.78356
-6.99999	1.49999	3.82551	9.49350
1.49999	-.99999	147.26536	130.06676
2.49999	-1.99999	40.00474	26.42953
-3.00000	-.99999	84.53f79	106.98282
-.99999	-1.49999	88.85226	92.24810
-1.99999	-3.00000	20.00749	25.33539
-4.00000	-1.99999	18.67744	30.35784

Output Data Obtained For Model No. 8

Using Program No. 3

x	y	Δ V	Δ T
.00000	.00000	2.85803	2.76049
.99999	.00000	2.80093	2.60891
1.99999	.00000	2.51370	2.19586
2.49999	.00000	2.13131	1.74261
3.00000	.00000	1.49896	1.08343
4.00000	.00000	.47994	.20449
.00000	.99999	1.95837	1.89145
.49999	.99999	1.94771	1.84066
.99999	.99999	1.91212	1.76276
1.49999	.99999	1.83887	1.64245
1.99999	.99999	1.69944	1.45056
2.49999	.99999	1.44315	1.14404
3.50000	.99999	.64323	.35867
5.00000	.99999	.15725	.01230
5.99999	.99999	.07815	-.01880
.00000	1.49999	1.22250	1.18066
.99999	1.49999	1.18643	1.07415
.49999	1.99999	.72672	.67275
1.49999	1.99999	.66990	.55804
2.49999	1.99999	.52508	.36407
4.00000	1.99999	.22245	.07336
5.99999	1.99999	.06431	-.01739
.49999	3.50000	.20127	.17950
3.00000	3.00000	.18698	.09149
3.00000	5.00000	.05867	.02087
.00000	4.50000	.10547	.10171
3.00000	5.49999	.04651	.01550
-.99999	.49999	2.56605	2.57150
-.99999	.75000	2.27911	2.29037
-.99999	.99999	1.91212	1.93079
-.99999	1.49999	1.18643	1.21747
-.99999	2.49999	.43771	.46942
-.99999	6.49999	.03709	.04369
-1.99999	.25000	2.46037	2.60546
-1.99999	.75000	2.03656	2.17449
-1.99999	.99999	1.69944	1.83218
-1.99999	1.49999	1.03768	1.15530
-1.99999	3.00000	.24747	.30840
-1.99999	4.50000	.09101	.12146
-3.00000	.49999	1.37861	1.67373
-3.00000	.75000	1.23170	1.50561
-3.00000	.99999	1.04368	1.29071
-3.00000	1.49999	.66987	.85928
-3.00000	1.99999	.41824	.56003
-3.00000	3.00000	.18698	.26941

x	y	Δ V	Δ T
-3.50000	.49999	.80493	1.08828
-4.00000	.49999	.45348	.68521
-4.00000	1.99999	.22245	.35608
-4.00000	3.00000	.12399	.20856
-4.00000	4.50000	.05833	.10387
-5.00000	.00000	.17761	.32592
-5.00000	1.49999	.13685	.25607
-5.00000	4.50000	.04313	.08773
-6.99999	1.49999	.04203	.10452
1.49999	-.99999	1.83887	1.64245
2.49999	-1.99999	.52508	.36407
-3.00000	-.99999	1.04368	1.29071
-.99999	-1.49999	1.18643	1.21747
-1.99999	-3.00000	.24747	.30840
-4.00000	-1.99999	.22245	.35608
-8.50000	.00000	.02316	.06790
-6.99999	3.50000	.02875	.07321
-6.49999	.00000	.05192	.11623
-5.99999	3.00000	.04916	.11001
-1.99999	5.99999	.04280	.05932
-.99999	4.00000	.13860	.15667

