MAGNETOMETERS FOR FIELD SURVEYING

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ARCHAEOLOGICAL SURVEYING UTILIZING A HIGH-SENSITIVITY DIFFERENCE MAGNETOMETER

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SUMMARY

Two pairs of alkali vapor magnetometers, one cesium, the other rubidium, have been employed in a difference mode together with a digital readout unit, for a detailed magnetic survey of an archaeological site in southern Italy. Fine grid intervals together with a system sensitivity approaching 0.05 γ have enabled quantitative interpretation of small anomalies subsequently verified by drilling.

High speed of operation, cancellation of time-varying fields, and direct digital readout allow generation of magnetic contour maps in the field. These features are well suited to the peculiar problems of archaeological magnetometry, and indeed to other geophysical applications.

INTRODUCTION

A portable high-sensitivity alkali vapor magnetometer has been developed for archaeological exploration. Special features are the two-sensor difference-mode of operation and the digital readout. This instrument was designed specifically for archaeological prospecting by Varian Associates at the request of the University Museum, University of Pennsylvania. It was developed after preliminary tests were conducted in 1964 (RALPH, 1964; BREINER, 1965) with the more elaborate and less portable Varian Associates rubidium magnetometer model V-4938. These tests demonstrated that the greater sensitivity obtainable with alkali vapor magnetometers would be practical and effective for highly detailed magnetometer surveys such as those required for archaeological exploration.

One system with two cesium sensors was tested in the fall of 1965 (LANGAN, 1966; RAINEY AND RALPH, 1966) and in the summer of 1966, two systems, one employing two cesium sensors and one utilizing two rubidium sensors, were used. It is the 1966 field program which is reported here. These surveys were made on the Plain of Sybaris in southern Italy where the University Museum has been

[3] Presently at University of California, Berkeley, Calif. (U.S.A.).

engaged in the search for the ancient Greek city of Sybaris since 1961 (RAINEY and LERICI, 1967).

Sybaris was a city of great affluence which flourished in the 7th and 6th centuries B.C. It was founded about 720 B.C. by Achaean colonists between two rivers which flow into the Ionian Sea. Since the destruction of Sybaris in 510 B.C., up to 6 m of flood plain alluvium has been deposited uniformly over the ancient Greek city. The depth of burial and the vastness of the present plain (approximately 30×20 km) combine to offer a challenge for magnetic prospecting. The water table is only 1–2 m below the surface which reduces the effectiveness of resistivity surveying and also makes large scale excavation impractical. From information obtained by drilling and a few test excavations (BROWN, 1963; RAINEY, 1962) we know that on the plain, the archaic 7th to 6th century B.C. level of occupation is at depths of 4–6 m. This is overlain by remnants of the 5th to 4th century B.C. city called Thurii, and on top of this are scattered Roman ruins, some starting at 1–3 m below the surface and extending downward. These archaeological deposits have been found in a limited region of the plain as shown in Fig.1. The sediments are so uniform that, with differential alkali vapor magnetometers, anomalies of 3–5 γ can easily be distinguished and related to sources such as roof-tiles, bricks and other fired ceramics at depths of 4–6 m.

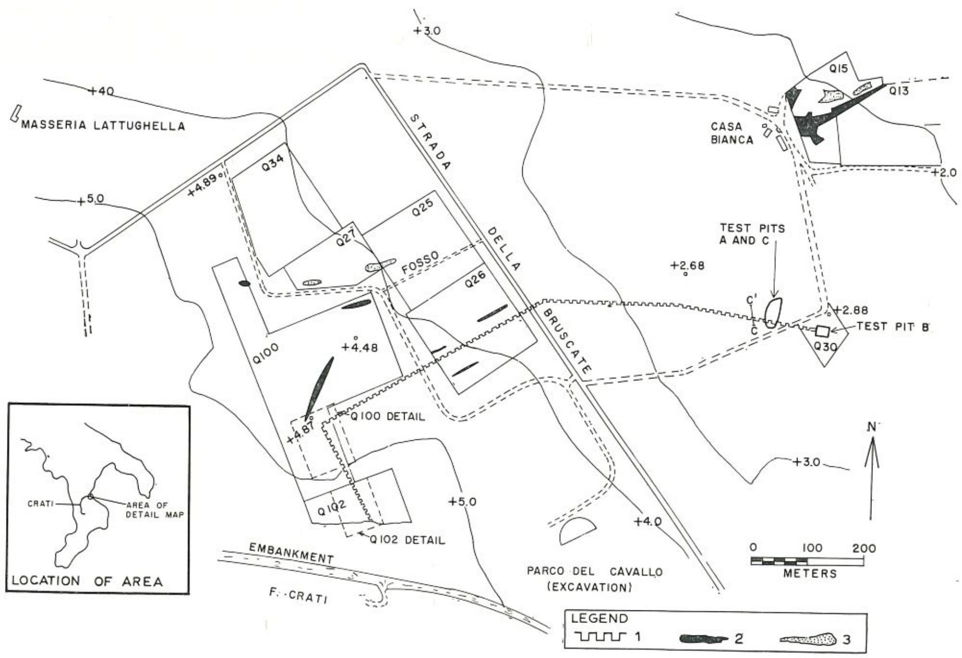

Fig.1. Map of the region of intensive search on the Plain of Sybaris. The magnetometer grids in this area in 1966 are shown and are labelled Q25, Q26, etc. *1* = Wall located from magnetometer surveys, drilling and excavation; *2* = anti magnetic lineation regions; *3* = magnetic lineation regions. Elevations and contours as indicated.

THE DIFFERENCE MAGNETOMETER

The principles of operation of an alkali vapor magnetometer have been described by BLOOM (1960, 1962) and its trial in archaeological exploration has recently been reported by BREINER (1965). The unit described in this article is essentially a development of the magnetometer described by Breiner.

Basically the alkali vapor magnetometer may be considered as an oscillator, the frequency of which is proportional to the total magnetic field. For rubidium vapor the constant of proportionality is 4.667 c/sec γ and for cesium it is 3.5 c/sec γ. In each sensor the vapor is energized by a 100-mc oscillator. This is then modulated by the Larmor precession frequency. In the portable readout this modulated frequency is then mixed with a crystal controlled reference oscillator so designed that the cycles counted (with preset time) numerically equal the field in γ. This is achieved by counting for a specific number of cycles of the reference oscillator. The total field is then displayed digitally at the end of each counting cycle. The repetition interval may be selected on the basis of desired speed of operation, from a minimum of 1.5 sec to infinite (or manual). With one sensor the maximum sensitivity is 0.1 γ.

When operated as a difference magnetometer, the second sensor replaces the crystal oscillator to regulate the counting interval. Now instead of counting for a specific number of cycles of the crystal reference, the counting is carried out for the same number of cycles but using the second sensor output as reference. The readings are no longer in γ, but are adjusted to an arbitrary base reading of 80,000. That is, if both sensors are in the same total magnetic field, the reading which appears in the instrument is 80,000.0. When used for surveying, one sensor is kept in a fixed position and the other is moved throughout the area to be explored. The reading of the movable sensor may be converted to change in γ by the formula:

$$\Delta H = \frac{H_F}{80{,}000}\,[N - 80{,}000]$$

where ΔH is the difference in γ between the fixed and movable sensors; H_F is the total field intensity (in γ) of the fixed sensor only; N is the instrument reading.

Since the total field intensity in southern Italy is approximately 45,000 γ, it can be seen that in the difference mode of operation, the sensitivity of the instrument is roughly double (0.56 γ/unit) that with one sensor only.

The maximum speed of survey is limited only by the repetition rate. In practice, the readings can be viewed continuously by the operator who can see when significant anomalies are encountered and slow down to record changes in readings. The advantages of operating in difference mode are obvious, especially, at the high sensitivities employed. If readings are taken to a precision of ca. 0.1 γ, it is essential to cancel out diurnal and other extraneous magnetic variations. Also, manual subtraction or cancellation would be much too time-consuming. Admit-

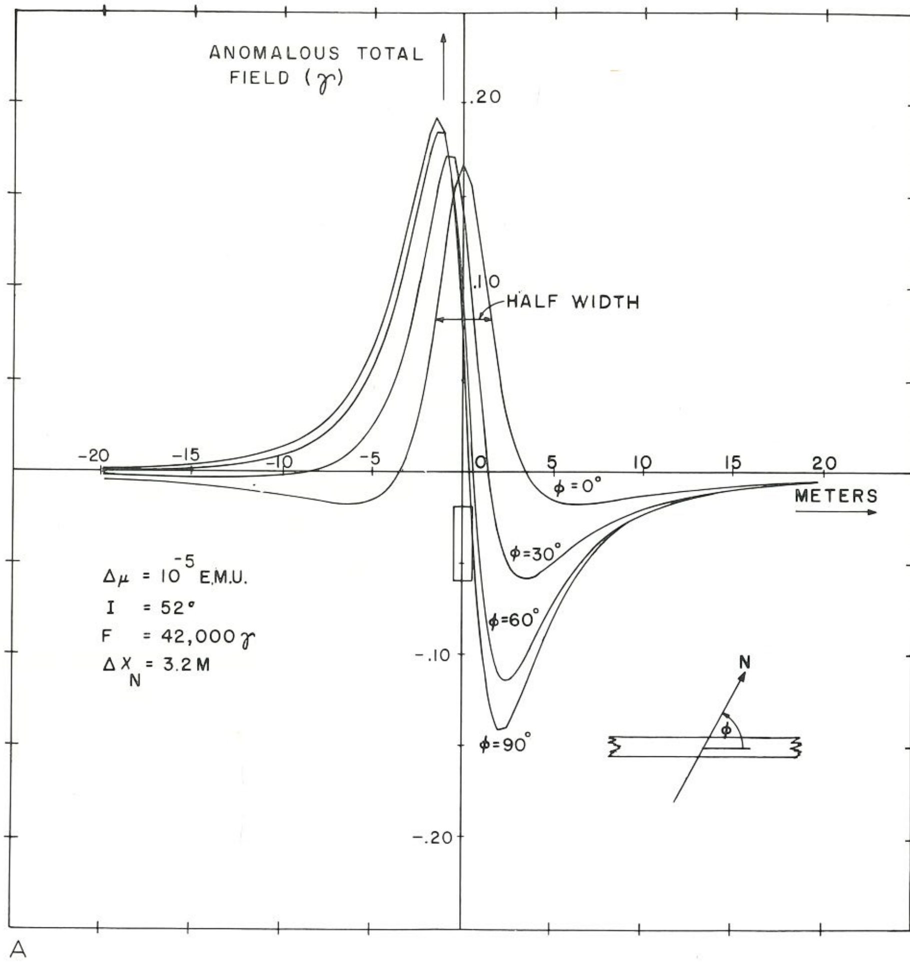

Fig.2. Calculated anomalous total magnetic field over two-dimensional hypothetical archaeological structure. The curves are plotted as functions of magnetic strike angles.

