II. HIGH SENSITIVITY MAGNETOMETERS IN ARCHAEOLOGICAL EXPLORATION

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Surveys of archaeological sites with compact, portable, magnetometers have been increasing in popularity as archaeologists come to realize the power of this technique in detecting and delineating subsurface features. From their original use in locating Roman kilns in Britain, magnetometers are now used in virtually all phases of archaeological exploration, from mapping city plans to studying differences in soil profiles between archaeological and non-archaeological sites. In this brief review we will present some of the applications of the newer high-sensitivity magnetometers.

The basic principle of the magnetic method of geophysical exploration is that inhomogeneities in magnetic properties of the ground cause departures from the normal configuration of the permanent magnetic field of the Earth. If these anomalies in the magnetic field can be detected in measurements made over the surface of the ground, using a magnetometer, their characteristics may be used to deduce the nature of this inhomogeneity. It is important to realize that with this technique no energy is transmitted or injected into the ground by the surveyor. The method is a passive one in which the magnetometer simply measures fields which are present all the time and which are properties of the subsurface features.

Two basic magnetic properties are involved in the study of magnetic anomalies. The first is ferromagnetic susceptibility, that property of certain metals, alloys, and minerals to assume a magnetization in the presence of an inducing magnetic field. This induced magnetization in turn results in a secondary magnetic field and it is this field that produces the anomaly that is measured at some point exterior to the region of high susceptibility. Other types of magnetic susceptibility exist (e.g. paramagnetic and diamagnetic) but the susceptibility is so low that the resulting geophysical anomalies are not presently measurable. With the rocks or dressed stone used in construction there is usually a sufficient contrast in ferromagnetic susceptibility with the enclosing soil to produce a measurable anomaly.

The second property is that of natural remanent magnetization. Certain minerals may possess a large natural magnetization, acquired through some process early in their history, which produces a field or anomaly that is independent of the inducing field. For many years magnetic field exploration was carried out, and the results interpreted, on the assumption that the majority of anomalies were of the induced type. Recently, however, geophysicists have realized that remanent magnetization predominates in many cases and in particular Aitken (1961) has shown that important archaeological anomalies are also of this type. Features of archaeological interest that possess large remanent magnetization are fired bricks and tile, kilns, and hearths.

The success of conventional magnetic surveying in the search for mineral deposits is well documented and presentations of these techniques are to be found in standard texts such as Dobrin (1960), Grant and West (1965), and Jakosky (1950).

These surveys have used either balance magnetometers (ground surveying only) with a maximum sensitivity of about 5 gammas (γ) (1 gamma = 10^{-5} oersted; the earth's normal field is approximately 0.5 oersted), or fluxgate magnetometers with a maximum sensitivity of about 5 γ. Both these devices measure the magnetic field in component directions. The introduction of the proton magnetometer (Packard and Varian, 1954; Waters and Francis, 1958) signalled the era of high sensitivity total field magnetometers. The proton magnetometer has a maximum practical sensitivity of 0.1 γ and its simplicity, light weight, and minimal associated read-out electronics have made it a particularly suitable device for rapid ground surveying. Aitken (1960) has summarized the principles of operation and the applications of proton magnetometers in archaeology. Alkali vapor magnetometers (Bloom, 1962) while retaining much of the operational efficiency of the proton magnetometer, have sensitivities as high as .003 γ and have opened up a whole new technology in magnetic exploration. Review articles on the applications of these new magnetometers have been presented by Breiner (1965), Langan (1966), Hood (1966), Rover (1967), and Giret and Malnar (1965). We will discuss briefly below the operating principles and modes of field operation and then discuss in detail the applications of interest to this review.