Output Data Obtained For Model No. 9

Using Program No. 3

.00000	.00000	2.85803	2.76046
.29998	.00000	2.77227	2.54263
.49999	.00000	2.62014	2.31243
.70000	.00000	2.39575	2.02386
.99999	.00000	1.95837	1.52829
1.29998	.00000	1.49480	1.05737
1.69999	.00000	.99456	.59890
2.29998	.00000	.54806	.24059
3.50000	.00000	.20333	.02270
-.49999	.00000	2.62014	2.74887
-.90001	.00000	2.11288	2.38497
-1.99999	.00000	.73299	1.03390
-3.00000	.00000	.29781	.50121
.00000	.99999	2.80093	2.70532
.39999	.99999	2.65035	2.38702
.89999	.99999	2.06481	1.65954
1.59999	.99999	1.06880	.67309
2.29998	.99999	.52697	.23150
-.49999	.99999	2.56605	2.69073
-.99999	.99999	1.91212	2.19967

x	y	Δ V	Δ T
-1.99999	.99999	.70681	.99655
.49999	.49999	2.60781	2.30194
.70000	.49999	2.38399	2.01437
1.29998	.49999	1.48545	1.05111
.00000	1.99999	2.51370	2.42788
.49999	1.99999	2.29954	2.03466
.99999	1.99999	1.69944	1.33172
1.49999	1.99999	1.03768	.68279
2.19999	1.99999	.50006	.23324
-.49999	1.99999	2.29954	2.40737
-.80000	1.99999	1.97341	2.17910
-1.49999	1.99999	1.03768	1.32150
-2.49999	1.99999	.37731	.58386
.00000	2.59999	2.02295	1.95385
.00000	3.00000	1.49896	1.44772
.00000	3.19999	1.22283	1.18097
.00000	3.50000	.86557	.83590
.00000	4.19999	.38443	.37115
.49999	3.00000	1.37861	1.21396
.99999	3.00000	1.04368	.81048
1.79998	3.00000	.50320	.28628
3.00000	3.00000	.18698	.04488
.49999	2.69999	1.74510	1.54266
.70000	4.00000	.42960	.35015
1.49999	4.00000	.29838	.18600
-1.49999	3.39999	.49469	.63860
.00000	5.00000	.17761	.17139
-.80000	2.69999	1.50233	1.66092
-1.99999	2.49999	.52508	.74114
-.75000	3.24999	.96352	1.06579
-5.00000	1.99999	.06935	.15438
-3.50000	1.99999	.17067	.31079
-5.49999	.00000	.06090	.14361
-4.00000	.00000	.14413	.28165
-3.00000	4.50000	.09837	.16790
-3.00000	3.00000	.18698	.31604
-3.00000	.99999	.28555	.48061
-4.00000	3.59999	.08366	.16439
-1.99999	4.79998	.13069	.18954
-1.99999	3.69999	.27238	.38949
-2.49999	.00000	.45587	.70519
-1.49999	.00000	1.22250	1.55993
-1.99999	1.49999	.66990	.94421
-.99999	3.00000	1.04368	1.20541
-.49999	3.00000	1.37861	1.44900
-.49999	2.49999	1.95127	2.04251
-.49999	1.99999	2.29954	2.40737
5.00000	.99999	.07667	-.02270
4.00000	.00000	.14413	-.00348
3.00000	1.99999	.24747	.06088

Output Data Obtained For Model No. 10

Using Program No. 3

x	y	ΔV	ΔT
.00000	.00000	1.78033	1.78033
.99999	.00000	1.74871	1.74871
1.99999	.00000	1.58185	1.58185
2.49999	.00000	1.34372	1.34372
3.00000	.00000	.92724	.92724
4.00000	.00000	.27041	.27041
.00000	.99999	.93521	.93521
.49999	.99999	.92956	.92956
.99999	.99999	.91077	.91076
1.49999	.99999	.87245	.87243
1.99999	.99999	.80148	.80148
2.49999	.99999	.67861	.67861
3.50000	.99999	.32398	.32397
5.00000	.99999	.08285	.08285
5.99999	.99999	.04108	.04108
.00000	1.49999	.54854	.54854
.99999	1.49999	.53021	.53021
.49999	1.99999	.32857	.32857
1.49999	1.99999	.30111	.30111
2.49999	1.99999	.23686	.23684
4.00000	1.99999	.10965	.10965
5.99999	1.99999	.03336	.03335
.49999	3.50000	.09665	.09665
3.00000	3.00000	.08986	.08984
3.00000	5.00000	.02934	.02932
.00000	4.50000	.05188	.05188
3.00000	5.49999	.02334	.02334
-.99999	.49999	1.45152	1.45150
-.99999	.75000	1.17476	1.17474
-.99999	.99999	.91077	.91076
-.99999	1.49999	.53021	.53021
-.99999	2.49999	.20219	.20218
-.99999	6.49999	.01867	.01867
-1.99999	.25000	1.50529	1.50527
-1.99999	.75000	1.04467	1.04467
-1.99999	.99999	.80148	.80148
-1.99999	1.49999	.45867	.45867
-1.99999	3.00000	.11706	.11706
-1.99999	4.50000	.04493	.04491
-3.00000	.49999	.77680	.77679
-3.00000	.75000	.63626	.63626
-3.00000	.99999	.50155	.50155