A. The wall is at depth of 2 m. B. The wall is at depth of 5 m.

$\Delta\mu$ = Susceptibility contrast; I = magnetic field inclination; F = total field intensity; Δx_N = half-width anomaly.

tedly, for reconnaissance surveys anomalies can be detected using sensitivities of ca. 1 γ, but again the detailed survey needed for quantitative interpretation is best obtained using the difference mode.

The cesium system proved to be a more successful field instrument due primarily to a greater independence of orientation of the sensor elements. It was necessary to keep the movable rubidium sensor very carefully aligned, and this slowed the surveys down by, at least, 20%.

No measurable instabilities were noted in the entire field season. Grids could be reoccupied or continued days later by the simple expedient of placing the roving

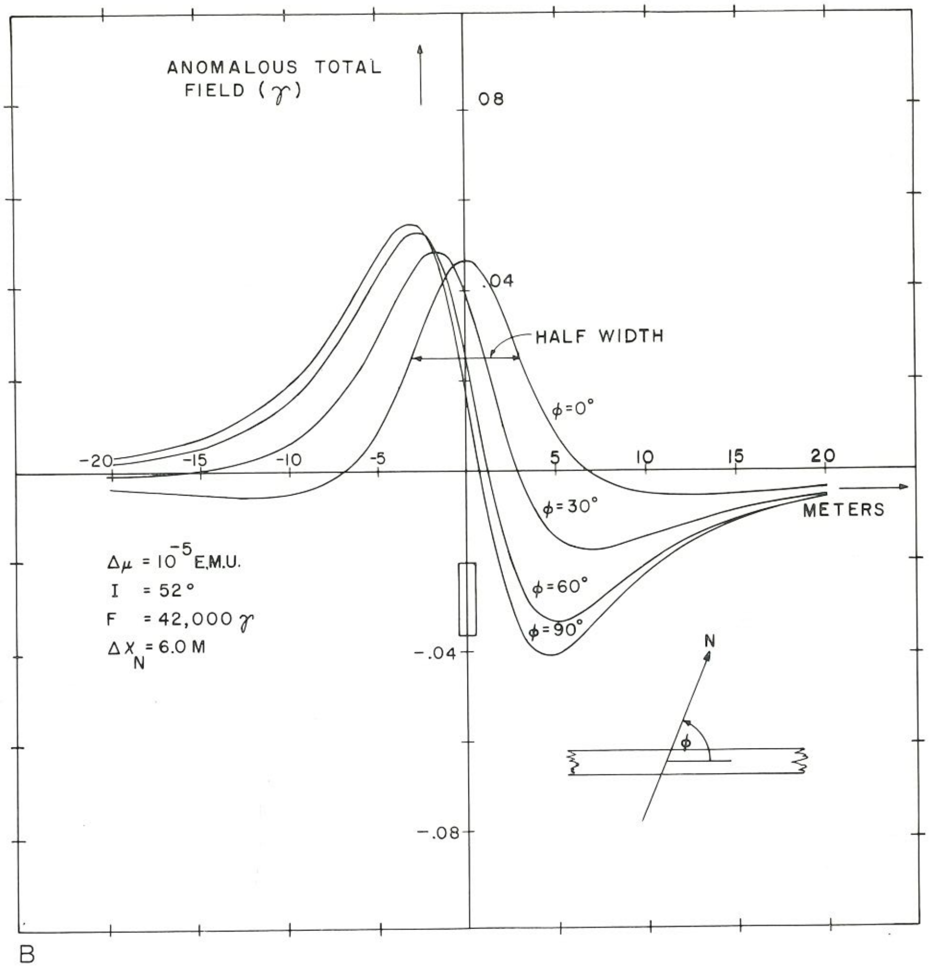

Fig.2B (Legend see p.113).

sensor at a previously occupied site and bringing the reading to the previous value by adjusting the position of a piece of iron placed near the fixed sensor. In this fashion continuous mapping can be carried out over as large an area as desired. The maximum grid that could be covered with a single set-up of the fixed sensor was approximately 80 × 100 m. This was limited only by the length of cable (100 m) connecting the sensors. A simple r.f. telemetering system for the mobile sensor would increase the versatility and speed of surveys immensely. The two systems used in this project were insensitive to temperature variations. Daily ambient temperatures of over 90 °F had no effect on stability, battery life, or repeatability of measurements.

EXTENT AND METHODS OF FIELD SURVEYS

During the months of May, June, and July, 1966, approximately 85 grids were surveyed. Several of these grids are shown in Fig.1 labelled Q26, Q30, etc. It was desired to establish the boundaries of the area shown in Fig.1 which possessed a great many anomalies and proven archaeological features. Excavations in this area (Parco del Cavallo, and Q30) had revealed Roman and 4th Century B.C. Greek remains, especially potsherds, but no structures from the time of Sybaris were found. Nevertheless, it was desired to know over how large an area these anomalies extended. The second goal was to establish the location of the parent city itself, either within or outside of this area. Locating the site for the main city is a formidable task when we consider that a city of roughly 3–5 km^2 buried under at least 3 m of sand and silt had to be located in an area of more than several hundred km^2. Let us consider the problems of searching for and in delineating archaeological areas.

The first consideration is the expected size and extent of a typical anomaly caused by an archaeological feature so that a proper grid interval may be established. Previously (RALPH, 1964), it was found that a wall 1,300 m long extended from south of Casa Bianca to an area northwest of Parco del Cavallo (see Fig.1) but its northwest limit had not been found. At the eastern limit of the wall, excavation revealed that it was buried 1–2 m below the surface, and that it was more than 4 m high. Fig.2A illustrates the shape of the theoretical total field anomaly that would be produced by a two-dimensional structure 4 m high and 1 m thick, the top of which lies 2 m below ground level. The magnitude and dip of the earth's static magnetic field is characteristic for southern Italy and the magnetization was assumed uniform in the wall. A positive susceptibility contrast of 10^{-5} e.m.u. was assumed for these numerical calculations. The susceptibility contrast of the actual wall was found to be much higher than this value.

As the direction of magnetic north is rotated from a direction perpendicular to the wall to that parallel with the wall, the negative part of the anomaly decreases, the slope increases sharply, and the anomaly becomes symmetric when the rotation angle, $\phi = 0°$. Let us define the "half-width" of an anomaly as the width of the line joining the inflection points of the positive parts of the total field anomaly, as illustrated in Fig.2A. Note that this "half-width" is nearly independent of the rotation angle ϕ. In order to avoid aliasing of the survey data, grid samples must then be taken at a separation less than or equal to this half-width. This is the so-called Nyquist criterion for data sampling. The reciprocal of the half-width is known as the Nyquist frequency.

With a criterion of this sort, the extent of that region of the anomaly curve where the variation in total field intensity is sharpest can be defined in a statistical sense. For our theoretical model, the half-width, Δx_N, is approximately 3 m. For a deeper structure, the Nyquist criterion suggests a greater sample interval. For example, in Fig.2B the same wall has been placed at a depth of 5 m, and requires a sample interval of 6.0 m.

In addition to wall-like features, field experience has shown that the remanent magnetization of roof-tiles produces significant anomalies (BREINER, 1965; RAINEY and RALPH, 1966). A typical anomaly of this type is illustrated in Fig.3. In this case the sides of the anomalies are not nearly as steep as those for the wall structure. This is because the roof-tiles are usually accumulated in building debris, and the mounds of tiles are less well defined than a wall. The half-width associated with these anomalies averages 5 m for a burial depth of approximately 4 m. A proper grid interval would be on the order of 3 m or less. This sampling interval could theoretically reproduce the anomaly due to a wall buried 2 m below ground level. However, the pre-Roman archaeological features in the regions actually

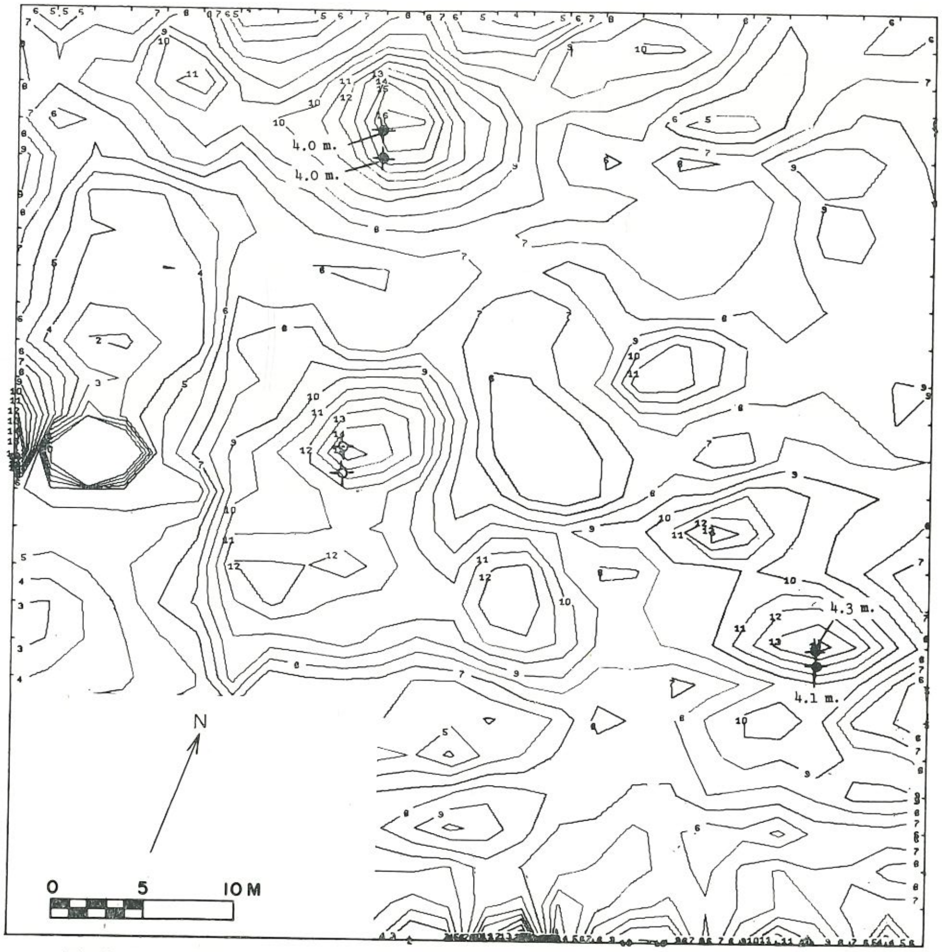

Fig.3. Magnetometer grid Q47. The contour intervals are 1 γ. Contours were calculated on an I.B.M. 7090–94 computer and drawn by a CalComp plotter.