The alkali vapor magnetometers work on the principle of optical pumping. The commonest varieties use cesium or rubidium although units have been designed using potassium, sodium, or metastable helium. We will consider the rubidium magnetometer for this simplified discussion. Light emitted from incandescent Rb^{85} is filtered to pass the spectral line at 7947 A. This light is passed through a cell containing Rb^{85} vapor and the transparency of this cell is a function of the amount of energy absorbed from the light to pump electrons in the Rb^{85} atoms up to higher energy levels. Eventually (a time measured in micro-seconds) the upper energy levels are filled and cell becomes transparent. This pumped, excited state can be disrupted if a weak, high-frequency magnetic field is applied to the cell. Especially if a frequency equal to the precession frequency of the electrons undergoing transition is applied, the disruption of the pumping effect is particularly effective and the cell becomes opaque to the light source. The effectiveness of the observation, however, is critically dependent on the ambient magnetic field and therefore can be used as a sensitive measure of the magnetic field in the immediate vicinity.

A simple magnetometer would then consist of the above cell with a photocell monitor and a variable frequency oscillator. Repeated pumping and monitoring of the frequency which decreases the transparency of the cell would yield sampled measurements of the magnetic field. In practice a self-oscillator principle is employed in which the photocell output is fed back, suitably phase shifted to the coil supplying the radio frequency. This system becomes self-oscillating at the resonance frequency and monitoring of this signal provides a continuous measure of the magnetic field strength. The theoretical sensitivity of this device (Bloom 1962) is estimated to be on the order of .003γ and in practice sensitivities of .01γ are relatively easy to obtain. Actual field measurement may be made with either a counter (count of number of cycles in a fixed time to determine the frequency) or with a discrimator device that in effect measures the period of the resonance oscillations. This latter approach provides continuous output while the former will only provide a field value at the end of each counting period. The electronics associated with such a magnetometer are simple. Power is supplied to the sensor unit via cable and the signal frequency is returned on the same cable for measurement. Portable instruments have been described by Breiner (1965) and by Ralph, Morrison and O'Brien (1968), and Morrison et al (1970, 1970a).

The disadvantages of the alkali vapor magnetometers are that they are sensitive to the orientation of the vapor cell with respect to the direction of the earth's magnetic field and that they cannot function in regions of high field gradient. The self-resonating oscillation discussed above occurs if the angle between the magnetic field and the light beam through the gas cell is approximately 45^{o} (Bell and Bloom 1957). The effective working angle for the cesium cell is about 30^{o} from the optimum, 45^{o}, and for rubidium it is less. For rubidium this orientation sensitivity can be as high as 0.1γ per degree for a single cell sensor. This difficulty is easily overcome in any application where the sensors can be rigidly mounted or transported with a mounting that maintains constant orientation. A further inherent difficulty is that the magnetic field must be uniform across the vapor cell for the output frequency to be a linear function of field strength. Thus, measured values taken in regions of high field gradient (close to highly magnetized bodies for example) will not be meaningful.

Obviously the first advantage of a higher sensitivity magnetometer is that it can detect smaller anomalies. Unfortunately the increased sensitivity brings with it the problem of low-frequency natural variations in the earth's magnetic field. These fields, called micropulsations, cover a wide period range from diurnal to 0.1 seconds and arise from a multitude of sources in the ionosphere and above. In amplitude they range from hundreds of gammas during magnetic storms to several gammas for normal 100-second period oscillations and down to milligammas for activity around one second period. The larger variations have always been a problem in traditional surveying and it has usually been the practice to have a continuously recording base station to monitor the field and thus prevent the interpretation of a time variation in the data as a spatial anomaly. In periods of high magnetic activity the data are not used. Elaborate techniques of reoccupying a base station at regular time intervals are also used to correct for time variations, but at higher sensitivities, where the micropulsations are more or less continuous, the problem is not so easily solved.

The difficulty may be overcome in two ways, each using two magnetometers. In the first, if the survey area is not too large, use of a base station connected to the roving field instrument so that the difference in field is recorded, provides a satisfactory mapping free from time variations. There is in this method an implicit assumption that the time varying fields are uniform over the area of interest. Micropulsation studies indicate that these fields are uniform at least over distances of 50 or 100 km.

The second method is to use the two magnetometers, closely spaced on a rigid mounting, to measure the gradient of the magnetic field. For small surveys such as are commonly conducted in archaeology both these methods have been used. Aitken (1960), Aitken and Tite (1969), and Mudie (1962) describe the use of proton gradient magnetometers and Scollar (1963) describes a proton difference magnetometer. The highest sensitivity surveys have been conducted using two alkali vapor sensors and these surveys are reported by Breiner (1965), Ralph et al (1968) and Morrison et al (1970, 1970a).