x	y	Δ V	Δ T
-3.00000	1.49999	.30488	.30486
-3.00000	1.99999	.19267	.19265
-3.00000	3.00000	.08986	.08984
-3.50000	.49999	.44858	.44858
-4.00000	.49999	.24873	.24871
-4.00000	1.99999	.10965	.10965
-4.00000	3.00000	.06138	.06137
-4.00000	4.50000	.02932	.02932
-5.00000	.00000	.09555	.09555
-5.00000	1.49999	.07092	.07092
-5.00000	4.50000	.02191	.02191
-6.99999	1.49999	.02194	.02194
1.49999	-.99999	.87245	.87243
2.49999	-1.99999	.23686	.23684
-3.00000	-.99999	.50155	.50155
-.99999	-1.49999	.53021	.53021
-1.99999	-3.00000	.11706	.11706
-4.00000	-1.99999	.10965	.10965

Output Data Obtained For Model No. 11

Using Program No. 1

x	y	Δ V (=Δ T)
.00000	.00000	1.78033
.29998	.00000	1.66397
.49999	.00000	1.48108
.70000	.00000	1.25870
.99999	.00000	.93521
1.29998	.00000	.67864
1.69999	.00000	.44614
2.29998	.00000	.25128
3.50000	.00000	.09762
-.49999	.00000	1.48108
-.90001	.00000	1.03723
-1.99999	.00000	.33169
-3.00000	.00000	.14062
.00000	.99999	1.74871
.39999	.99999	1.54995
.89999	.99999	1.01161
1.59999	.99999	.47714
2.29998	.99999	.24102
-.49999	.99999	1.45152
-.99999	.99999	.91077

x	y	ΔV (= ΔT)
-1.99999	.99999	.31878
.49999	.49999	1.47436
.70000	.49999	1.25236
1.29998	.49999	.67378
.00000	1.99999	1.58185
.49999	1.99999	1.30268
.99999	1.99999	.80148
1.49999	1.99999	.45867
2.19999	1.99999	.22692
-.49999	1.99999	1.30268
-.80000	1.99999	.99319
-1.49999	1.99999	.45867
-2.49999	1.99999	.17422
.00000	2.59999	1.27392
.00000	3.00000	.92724
.00000	3.19999	.74334
.00000	3.50000	.51022
.00000	4.19999	.21371
.49999	3.00000	.77680
.99999	3.00000	.50155
1.79998	3.00000	.23005
3.00000	3.00000	.08986
.49999	2.69999	.98654
.70000	4.00000	.23069
1.49999	4.00000	.14916
-1.49999	3.39999	.23443
.00000	5.00000	.09555
-.80000	2.69999	.75526
-1.99999	2.49999	.23686
-.75000	3.24999	.50364