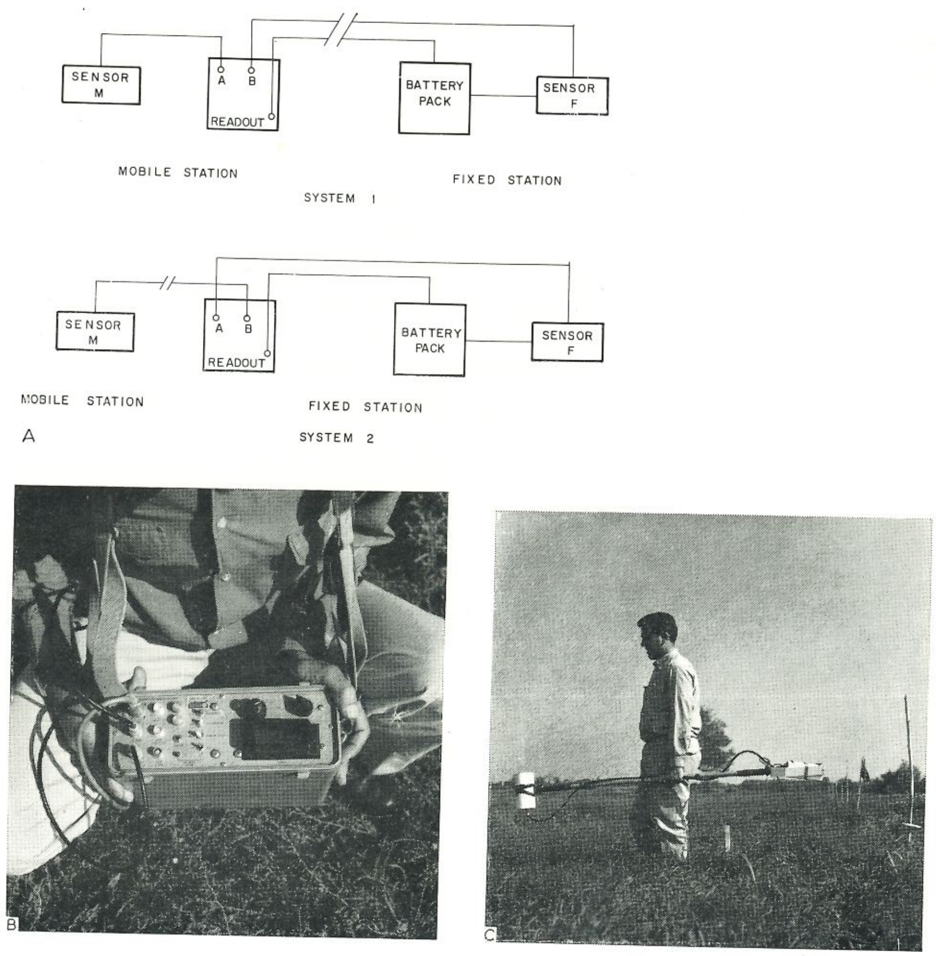

Fig.4A. Block diagrams of two configurations for the fixed and mobile magnetometer stations for difference mode of operation.
B. Digital readout unit (weight 8 lb.).
C. Mobile sensor (weight 6 lb.). Fixed sensor (not shown) identcial. Battery pack (not shown) weight 15 lb.

surveyed were known to be deeper than at least 4 m, and, therefore, a sample interval of 5 m was considered sufficient.

Parallel lines were marked out with a separation of 5 m. Measurements were made at 2 m intervals along each line. Where the site was relatively free of anomalies, the sample interval was lengthened to 4 m. The end points of the survey lines were surveyed, but the 2 m intervals were estimated by pacing. This type of surveying was used in grids Q1–Q102, excepting Q47 and Q100. In grids Q47 and Q100 a 50 m string marked in 2 m intervals was substituted for the less reliable pace method. Q100 was surveyed on a 4×5 m grid interval, while in Q47 a 2×2 m interval was employed. In both of these methods, the Nyquist criterion was satisfied if the exploration depths were greater than 4 m. A 2×5 m paced survey, with readout and roving sensor mobile (Fig.4, system 1), enabled data to be collected very rapidly.

In the examples of magnetic contour maps, shown in Fig. 5 and 6, the contours were traced from the original field data sheets. Field data are taken by recording readings directly on coordinate paper and contours are drawn usually at intervals of 5 units. The contour interval in Fig.5 is thus 2.5 γ approximately. Fig.3 is an example of high speed processing and plotting of field data using a digital computer. Here the data of grid Q47 have been converted to γ and contoured automatically using an off-line plotter.

The zero contours of Fig.5 and 6 do not correspond to the zero of the model interpretation, Fig.7. The zero in the field data is in fact the last digit in 80,000 and thus the numbers such as 995 are in fact 79,995 and 5 is actually 80,005. This zero is a function only of the fixed sensor location and is not related to the average field in the area. For technical reasons it was found necessary to use the rubidium system in inverted mode, using the mobile sensor as the counting reference fre-

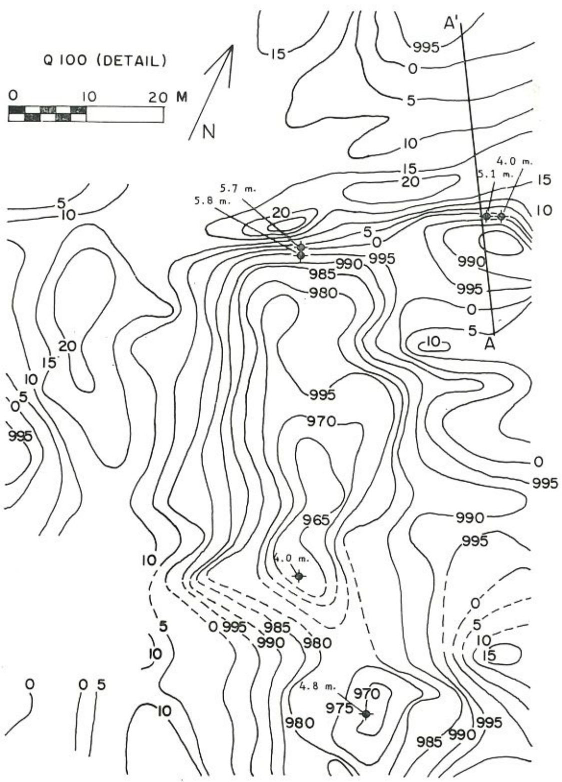

Fig.5. Part of grid Q100. Contours are in intervals of five different units.

quency. This results in an inverted contour map. As an example, Q100 (Fig.5) is inverted (the section *A'A*, Fig.5, has been corrected in Fig.8 for interpretation purposes). Q102 (Fig.6) is in the correct convention. In practice, system 1 allowed the fastest surveys. With this system a typical grid of 80 by 100 m could be surveyed in 4 h.

Interesting anomalies were probed immediately after contouring of the field data. A gasoline motor-powered auger was used for drilling and a probe consisting of 12 mm diameter connectable steel rods one meter long with a sharpened first section was used for establishing the depth of stone or tile sources. This probe, called a "spillo", could be used to a depth of 7 m and with experience the operators could tell by the type of resistance encountered whether the material was sand, pebbles, tiles, or stonework. The drill was slower to use but afforded the added advantage of bringing up fragments of pottery, stone, roof-tiles, etc., that in many instances allowed determination of the age of the material giving rise to the anomaly. The locations of "spillo" holes are shown in Fig.5. Filled-in symbols indicate probings which encountered solid resistance (tiles or stone) and the numbers associated with these symbols indicate the depth at which the obstacle was encountered. Open symbols indicate that no solid structures were detected.

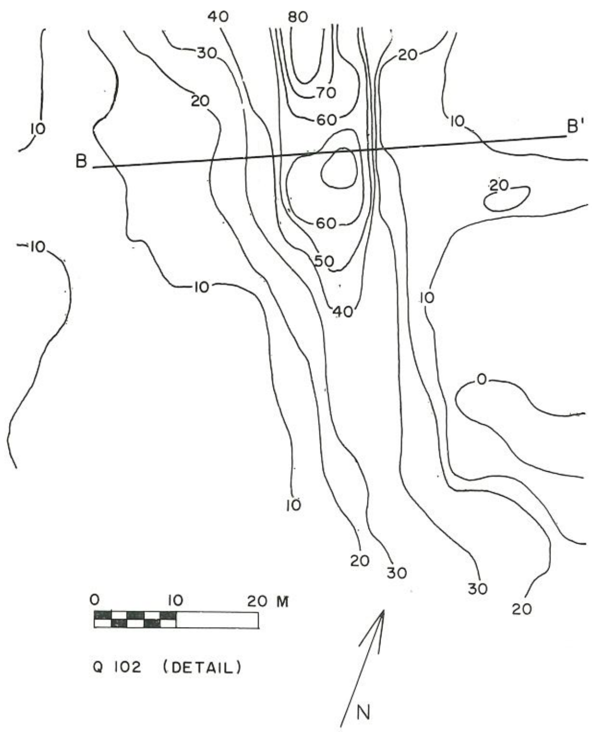

Fig.6. Grid Q102. Contours are in intervals of ten different units.

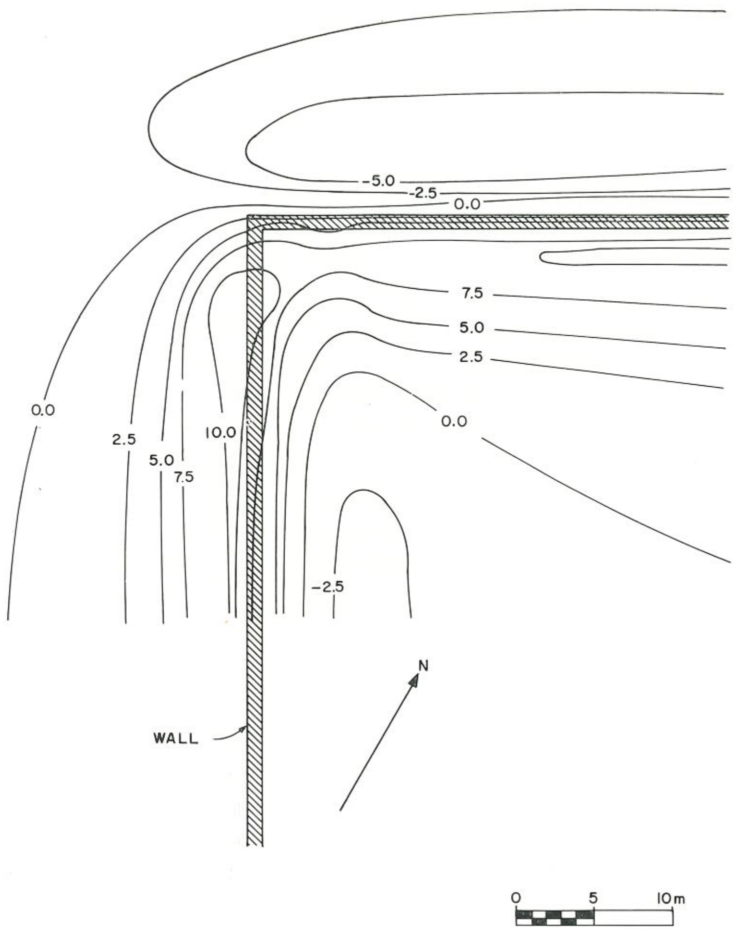

Fig.7. Anomalous total magnetic field for a wall describing a 90° turn. $F = 44{,}000\ \gamma$; $I = 52$, susceptibility contrast $= 2\ 0 \cdot 10^{-3}$ e.m.u. Contour interval $= 2.5\,\gamma$. Wall depth $= 5.0$ m; wall height $= 4.0$ m.