It should be noted that there is no new or better information in the magnetic gradient data compared to the total field data. It is a property of the potential fields being studied that if the field is known over a plane, it can be continued, or calculated, at any higher plane, and this process would also allow us to calculate the vertical derivative from the total field data. However, if the data over the plane are subject to error (time variations, errors in position and of course a basic sampling problem) then the calculated derivative is also in error. Since this derivative has certain advantages for interpretation in that the broad unwanted regional anomalies are suppressed and the resolution of local anomalies is increased (Hood, 1965; Slack et al, 1967), it seems evident that direct measurement of the vertical derivative would be highly desirable. There is a further practical advantage and that concerns the ease of data acquisition and processing. Since the time variations are cancelled in such an array no corrections have to be made in the data, profiles do not have to be 'tied' to compensate for time variations, and the frequency output of the device is ideally suited to digital recording. In addition, the gradiometer has an essentially zero base reading so there is no need to remove regional trends -- a common problem in total field surveys. These latter practical advantages are also present with the difference magnetometer array. A complete study of the field procedures, instrument requirements and sensitivities obtainable with the difference magnetometer array is presented by Morrison et al (1970a).

The field survey usually consists in laying out a rectangular grid on the surface of the ground and the magnetometer readings are taken at the intersection of grid lines. The data are normally recorded in a field notebook or on gridded paper, and later plotted to scale and contoured with lines of equal magnetic intensity. Highly sophisticated methods of automatic digital recording of the field data have been described by Scollar and Kruckeberg (1966). Acquiring the data in digital form has the advantage that all the contouring can be done by the computer and the resulting magnetic maps are likely to be more accurate and certainly easier and faster to produce. In addition, data interpreting techniques such as filtering of the data to reveal certain sought-after features are easily carried out (Scollar 1968).

It is usually evident from the contoured field data where the striking anomalies are located and also whether the data possess any patterns that might be related to street plans, building, drainage tiles, etc. Often this much information is all that the archaeologist requires. The magnetic map pinpoints certain areas of interest where excavation is likely to yield fruitful results or the map indicates in which directions existing excavations should be extended.

If a more detailed interpretation of the data is required, recourse is had to the comparison of the field data with theoretical anomalies calculated for hypothetical subsurface bodies. By a trial and error fitting procedure a model is finally selected which best corresponds to the observed data. The model calculations are usually carried out on a computer and the techniques used in these calculations are described by Heirtzler et al (1962) for two-dimensional features and by Bhattacharyya (1964) for three-dimensional rectangular bodies.

The use of the high-sensitivity alkali-vapor magnetometer is not always warranted. For many cases the proton magnetometer, used singly with some simple corrections for diurnal variations, is adequate for archaeological surveys. While the greater sensitivity of the alkali vapor magnetometer would seem to imply a greater ability to detect subtle changes in susceptibility or to reveal deeply buried features there is a practical limitation that is caused by near-surface magnetic effects. Le Borgne (1955, 1960, 1960a), Aitken (1961), Cook and Carts (1962), and Scollar (1966) have all reported on the anomalously high values of magnetization occurring in soils. This effect is apparently caused by organic action on iron minerals and the result is that the soil assumes a remanent magnetization larger than the magnetization of the parent rock. If this soil layer is broken up, plowed or otherwise rendered non-uniform, anomalies of the same order as, or greater than the anomaly anticipated from the deeply buried feature can result. The desired anomaly is thus obscured in noise and an increase in sensitivity will be of no use.

Scollar (1966) has noticed the interesting effect that in undisturbed soil the various soil horizons may be distinguished on the basis of their magnetization and that archaeological horizons might be detected in vertical section magnetic surveys.