Output Data Obtained For Model No. 12

Using Program No. 1

x	y	ΔV (= ΔT)
.00000	.00000	4.64471
1.25000	.00000	4.59176
2.25000	.00000	4.36285
2.74999	.00000	4.11825
3.00000	.00000	3.91464
3.24999	.00000	3.69033
3.50000	.00000	3.38762
3.79999	.00000	2.85256
4.50000	.00000	1.52349
5.49999	.00000	.62594
5.99999	.00000	.43145
6.99999	.00000	.23038
7.99999	.00000	.13784
-.99999	.00000	4.59991
-1.49999	.00000	4.57491
-2.25000	.00000	4.36285
-2.80000	.00000	4.07940
-3.50000	.00000	3.38762
-4.10000	.00000	2.23001
-4.30000	.00000	1.84862
-4.50000	.00000	1.52349
-4.79999	.00000	1.14471
-5.20001	.00000	.80081
-5.49999	.00000	.62594
-6.49999	.00000	.30993
-7.99999	.00000	.13784
.99999	.99999	4.48456
2.19999	.99999	4.26956
3.00000	.99999	3.82432
3.50000	.99999	3.31046
4.50000	.99999	1.47663
5.39999	.99999	.65298
6.09999	.99999	.38773
.00000	1.99999	4.02756
1.59999	1.99999	3.95968
2.79998	1.99999	3.56440
3.39999	1.99999	3.08999
3.79999	1.99999	2.49166
5.29998	1.99999	.61931
5.99999	1.99999	.36684
6.99999	1.99999	.20132
-.99999	.99999	4.48456

x	y	Δ V (= Δ T)
-1.49999	1.99999	Δ 3.97801
-2.20001	1.99999	3.80963
-3.00000	.99999	3.82432
-4.20001	1.99999	1.75120
-4.50000	1.99999	1.29723
-5.20001	1.99999	.67356
-6.20000	1.99999	.32150
.00000	3.00000	2.53308
1.49999	3.00000	2.48732
2.39999	3.00000	2.34225
3.24999	3.00000	2.00471
3.69999	3.00000	1.66995
4.50000	3.24999	.75354
5.79998	3.00000	.32925
-1.80000	3.00000	2.43963
-2.70001	3.00000	2.25282
-4.00000	3.00000	1.35354
-5.00000	3.00000	.57980
-5.99999	3.00000	.29092
-6.99999	3.00000	.16946
1.49999	4.00000	.98417
2.69999	4.00000	.86480
3.50000	4.00000	.71076
4.50000	4.00000	.45687
6.59999	4.00000	.15966
5.00000	4.50000	.27092
.00000	3.79999	1.22152
-1.49999	4.00000	.98417
-1.99999	3.50000	1.50549
-2.49999	4.00000	.89279
-3.00000	3.50000	1.30875
-4.00000	3.50000	.88331
-4.00000	3.79999	.68527
-4.50000	3.50000	.63784
-4.30000	4.00000	.50611
-5.00000	4.00000	.35034
-5.29999	4.29999	.26050
-6.99999	5.00000	.10320
.00000	4.50000	.68545
.99999	4.50000	.67197
3.00000	4.50000	.53976
4.00000	4.79998	.33477
1.99999	4.79998	.50251
-.49999	5.00000	.47762
-3.00000	5.00000	.37867
-4.00000	4.79998	.33477

x	y	ΔV (= ΔT)
-3.00000	4.50000	.53976
-1.99999	4.79998	.50251
-.99999	4.29999	.78541
6.99999	5.99999	.07849
5.49999	5.99999	.11999
3.00000	5.99999	.21143
.00000	5.99999	.26248
-1.60000	5.59998	.31074
.00000	6.79998	.17471
-6.99999	6.49999	.06860
5.99999	-1.99999	.36684
.00000	1.25000	4.47186

VITA

Afif Hani Saad was born on April 14, 1936, in Dermawas, Minia, Egypt. He received his primary and secondary school education in Dermawas and Mallawi, Egypt.

In September, 1953, he enrolled in the University of Alexandria, Faculty of Science, and obtained the degree of B. Sc. Special in Geology in June, 1957. At this time he enrolled in Cairo University as a research student. In August, 1958, he was appointed a demonstrator in Geology, Cairo University. Along with teaching work he was carrying a research in micropaleontology entitled "The Biostratigraphy of Dakhla Oasis, Egypt." In January, 1960, he was granted a scholarship from the U. A. R. government for a 4-year period of study in the U. S. A. to obtain a Ph.D. degree in Geophysics. In September, 1960, he enrolled in the Graduate School in the Department of Geology at Missouri School of Mines and Metallurgy.

He is a member of Sigma Gamma Epsilon, the earth sciences honorary society; Kappa Mu Epsilon, Mathematics honorary society; an associate member of Sigma Xi, the honorary scientific research society; and a student member of the Society of Exploration Geophysicists and the Association of Computing Machinery. He is also a member of the Egyptian Geological Society.