INTERPRETATION

The most significant archaeological feature inferred from the magnetometer surveys and confirmed by drilling in 1966 was the northwestern extent and right angle turn of the long wall. As illustrated in Fig.1, this wall was traced precisely in grids Q30, Q26, Q100, and Q102. The wall shows as a strong linear magnetic feature as seen in Fig. 5 and 6. In many places along its length, positive identification was augmented by drilling.

Excavations near and within Q30 (RAINEY, 1962) had revealed the existence of a wall buried in this particular location, 1 m below the ground surface, and about 5 m high. The wall was constructed of very weakly magnetic sandstone embedded in a matrix of slightly more magnetic silt and clay layers. The upper part of the wall was of Roman construction, but the distinctly different lower part was dated as a 4th Century B.C. Greek wall. The wall was excavated as a result of data gathered from a proton magnetometer survey of the area. The wall was mapped from the excavation for a distance of more than 1 km, first with a proton magnetometer and later much more rapidly by a rubidium vapor magnetometer equipped with an audio output (BREINER, 1965). The northwestern limit in the Parco del Cavallo was not determined precisely until grids Q100 and Q102 were made with the portable differential magnetometers. Grid Q100 was surveyed with a Rb–Rb system, while a Cs–Cs configuration was employed for a grid Q102.

In Q100 (Fig.5), the magnetic lineation is seen to strike first to the southwest, and then suddenly to shift 90° to the southeast. The lineation is continuous to the southeast in grid Q102. This shift suggests that the wall has turned a 90° corner and then strikes towards the Crati River. A three-dimensional model of a wall structure turning 90° in a static magnetic field environment characteristic of southern Italy is shown in Fig.7. The model is based upon the "spillo" holes of Q100 which encountered the top of the wall. The various wall parameters (height, thickness, susceptibility contrast, natural remanent magnetization) were varied to produce the most satisfactory fit to the field data. The profile line *A–A'* of Fig.8 shows the extremely good fit between the theoretical anomaly and that actually found in the field. The northern side of the wall is located directly below the steepest descending portion of the theoretical contours, and the drill data bear this out. The discrepancy of the northwestern corner between the model and field data is due to a strong anti-magnetic feature running northeast just past the northwestern corner of the wall. We have interpreted this feature as a trace of an old channel of the Crati. Its features may be seen in other grids, notably Q13, Q15,

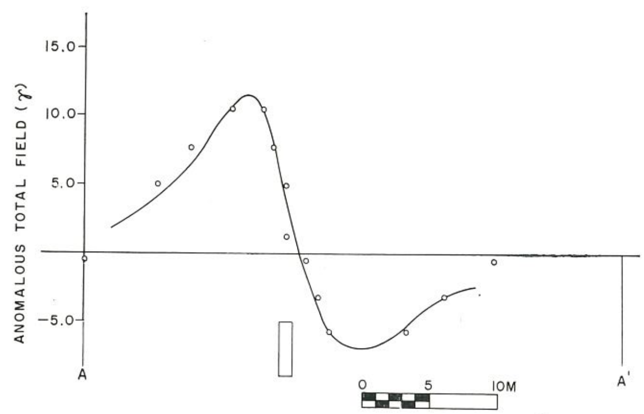

Fig.8. Theoretical fit (curve) to data (circles) from profile *A–A'* of Q100. Magnetic parameters are the same as in Fig.7. Apparent susceptibility contrast between wall and silt = $2.0 \cdot 10^{-3}$ e.m.u.

and Q26, where its appearance is linear and well defined. We also note that the direction of magnetization of the best fitting model was parallel to the present direction of the earth's magnetic field. If no natural remanent magnetization is present, the data indicate that the susceptibility contrast between the north part of the wall and the surrounding silt and clay is positive, with a magnitude of $2.0 \cdot 10^{-3}$ e.m.u. This indicates that an ultrabasic rock type was employed as construction material in the wall. This is in marked contrast to the antimagnetic nature of the anomaly found in Q30. Either the wall at Q100 was built of different material from that near the excavation, or the flood plain deposits were markedly different in magnetic character. One additional point seems to bear out the former observation, namely that the drill bit encountered numerous fourth century Greek pottery fragments near the top of the wall, at its western limit, which may possibly indicate that the Roman upper part is absent at this end. The southeastern striking portion of the wall appears to be at a slightly greater depth of burial than that portion striking southwest (Fig.9). The variation in depths to the wall as found by the "spillo" is presumably an indication of the state of ruin of the wall. In fact the general broadening of the anomaly to the south in Q100 (Fig.5) indicates a broader structure brought about either by collapse of the wall or additional structures at greater depth.

The magnetic contour map of Q47 (Fig.3) shows several typical anomalies of a less distinctive nature than the wall anomaly of Q100. This grid was made in an area of clustered anomalies in which another excavation revealed foundations and roof-tiles from small dwellings. The grid is located 800 m due north of the Masseria Lattughella shown in the location map, Fig.1. As in the anomalies of Q100 and Q102 the "spillo" holes are located precisely with respect to the contour lines, and in three out of five attempts roof-tiles and stone obstructions were encountered. These types of anomalies demand the high sensitivity of the gradio-

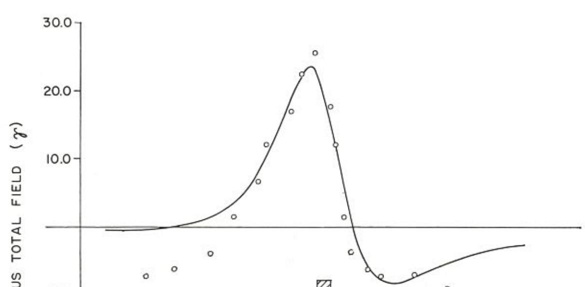

Fig.9. Theoretical fit (curve) to data (circles) from profile *B–B'* of Q102. Magnetic parameters are the same as in Fig.7. Apparent susceptibility contrast between wall and silt = $5 \cdot 10^{-3}$ e.m.u.

meter system for the detection of inflection points, maxima, etc., which is necessary for the successful location of features by drilling. These anomalies are typical of ones caused by remanent magnetization.

CONCLUSION

The city of Sybaris was not found, but this field season demonstrated that anomalies due to deeply buried archaeological features could readily be detected with high-sensitivity alkali vapor magnetometers. Also, with these light-weight portable instruments, large areas could be surveyed very quickly. The difference mode of operation afforded instantaneous cancellation of extraneous magnetic variations and permitted the use of the maximum sensitivity where needed. This, combined with the digital readout, facilitated rapid plotting and interpretation of the results.

The finding of the turning of the long wall at its southwestern limit indicates that the wall may have had a more important function than had been realized previously. Perhaps it was the outer wall of the 5th Century B.C. city of Thurii or of its port. Although not "sybaritic", this may prove to be a significant find.

ACKNOWLEDGEMENT

We wish to express our gratitude to the National Science Foundation for financial support of part of the instrument development and for some of the travel funds.

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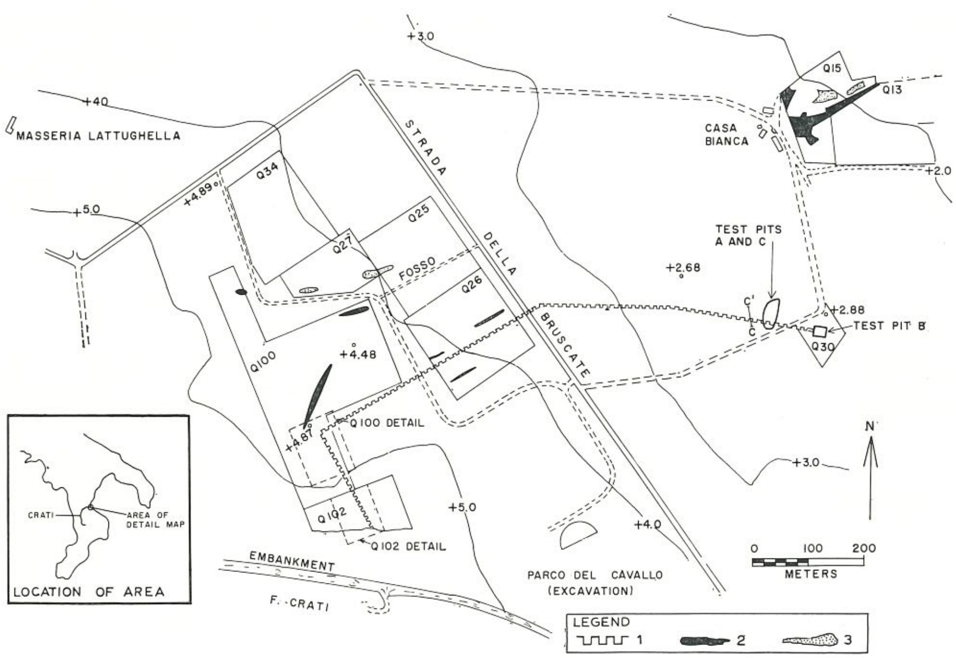

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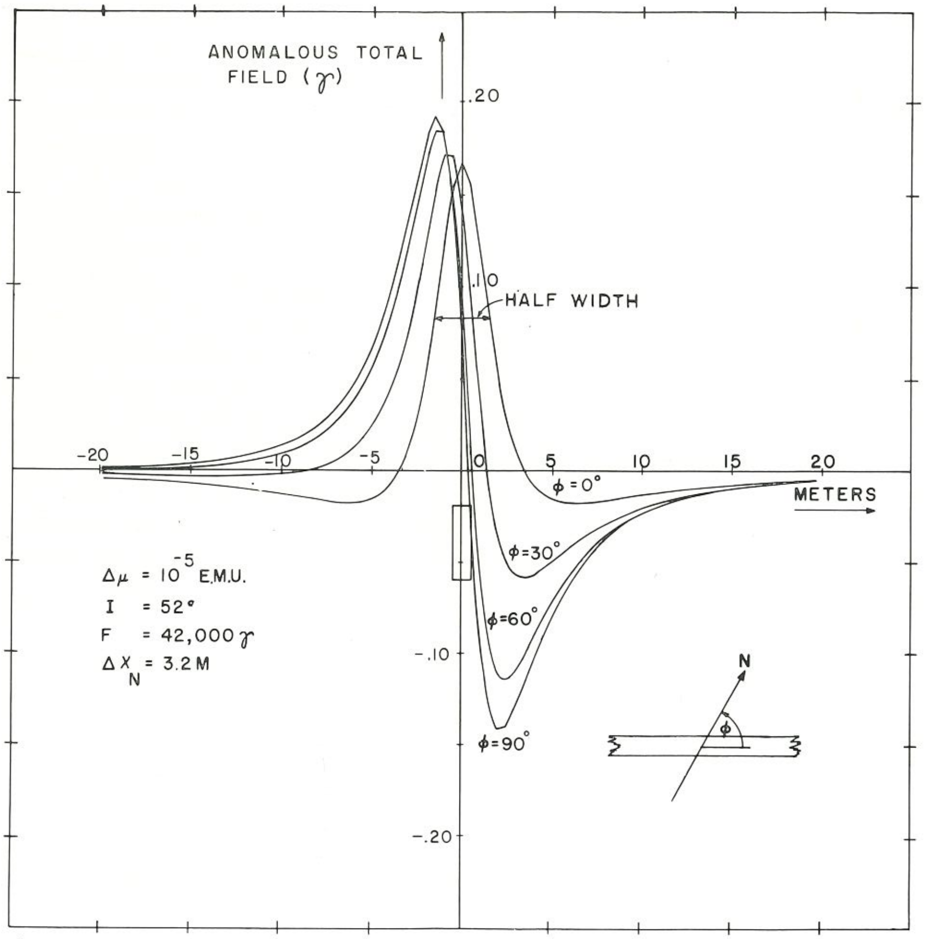
When operated as a difference magnetometer, the second sensor replaces the crystal oscillator to regulate the counting interval. Now instead of counting for a specific number of cycles of the crystal reference, the counting is carried out for the same number of cycles but using the second sensor output as reference. The readings are no longer in γ, but are adjusted to an arbitrary base reading of 80,000. That is, if both sensors are in the same total magnetic field, the reading which appears in the instrument is 80,000.0. When used for surveying, one sensor is kept in a fixed position and the other is moved throughout the area to be explored. The reading of the movable sensor may be converted to change in γ by the formula:

$$\Delta H = \frac{H_F}{80{,}000}\,[N - 80{,}000]$$

where ΔH is the difference in γ between the fixed and movable sensors; H_F is the total field intensity (in γ) of the fixed sensor only; N is the instrument reading.

Since the total field intensity in southern Italy is approximately 45,000 γ, it can be seen that in the difference mode of operation, the sensitivity of the instrument is roughly double (0.56 γ/unit) that with one sensor only.

The maximum speed of survey is limited only by the repetition rate. In practice, the readings can be viewed continuously by the operator who can see when significant anomalies are encountered and slow down to record changes in readings. The advantages of operating in difference mode are obvious, especially, at the high sensitivities employed. If readings are taken to a precision of ca. 0.1 γ, it is essential to cancel out diurnal and other extraneous magnetic variations. Also, manual subtraction or cancellation would be much too time-consuming. Admit-



A

Fig.2. Calculated anomalous total magnetic field over two-dimensional hypothetical archaeological structure. The curves are plotted as functions of magnetic strike angles.

A. The wall is at depth of 2 m. B. The wall is at depth of 5 m.

$\Delta\mu$ = Susceptibility contrast; I = magnetic field inclination; F = total field intensity; Δx_N = half-width anomaly.

tedly, for reconnaissance surveys anomalies can be detected using sensitivities of ca. 1 γ, but again the detailed survey needed for quantitative interpretation is best obtained using the difference mode.

The cesium system proved to be a more successful field instrument due primarily to a greater independence of orientation of the sensor elements. It was necessary to keep the movable rubidium sensor very carefully aligned, and this slowed the surveys down by, at least, 20%.

No measurable instabilities were noted in the entire field season. Grids could be reoccupied or continued days later by the simple expedient of placing the roving

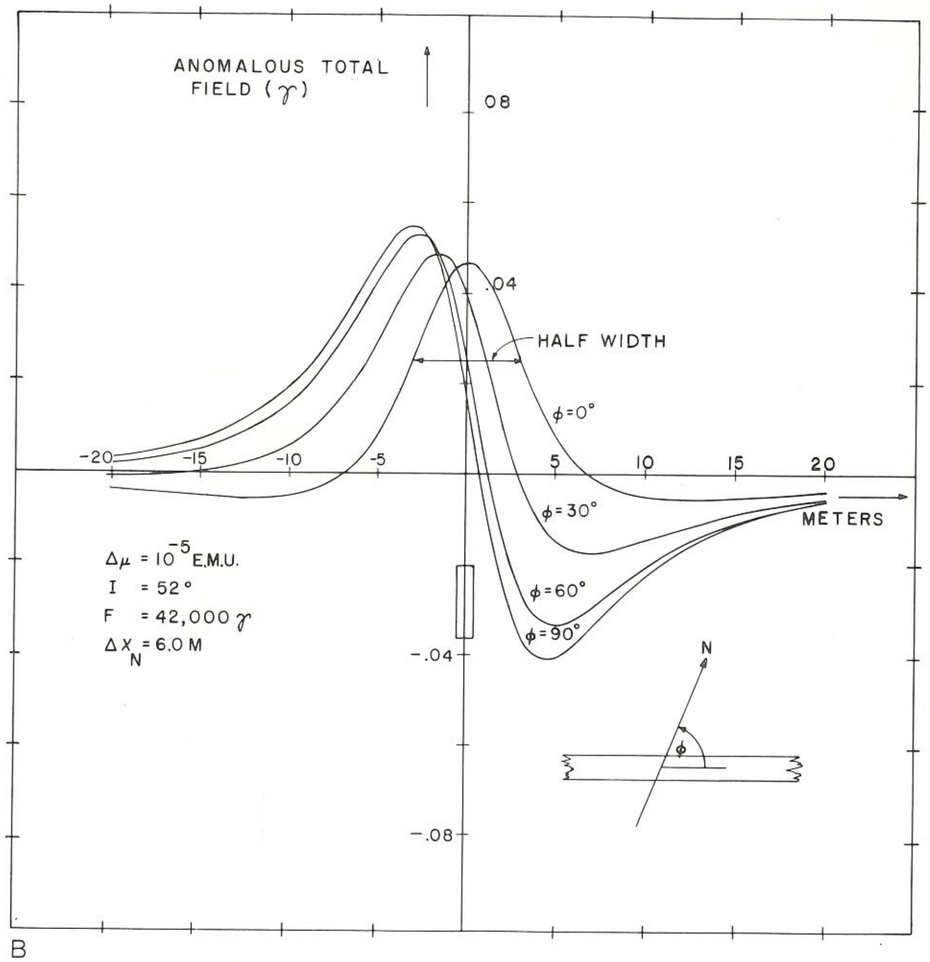


Fig.2B (Legend see p.113).

sensor at a previously occupied site and bringing the reading to the previous value by adjusting the position of a piece of iron placed near the fixed sensor. In this fashion continuous mapping can be carried out over as large an area as desired. The maximum grid that could be covered with a single set-up of the fixed sensor was approximately 80 × 100 m. This was limited only by the length of cable (100 m) connecting the sensors. A simple r.f. telemetering system for the mobile sensor would increase the versatility and speed of surveys immensely. The two systems used in this project were insensitive to temperature variations. Daily ambient temperatures of over 90 °F had no effect on stability, battery life, or repeatability of measurements.

EXTENT AND METHODS OF FIELD SURVEYS

During the months of May, June, and July, 1966, approximately 85 grids were surveyed. Several of these grids are shown in Fig.1 labelled Q26, Q30, etc. It was desired to establish the boundaries of the area shown in Fig.1 which possessed a great many anomalies and proven archaeological features. Excavations in this area (Parco del Cavallo, and Q30) had revealed Roman and 4th Century B.C. Greek remains, especially potsherds, but no structures from the time of Sybaris were found. Nevertheless, it was desired to know over how large an area these anomalies extended. The second goal was to establish the location of the parent city itself, either within or outside of this area. Locating the site for the main city is a formidable task when we consider that a city of roughly 3–5 km^2 buried under at least 3 m of sand and silt had to be located in an area of more than several hundred km^2. Let us consider the problems of searching for and in delineating archaeological areas.

The first consideration is the expected size and extent of a typical anomaly caused by an archaeological feature so that a proper grid interval may be established. Previously (RALPH, 1964), it was found that a wall 1,300 m long extended from south of Casa Bianca to an area northwest of Parco del Cavallo (see Fig.1) but its northwest limit had not been found. At the eastern limit of the wall, excavation revealed that it was buried 1–2 m below the surface, and that it was more than 4 m high. Fig.2A illustrates the shape of the theoretical total field anomaly that would be produced by a two-dimensional structure 4 m high and 1 m thick, the top of which lies 2 m below ground level. The magnitude and dip of the earth's static magnetic field is characteristic for southern Italy and the magnetization was assumed uniform in the wall. A positive susceptibility contrast of 10^{-5} e.m.u. was assumed for these numerical calculations. The susceptibility contrast of the actual wall was found to be much higher than this value.

As the direction of magnetic north is rotated from a direction perpendicular to the wall to that parallel with the wall, the negative part of the anomaly decreases, the slope increases sharply, and the anomaly becomes symmetric when the rotation angle, $\phi = 0°$. Let us define the "half-width" of an anomaly as the width of the line joining the inflection points of the positive parts of the total field anomaly, as illustrated in Fig.2A. Note that this "half-width" is nearly independent of the rotation angle ϕ. In order to avoid aliasing of the survey data, grid samples must then be taken at a separation less than or equal to this half-width. This is the so-called Nyquist criterion for data sampling. The reciprocal of the half-width is known as the Nyquist frequency.

With a criterion of this sort, the extent of that region of the anomaly curve where the variation in total field intensity is sharpest can be defined in a statistical sense. For our theoretical model, the half-width, Δx_N, is approximately 3 m. For a deeper structure, the Nyquist criterion suggests a greater sample interval. For example, in Fig.2B the same wall has been placed at a depth of 5 m, and requires a sample interval of 6.0 m.