In favorable circumstances, however, the high-sensitivity instruments can be used with spectacular success. The first application was in the search for Sybaris in Southern Italy (Ralph 1964, Breiner 1965, Rainey and Ralph 1966 and Ralph et al 1968). Initial surveys with a proton magnetometer detected a massive brick Roman wall that excavation revealed was built on an older, stone, Greek wall. It was realized that the proton magnetometer would be unable to detect features at the depth of the Greek wall (4 to 5 meters) so that greater sensitivity would be required. Using a difference magnetometer with a sensitivity of approximately 0.05γ it was possible to map magnetic anomalies with a 1γ contour interval. In several locations this procedure located buried roof tiles at depths of 4 meters when the total anomaly was only 3 to 4γ (Fig. 1). Further, the extension of the Greek wall was mapped and quantitative interpretations were made on the depth and the susceptibility of the wall material (Figs. 2 and 3). The soil conditions on the Plain of Sybaris were perfect for a magnetometer survey, there being virtually no surface magnetic noise over much of the area. A similar situation was found at the site of ancient Elis, Greece (MASCA Newsletter 1968). The difference magnetometer here yielded a large portion of the city plan and traced walls at depths up to 4 to 5 meters.

On the other hand, the high sensitivity was found to be unnecessary in a survey conducted on the LaVenta pyramid in Mexico. Originally the difference magnetometer was planned in order to detect the small anomalies that would be associated with basalt structures at the base and center of the pyramid. An unexpectedly high soil magnetization reduced the effective sensitivity to about one gamma but fortunately a large 20 to 30γ anomaly was detected indicating a relatively large structure close to the surface (Fig. 4) (Morrison et al 1970).

In summary, the high sensitivity magnetometers have become practical aids to the archaeologist in finding and delineating subtle subsurface features. They are unfortunately expensive and consequently some care should be taken in advance to determine the magnetic properties of the site to be surveyed. Often soil samples are available from previous excavations and these can be tested in the laboratory with a susceptibility meter. If samples representative of the near surface soils are not available, instruments are manufactured which measure the magnetic susceptibility in situ.

The cost of a high-sensitivity magnetometer survey can vary so much that it would be unwise to quote dollar figures in a review paper of this nature. In many cases established archaeological research facilities may be interested in conducting surveys on a cost sharing basis. The Applied Science Center for Archaeology of the University Museum, University of Pennsylvania under the direction of Miss Elizabeth Ralph, has conducted a wide variety of magnetometer surveys and this group has a wealth of experience upon which to base survey plans for a new site. The Laboratory of the Rheinisches Landesmuseum, Bonn, under the direction of Dr. Irwin Scollar, has also conducted a large number of surveys and this group has indicated that arrangements can be made for processing and interpreting field data. The author has participated in archaeological surveys in Italy, Greece and Mexico and in certain cases could advise on the best survey method. Inquiries should be addressed in care of the author, Engineering Geoscience, University of California, Berkeley.

Assuming that a high-sensitivity survey is contemplated, soil samples should be tested for their magnetic susceptibility. Portable magnetic susceptibility bridges that will accept soil, rock chips, powder, and drill cores are available from Geophysical Instrument and Supply Co., 900 Broadway, Denver, Colorado 80203 and from Bison Instruments Inc., 3401 48th Ave. N. Minneapolis, Minnesota 55429. An in situ coil system is available from Bison that allows one to estimate soil susceptibility by simply placing a coil on the ground.

The alkali vapor sensors themselves are manufactured solely by Varian Associates, Palo Alto, California, and are available on a lease or purchase basis. Inquiries should be addressed to the Geophysical Products Group, Analytical Instruments Division. Those interested in carrying out a difference magnetometer survey should give some attention to the field system utilizing a simple digital counter and portable generator reported by Morrison _et al_ 1970a. This system requires that the sensors alone be leased, the rest of the equipment being readily available in an electroncis laboratory.