In addition to wall-like features, field experience has shown that the remanent magnetization of roof-tiles produces significant anomalies (BREINER, 1965; RAINEY and RALPH, 1966). A typical anomaly of this type is illustrated in Fig.3. In this case the sides of the anomalies are not nearly as steep as those for the wall structure. This is because the roof-tiles are usually accumulated in building debris, and the mounds of tiles are less well defined than a wall. The half-width associated with these anomalies averages 5 m for a burial depth of approximately 4 m. A proper grid interval would be on the order of 3 m or less. This sampling interval could theoretically reproduce the anomaly due to a wall buried 2 m below ground level. However, the pre-Roman archaeological features in the regions actually

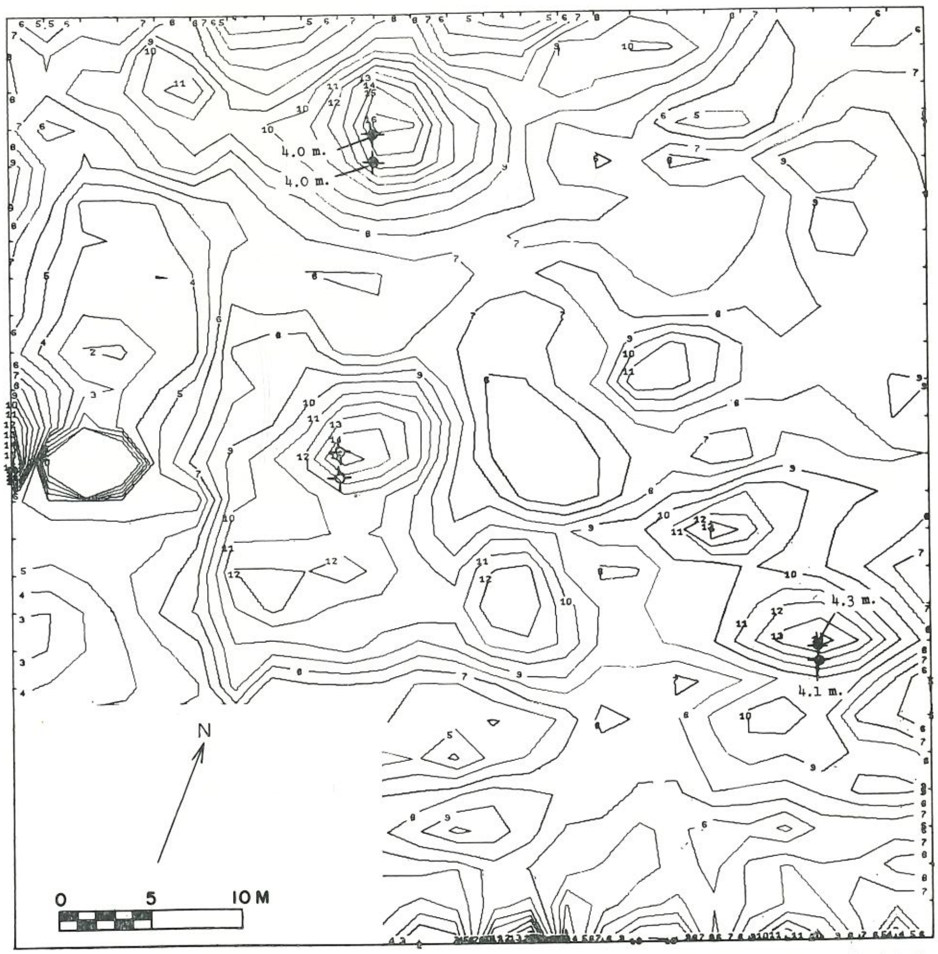


Fig.3. Magnetometer grid Q47. The contour intervals are 1 γ. Contours were calculated on an I.B.M. 7090–94 computer and drawn by a CalComp plotter.

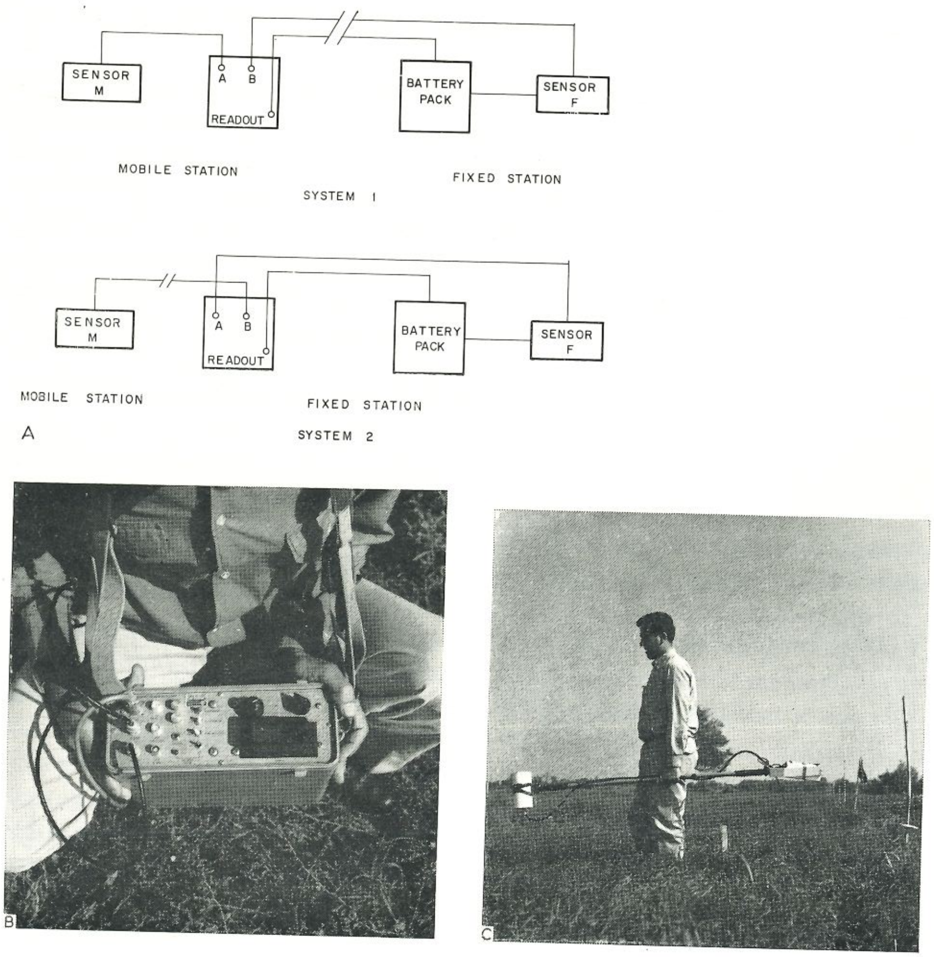


Fig.4A. Block diagrams of two configurations for the fixed and mobile magnetometer stations for difference mode of operation.

B. Digital readout unit (weight 8 lb.).

C. Mobile sensor (weight 6 lb.). Fixed sensor (not shown) identcial. Battery pack (not shown) weight 15 lb.

surveyed were known to be deeper than at least 4 m, and, therefore, a sample interval of 5 m was considered sufficient.

Parallel lines were marked out with a separation of 5 m. Measurements were made at 2 m intervals along each line. Where the site was relatively free of anomalies, the sample interval was lengthened to 4 m. The end points of the survey lines were surveyed, but the 2 m intervals were estimated by pacing. This type of surveying was used in grids Q1–Q102, excepting Q47 and Q100. In grids Q47 and Q100 a 50 m string marked in 2 m intervals was substituted for the less reliable pace method. Q100 was surveyed on a 4×5 m grid interval, while in Q47 a 2×2 m interval was employed. In both of these methods, the Nyquist criterion was satisfied if the exploration depths were greater than 4 m. A 2 × 5 m paced survey, with readout and roving sensor mobile (Fig.4, system 1), enabled data to be collected very rapidly.

In the examples of magnetic contour maps, shown in Fig. 5 and 6, the contours were traced from the original field data sheets. Field data are taken by recording readings directly on coordinate paper and contours are drawn usually at intervals of 5 units. The contour interval in Fig.5 is thus 2.5 γ approximately. Fig.3 is an example of high speed processing and plotting of field data using a digital computer. Here the data of grid Q47 have been converted to γ and contoured automatically using an off-line plotter.

The zero contours of Fig.5 and 6 do not correspond to the zero of the model interpretation, Fig.7. The zero in the field data is in fact the last digit in 80,000 and thus the numbers such as 995 are in fact 79,995 and 5 is actually 80,005. This zero is a function only of the fixed sensor location and is not related to the average field in the area. For technical reasons it was found necessary to use the rubidium system in inverted mode, using the mobile sensor as the counting reference fre-

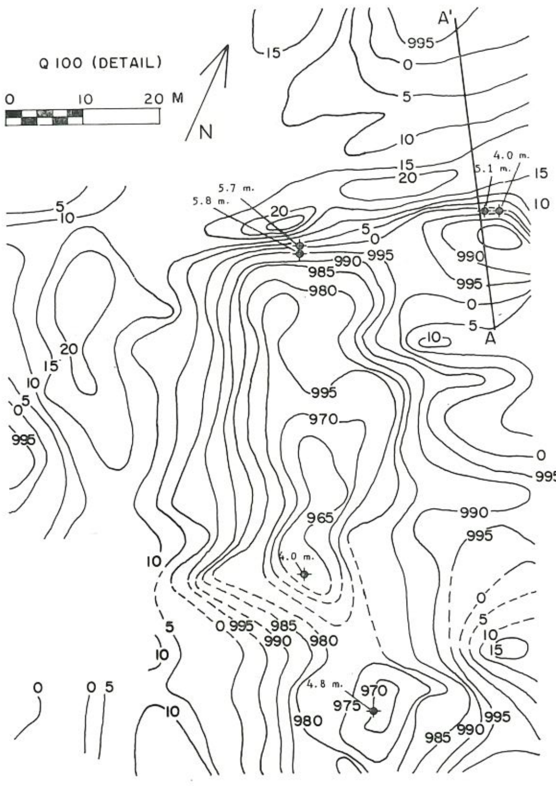


Fig.5. Part of grid Q100. Contours are in intervals of five different units.

quency. This results in an inverted contour map. As an example, Q100 (Fig.5) is inverted (the section *A'A*, Fig.5, has been corrected in Fig.8 for interpretation purposes). Q102 (Fig.6) is in the correct convention. In practice, system 1 allowed the fastest surveys. With this system a typical grid of 80 by 100 m could be surveyed in 4 h.

Interesting anomalies were probed immediately after contouring of the field data. A gasoline motor-powered auger was used for drilling and a probe consisting of 12 mm diameter connectable steel rods one meter long with a sharpened first section was used for establishing the depth of stone or tile sources. This probe, called a "spillo", could be used to a depth of 7 m and with experience the operators could tell by the type of resistance encountered whether the material was sand, pebbles, tiles, or stonework. The drill was slower to use but afforded the added advantage of bringing up fragments of pottery, stone, roof-tiles, etc., that in many instances allowed determination of the age of the material giving rise to the anomaly. The locations of "spillo" holes are shown in Fig.5. Filled-in symbols indicate probings which encountered solid resistance (tiles or stone) and the numbers associated with these symbols indicate the depth at which the obstacle was encountered. Open symbols indicate that no solid structures were detected.

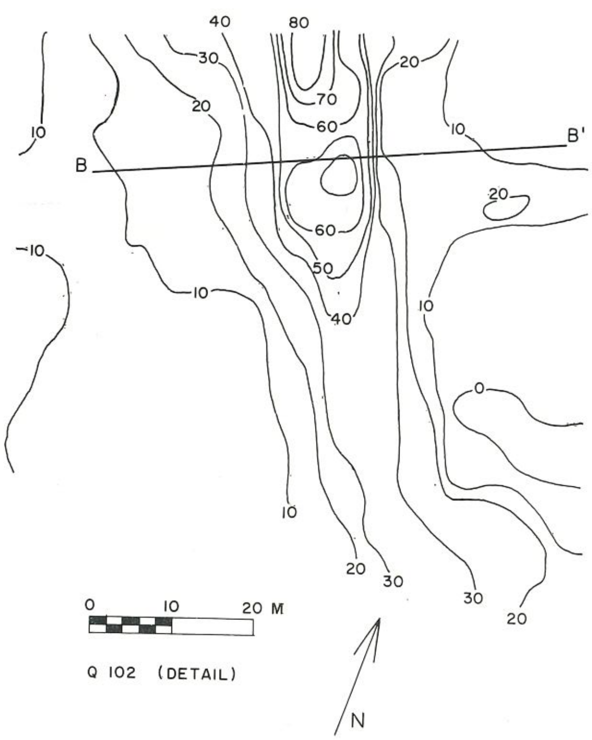


Fig.6. Grid Q102. Contours are in intervals of ten different units.