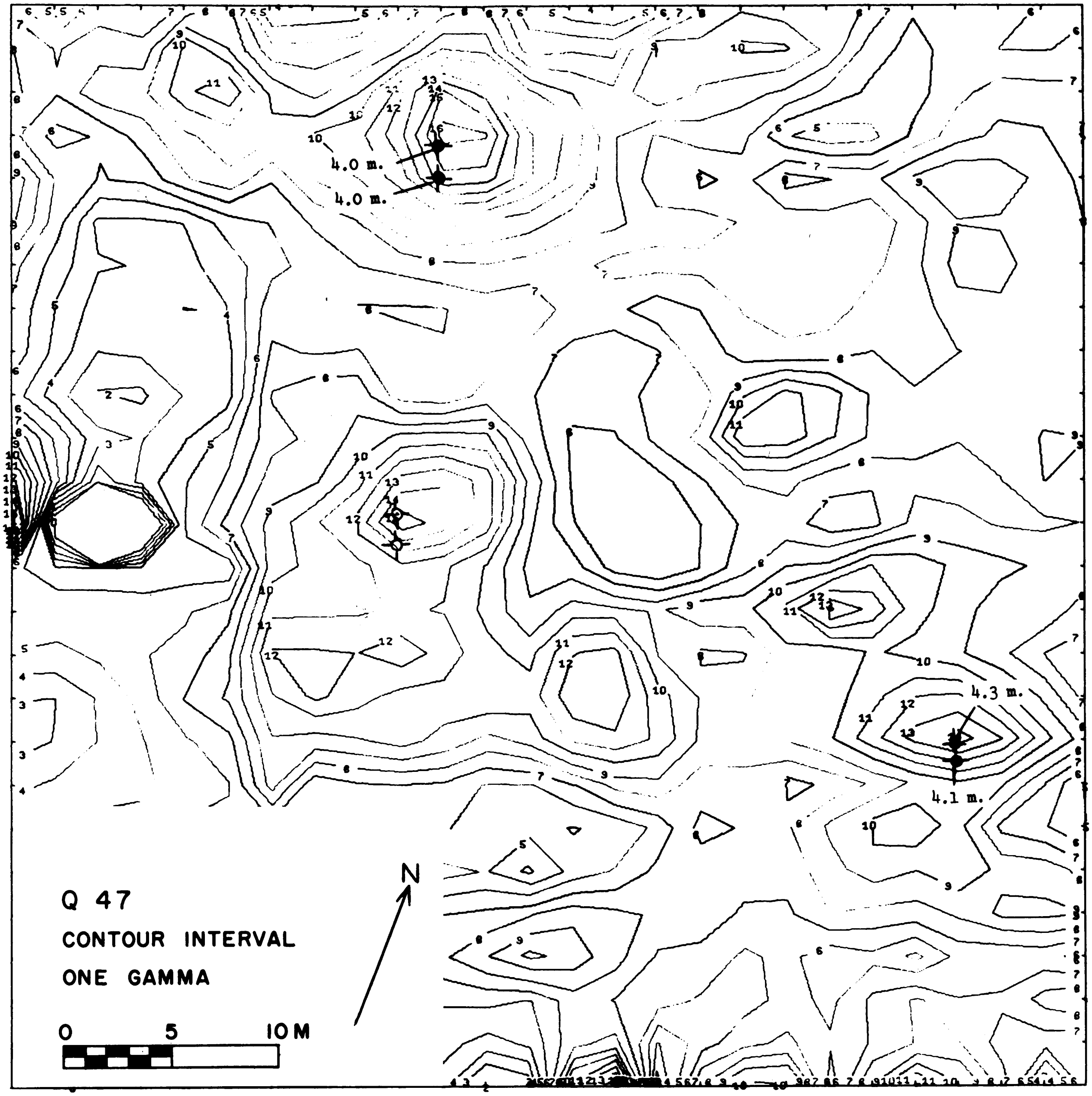

Fig. 1. Computer drawn contours for difference magnetometer survey, Sybaris. Data taken on two meter grid interval. Solid black circles indicate location of drill hole and accompanying number gives the depth to the causative body (in this case fired roof tile). From Ralph <u>et al</u> 1968.

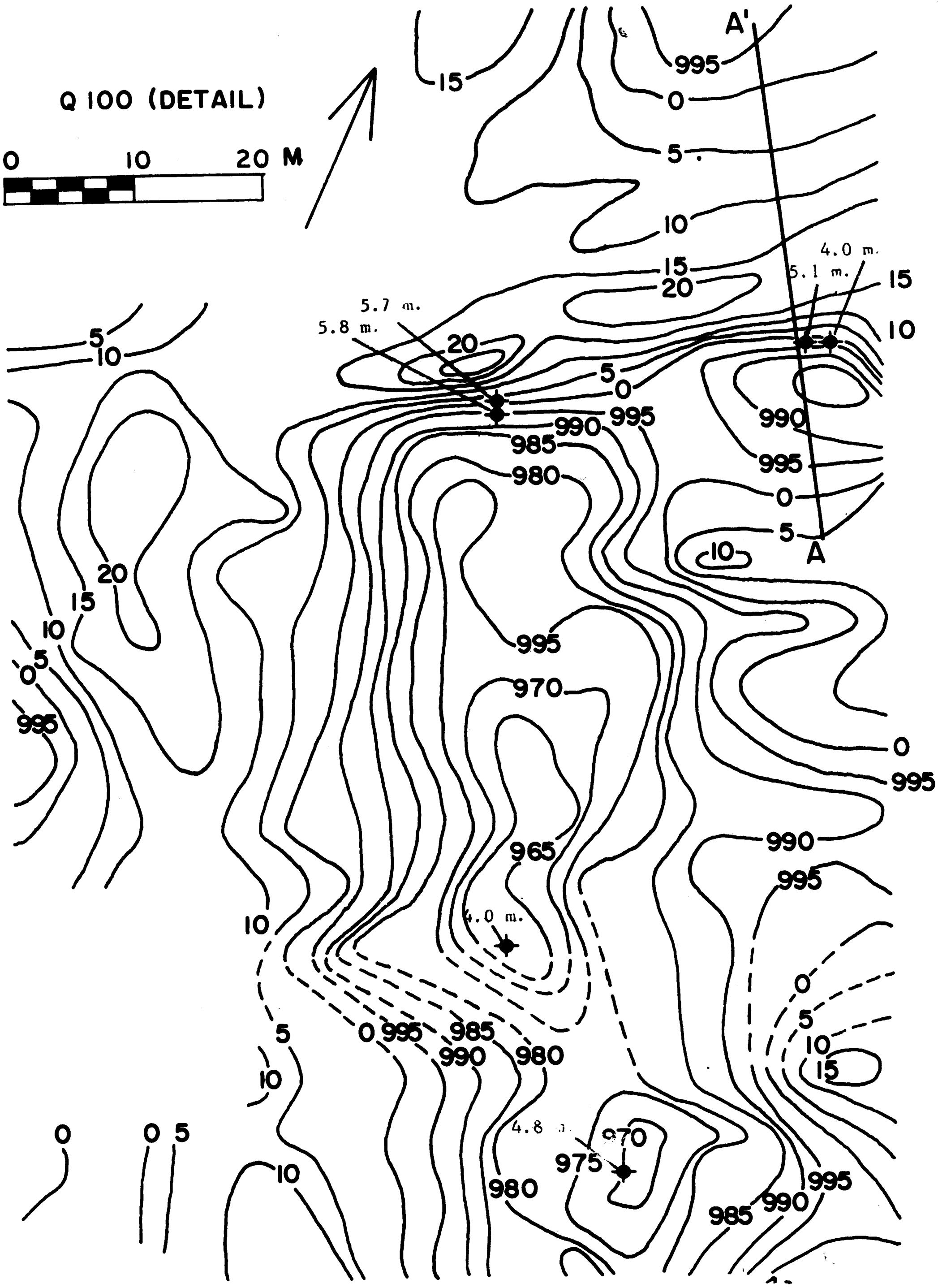

Fig. 2. Hand contoured field data. (Readings are the last three digits of 79,000 and 80,000, i.e. 5 is actually 80,005 arbitrary instrument readings.) The contour interval is approximately 2.5γ and the contour map is inverted - numbers less than 80,000 are positive and those greater are negative. Solid black circles indicate drill locations and the numbers indicate the depth at which stone (wall) was encountered. (From Ralph et al 1968).