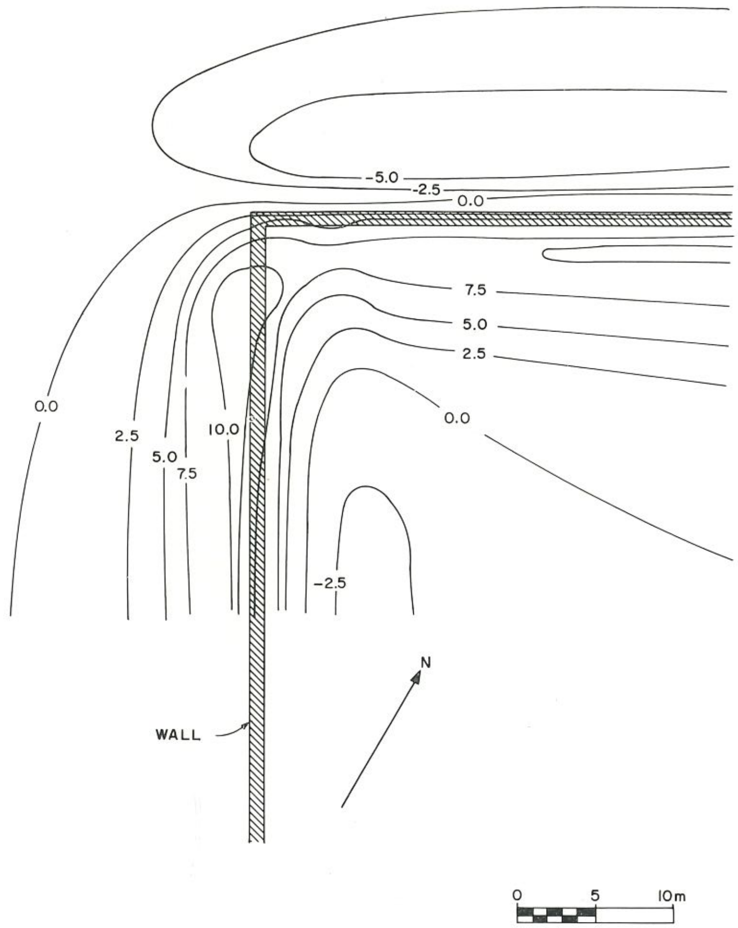


Fig.7. Anomalous total magnetic field for a wall describing a 90° turn. $F = 44{,}000\ \gamma$; $I = 52$, susceptibility contrast $= 2\ 0 \cdot 10^{-3}$ e.m.u. Contour interval $= 2.5\ \gamma$. Wall depth $= 5.0$ m; wall height $= 4.0$ m.

INTERPRETATION

The most significant archaeological feature inferred from the magnetometer surveys and confirmed by drilling in 1966 was the northwestern extent and right angle turn of the long wall. As illustrated in Fig.1, this wall was traced precisely in grids Q30, Q26, Q100, and Q102. The wall shows as a strong linear magnetic feature as seen in Fig. 5 and 6. In many places along its length, positive identification was augmented by drilling.

Excavations near and within Q30 (Rainey, 1962) had revealed the existence of a wall buried in this particular location, 1 m below the ground surface, and about 5 m high. The wall was constructed of very weakly magnetic sandstone embedded in a matrix of slightly more magnetic silt and clay layers. The upper part of the wall was of Roman construction, but the distinctly different lower part was dated as a 4th Century B.C. Greek wall. The wall was excavated as a result of data gathered from a proton magnetometer survey of the area. The wall was mapped from the excavation for a distance of more than 1 km, first with a proton magnetometer and later much more rapidly by a rubidium vapor magnetometer equipped with an audio output (BREINER, 1965). The northwestern limit in the Parco del Cavallo was not determined precisely until grids Q100 and Q102 were made with the portable differential magnetometers. Grid Q100 was surveyed with a Rb–Rb system, while a Cs–Cs configuration was employed for a grid Q102.

In Q100 (Fig.5), the magnetic lineation is seen to strike first to the southwest, and then suddenly to shift 90° to the southeast. The lineation is continuous to the southeast in grid Q102. This shift suggests that the wall has turned a 90° corner and then strikes towards the Crati River. A three-dimensional model of a wall structure turning 90° in a static magnetic field environment characteristic of southern Italy is shown in Fig.7. The model is based upon the "spillo" holes of Q100 which encountered the top of the wall. The various wall parameters (height, thickness, susceptibility contrast, natural remanent magnetization) were varied to produce the most satisfactory fit to the field data. The profile line *A–A'* of Fig.8 shows the extremely good fit between the theoretical anomaly and that actually found in the field. The northern side of the wall is located directly below the steepest descending portion of the theoretical contours, and the drill data bear this out. The discrepancy of the northwestern corner between the model and field data is due to a strong anti-magnetic feature running northeast just past the northwestern corner of the wall. We have interpreted this feature as a trace of an old channel of the Crati. Its features may be seen in other grids, notably Q13, Q15,

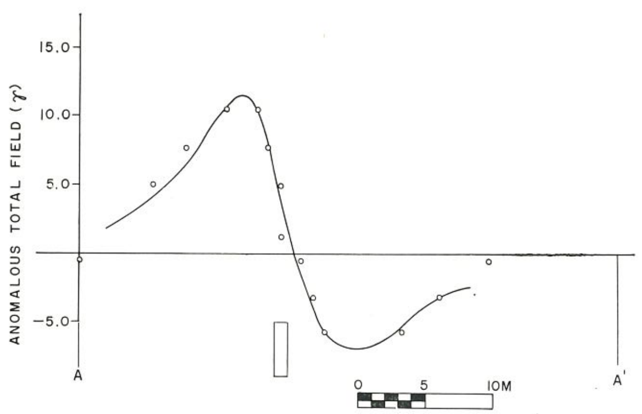


Fig.8. Theoretical fit (curve) to data (circles) from profile *A–A'* of Q100. Magnetic parameters are the same as in Fig.7. Apparent susceptibility contrast between wall and silt $= 2.0 \cdot 10^{-3}$ e.m.u.

and Q26, where its appearance is linear and well defined. We also note that the direction of magnetization of the best fitting model was parallel to the present direction of the earth's magnetic field. If no natural remanent magnetization is present, the data indicate that the susceptibility contrast between the north part of the wall and the surrounding silt and clay is positive, with a magnitude of $2.0 \cdot 10^{-3}$ e.m.u. This indicates that an ultrabasic rock type was employed as construction material in the wall. This is in marked contrast to the antimagnetic nature of the anomaly found in Q30. Either the wall at Q100 was built of different material from that near the excavation, or the flood plain deposits were markedly different in magnetic character. One additional point seems to bear out the former observation, namely that the drill bit encountered numerous fourth century Greek pottery fragments near the top of the wall, at its western limit, which may possibly indicate that the Roman upper part is absent at this end. The southeastern striking portion of the wall appears to be at a slightly greater depth of burial than that portion striking southwest (Fig.9). The variation in depths to the wall as found by the "spillo" is presumably an indication of the state of ruin of the wall. In fact the general broadening of the anomaly to the south in Q100 (Fig.5) indicates a broader structure brought about either by collapse of the wall or additional structures at greater depth.

The magnetic contour map of Q47 (Fig.3) shows several typical anomalies of a less distinctive nature than the wall anomaly of Q100. This grid was made in an area of clustered anomalies in which another excavation revealed foundations and roof-tiles from small dwellings. The grid is located 800 m due north of the Masseria Lattughella shown in the location map, Fig.1. As in the anomalies of Q100 and Q102 the "spillo" holes are located precisely with respect to the contour lines, and in three out of five attempts roof-tiles and stone obstructions were encountered. These types of anomalies demand the high sensitivity of the gradio-

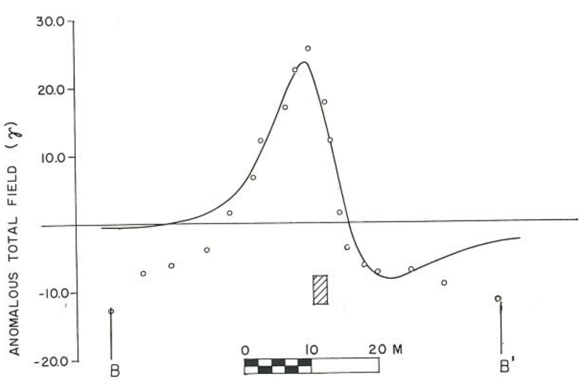


Fig.9. Theoretical fit (curve) to data (circles) from profile *B–B′* of Q102. Magnetic parameters are the same as in Fig.7. Apparent susceptibility contrast between wall and silt = $5 \cdot 10^{-3}$ e.m.u.

meter system for the detection of inflection points, maxima, etc., which is necessary for the successful location of features by drilling. These anomalies are typical of ones caused by remanent magnetization.

CONCLUSION

The city of Sybaris was not found, but this field season demonstrated that anomalies due to deeply buried archaeological features could readily be detected with high-sensitivity alkali vapor magnetometers. Also, with these light-weight portable instruments, large areas could be surveyed very quickly. The difference mode of operation afforded instantaneous cancellation of extraneous magnetic variations and permitted the use of the maximum sensitivity where needed. This, combined with the digital readout, facilitated rapid plotting and interpretation of the results.

The finding of the turning of the long wall at its southwestern limit indicates that the wall may have had a more important function than had been realized previously. Perhaps it was the outer wall of the 5th Century B.C. city of Thurii or of its port. Although not "sybaritic", this may prove to be a significant find.

ACKNOWLEDGEMENT

We wish to express our gratitude to the National Science Foundation for financial support of part of the instrument development and for some of the travel funds.

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Dr. E.K. Ralph
University Museum
University of Pennsylvania
Philadelphia, Pa.

U.S.A.

Our ref. LK/TD

Amsterdam, March 6, 1968

Dear Dr. Ralph:

After a preliminary examination of the manuscript by you, F. Morrison and D.P. O'Brien entitled "Archaeological surveying utilizing a high-sensitivity difference magnetometer" which has been accepted for publication in GEOEXPLORATION, we find it necessary to request certain information needed to bring the manuscript in accordance with standard rules established for our journal. We would be grateful for your answers to the enclosed questionnaire as quickly as possible.

Thanking you in advance for your cooperation, we remain

Yours sincerely,

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GEOEXPLORATION

L. Kempers.

L.Kempers, M.Sc.

P.S. Will you please send the correspondence to Editorial Office Geoexploration, P.O. Box 9061, Amsterdam-W III, The Netherlands?

Questionnaire belonging to the manuscript "Archaeological Surveying Utilizing a High-Sensitivity Difference Magnetometer" by E.K. Ralph, F. Morrison, D.P. O'Brien, submitted for publication in GEOEXPLORATION.