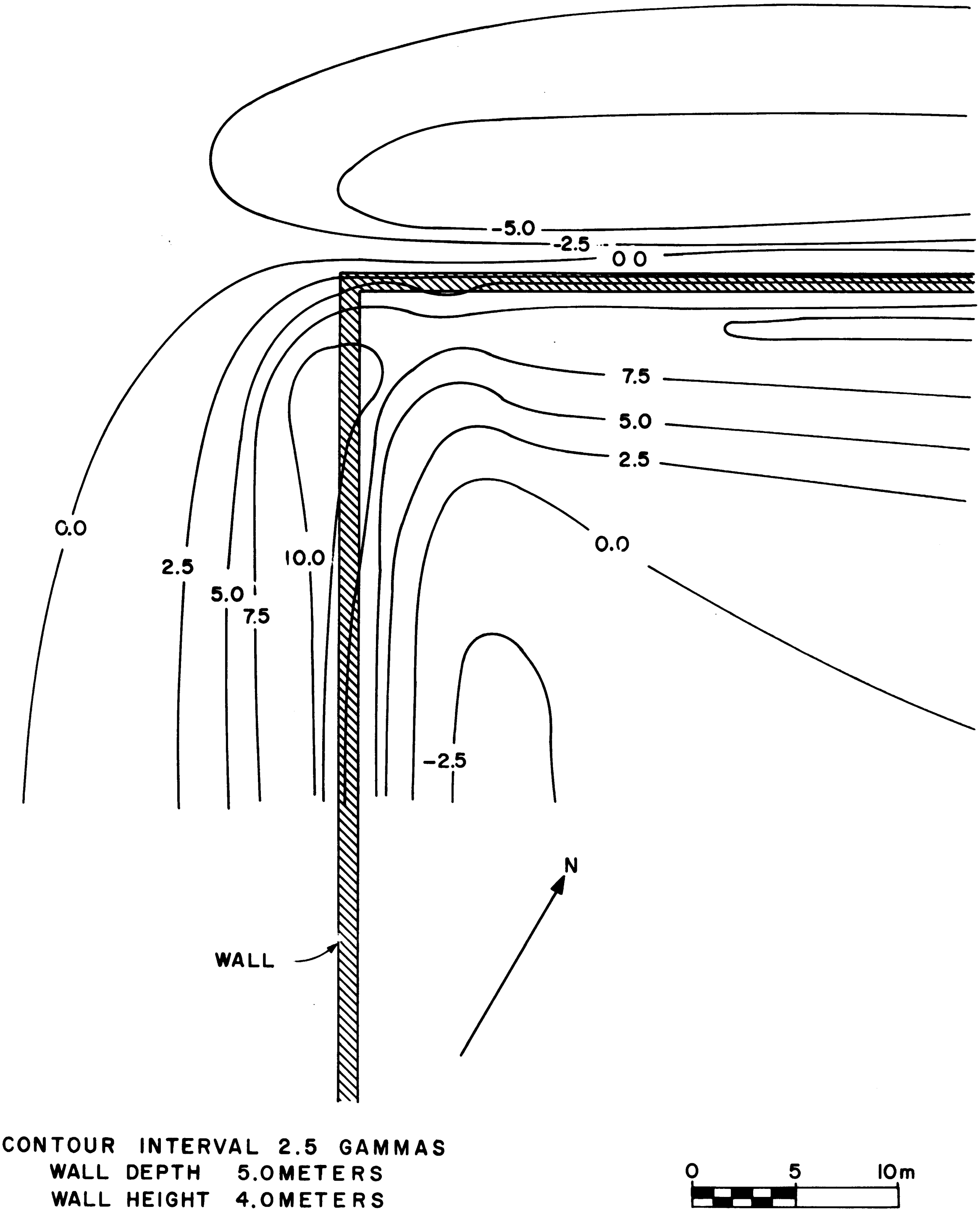

Fig. 3. Computer calculated wall model adjusted to give a good fit to the data of figure 2. (From Ralph et al 1968).

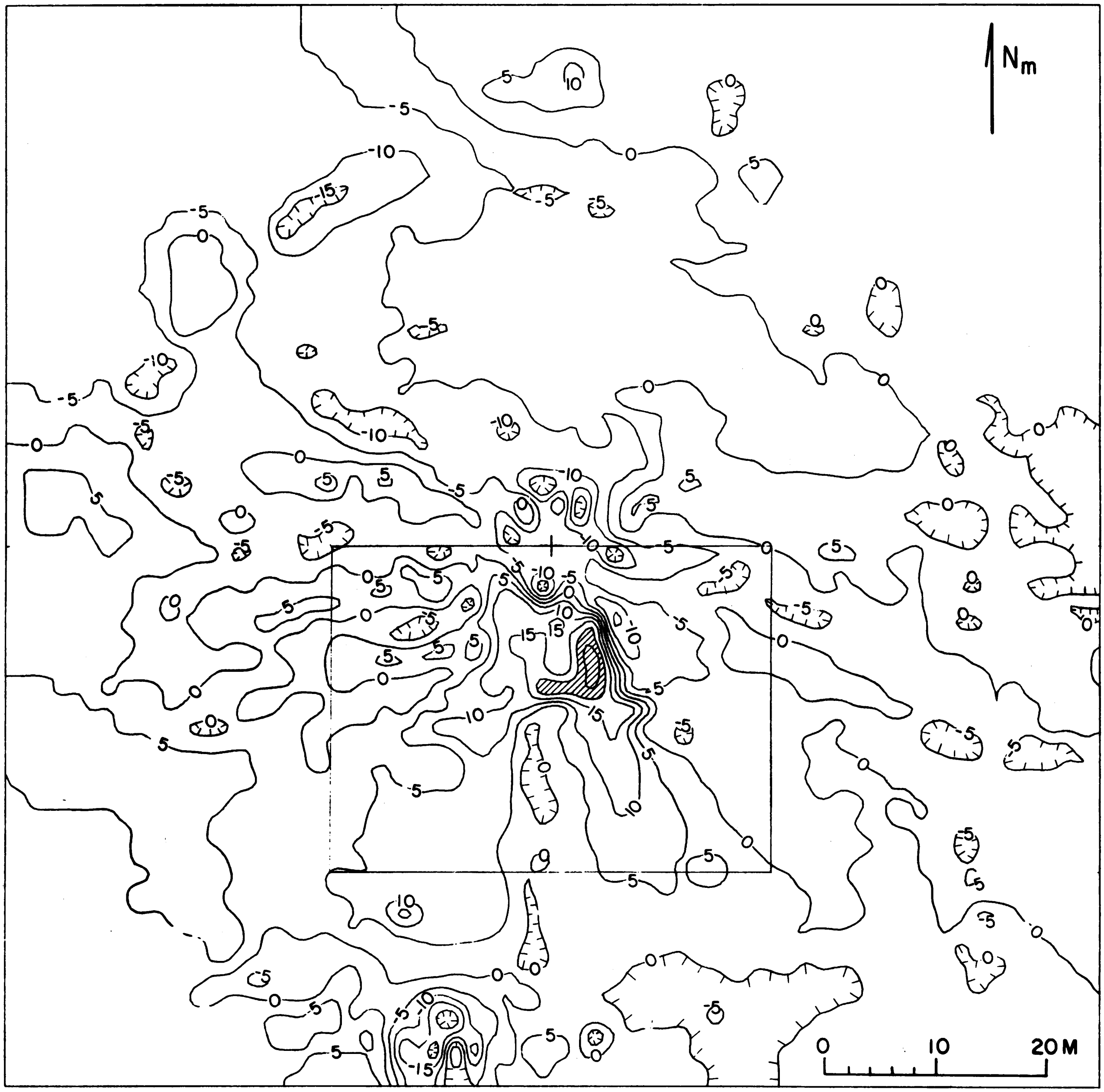

Fig. 4. Computer drawn contours for difference magnetometer survey, La Venta. Data taken at 2 meter intervals along radial lines. Contour interval; 5 gammas. The base of the pyramid is roughly circular and reaches to the margins of the figure. The main anomaly detected is shown in the inner rectangular area. (From Morrison _et al_ 1970).

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