1. Please give the volume number and the first and last numbers of the article for your reference to Bloom 1960.

2. Please give the names and initials of the other authors in your reference to Rainey, Lerici et al.

[n.d.]

COPY

Dr. L. Kempers
Editorial Office Geoexploration
P. O. Box 9061
Amsterdam - W III
The Netherlands

Dear Dr. Kempers:

In regard to your questionnaire for the manuscript entitled "Archaeological Surveying Utilizing a High-Sensitivity Difference Magnetometer" by Ralph, Morrison, and O'Brien, the answers are as follows:

1. Bloom, A. L., Optical Pumping, Sci. Amer., 203, 4, pp. 72-80, 1960.

2. Rainey, F. and Lerici, C. M., The Search for Sybaris. Lerici Editori, Rome, 1967.

and change reference on page 2 of text to: (Rainey and Lerici, 1967).

(I have enclosed a copy of the front page of this monograph so that you can see what the problem is with the authors.)

I hope that these answers are satisfactory.

Sincerely yours,

R/RS

Elizabeth K. Ralph

Accepted for publication in Geoexploration
2/68

A High-Sensitivity Difference Magnetometer: An Archaeological Application

by

Elizabeth K. Ralph*, Frank Morrison**, and Douglas P. O'Brien***

ABSTRACT

Two pairs of alkali vapor magnetometers, one cesium, the other rubidium, have been employed in a difference mode together with a digital readout unit, for a detailed magnetic survey of an archaeological site in southern Italy. Fine grid intervals together with a system sensitivity approaching 0.05 gammas have enabled quantitative interpretation of small anomalies subsequently verified by drilling.

High speed of operation, cancellation of time-varying fields, and direct digital readout allow generation of magnetic contour maps in the field. These features are well suited to the peculiar problems of archaeological magnetometry, and indeed to other geophysical applications.

---

*University Museum, University of Pennsylvania, Philadelphia, Pa.

**Varian Associates, Palo Alto, Calif. Presently at Dept of Mineral Technology, University of California, Berkeley, California.

***Varian Associates, Palo Alto, California.

Introduction

A portable high-sensitivity alkali vapor magnetometer has been developed for archaeological exploration. Special features are the two-sensor difference-mode of operation and the digital readout. This instrument was designed specifically for archaeological prospecting by Varian Associates at the request of the University Museum, University of Pennsylvania. It was developed after preliminary tests were conducted in 1964 (Ralph, 1964, 1965; Breiner, 1965) with the more elaborate and less portable Varian Associates rubidium magnetometer model V-4938. These tests demonstrated that the greater sensitivity obtainable with alkali vapor magnetometers would be practical and effective for highly detailed magnetometer surveys such as those required for archaeological exploration.

One system with two cesium sensors was tested in the fall of 1965 (Langan,1966; Rainey and Ralph, 1966) and in the summer of 1966, two systems, one employing two cesium sensors and one utilizing two rubidium sensors, were used. It is the 1966 field program which is reported here. These surveys were made on the Plain of Sybaris in southern Italy where the University Museum has been engaged in the search for the ancient Greek city of Sybaris since 1961 (Rainey, Lerici, *et al*., in press).

Sybaris was a city of great affluence which flourished in the 7th and 6th centuries B.C. It was founded about 720 B.C. by Achaean colonists between two rivers which flow into the Ionian Sea. Since the destruction of Sybaris in 510 B.C., up to six meters of flood plain alluvium has been deposited uniformly over the ancient Greek city. The depth of burial and the vastness of the present plain (approximately 30 by 20 kilometers) combine to offer a challenge for magnetic prospecting. The water table is only 1 to 2 meters below the surface which reduces the effectiveness of resistivity surveying and also makes large scale excavation impractical. From information obtained by drilling and a few test excavations (Brown, 1963; Rainey, 1962) we know that on the plain, the archaic 7th to 6th century B.C. level of occupation is at depths of 4 to 6 meters. This is overlain by remnants of the 5th to 4th century B.C. city called Thurii, and on top of this are scattered Roman ruins, some starting at 1 to 3 meters below the surface and extending downward. These archaeological deposits have been found in a limited region of the plain as shown in Figure 1. The sediments are so uniform that, with differential alkali vapor magnetometers, anomalies of 3-5 gammas can easily be distinguished and related to sources such as roof tiles, bricks and other fired ceramics at depths at 4 to 6 meters.

The difference magnetometer

The principles of operation of an alkali vapor magnetometer have been described by Bloom (1960 and 1962) and its trial in archaeological exploration has recently been reported by Breiner (1965). The unit described in this article is essentially a development of the magnetometer described by Breiner.

Basically the alkali vapor magnetometer may be considered as an oscillator, the frequency of which is proportional to the total magnetic field. For rubidium vapor the constant of proportionality is 4.667 cycles/sec/gamma and for cesium it is 3.5 cycles/sec/gamma. In each sensor the vapor is energized by a 100 mc oscillator.

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$$\Delta H = \frac{H_F}{80,000}\left[N - 80,000\right]$$

Where ΔH is the difference in gammas between the fixed and movable sensors

H_F is the total field intensity (in gammas) of the fixed sensor only.

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The cesium system proved to be a more successful field instrument due primarily to a greater independence on orientation of the sensor elements. It was necessary to keep the movable rubidium sensor very carefully aligned, and this slowed the surveys down by, at least, 20 percent.

No measurable instabilities were noted in the entire field season. Grids could be reoccupied or continued days later by the simple expedient of placing the roving sensor at a previously occupied site and bringing the reading to the previous value by adjusting the position of a piece of iron placed near the fixed sensor. In this fashion continuous mapping can be carried out over as large an area as desired. The maximum grid that could be covered with a single set-up of the fixed sensor was approximately 80 x 100 meters. This was limited only by the length of cable (100 meters) connecting the sensors. A simple r.f. telemetering system for the mobile sensor would increase the versatility and speed of surveys immensely. The two systems used in this project were insensitive to temperature variations. Daily ambient temperatures of over 90° F had no effect on stability, battery life, or repeatability of measurements.

Extent and methods of field surveys

During the months of May, June, and July, 1966, approximately 85 grids were surveyed. Several of these grids are shown in Figure 1 labelled Q26, Q30, etc. It was desired to establish the boundaries of the area shown in Figure 1 which possessed a great many anomalies and proven archaeological features. Excavations in this area (Parco del Cavallo, and Q30) had revealed Roman and 4th Century B.C. Greek remains, especially, potsherds, but no structures from the time of Sybaris were found. Nevertheless, it was desired to know over how large an area these anomalies extended. The second goal was to establish the location of the parent city itself, either within or outside of this area. Locating the site for the main city is a formidable task when we consider that a city of roughly 3 to 5 square kilometers buried under at least 3 meters of sand and silt had to be located in an area of more than several hundred square kilometers. Let us consider the problems inherent in searching for and in delineating archaeological areas.

The first consideration must be the expected size and extent of a typical anomaly caused by an archaeological feature so that a proper grid interval may be established. Previously (Ralph, 1964), it was determined that a wall 1300 meters long extended from south of Casa Bianca to an area northwest of Parco del Cavallo (see Figure 1), but its northwest limit had not been found. At the eastern limit of the wall, excavation revealed that it was buried 1-2 meters below the surface, and that it was more than 4 meters high. Figure 2a illustrates the shape of the theoretical total field anomaly that would be produced by a 2-dimensional structure 4 meters high and 1 meter thick, the top of which lies 2 meters below ground level. The magnitude and dip of the earth's static magnetic field is characteristic for southern Italy. A positive susceptibility contrast of 10^{-5} emu units was assumed for these calculations. The susceptibility of the actual wall was found to be much higher than this value.

As the direction of magnetic north is rotated from a direction perpendicular to the wall to that parallel with the wall, the negative part of the anomaly decreases, the slope increases sharply, and the anomaly becomes symmetric when the rotation angle, $\emptyset = 0^{\circ}$. Let us define the "half-period" of an anomaly as the width of the line joining the inflection points of the positive parts of the total field anomaly, as illustrated in Figure 2a. Note that this "half-period" is nearly independent of the rotation angle $\emptyset$. In order to avoid aliasing of the survey data, grid samples must then be taken at a separation less than or equal to this half-period. This is the so-called Nyquist criterion for data sampling. The reciprocal of the half-period is known as the Nyquist frequency. With a criterion of this sort, the extent of that region of the anomaly curve where the variation in total field intensity is sharpest can be defined in a statistical sense. For our theoretical model, the half-period, Δx_N, is approximately 3 meters. For a deeper structure, the Nyquist criterion suggests a greater sample interval. For example, in Figure 2b the same wall has been placed at a depth of 5 meters, and requires a sample interval of 6.0 meters.

In addition to wall-like features, field experience has shown that the remanent magnetization of roof-tiles produces significant anomalies (Breiner, 1965; Rainey and Ralph, 1966). A typical anomaly of this type is illustrated in Figure 3. In this case the sides of the anomalies are not nearly as steep as those for the wall structure. This is because the roof tiles are usually accumulated in building debris, and the mounds of tiles are less well defined than a wall. The half-period associated with these anomalies averages 5 meters for a burial depth of approximately 4 meters. A proper grid interval would be on the order of 3 meters or less. This sampling interval could theoretically reproduce the anomaly due to a wall buried 2 meters below ground level. However, the pre-Roman archaeological features in the regions actually surveyed were known to be deeper than at least 4 meters, and, therefore, a sample interval of 5 meters was considered sufficient.

Parallel lines were marked out with a separation of 5 meters, Measurements were made at 2 meter intervals along each line. Where the site was relatively free of anomalies, the sample interval was lengthened to 4 meters. The end points of the survey lines were surveyed, but the 2 meter intervals were estimated by pacing. This type of surveying was used in grids Q1-Q102, excepting Q47 and Q100. In grids Q47 and Q100 a 50 meter string marked in 2 meter intervals was substituted for the less reliable pace method. Q100 was surveyed on a 4 x 5 meter grid interval, while in Q47 a 2 x 2 meter interval was employed. In both of these methods, the Nyquist criterion was satisfied if the exploration depths were greater than 4 meters. A 2 x 5 meter paced survey, with read-out and roving sensor mobile (Figure 4, System 1) enabled data to be collected very rapidly.

In the examples of magnetic contour maps, shown in Figures 5 and 6, the contours were traced from the original field data sheets. Field data are taken by recording readings on the coordinate pages of a notebook oriented in the same direction in which the grid is run. Then the pages are pasted together and contours are drawn usually at intervals of 5 units. Thus the contour interval in Figure 5 is approximately 2.5 gammas.

The zero contours of Figures 5 and 6 do not correspond to the zero of the model interpretation, Figure 7. The zero in the field data is in fact the last digit in 80,000 and thus the numbers such as 995 are in fact 79,995 and 5 is actually 80,005. This zero is a function only of the fixed sensor location and is not related to the average field in the area. For technical reasons it was found necessary to use the rubidium system in inverted mode, using the mobile sensor as the counting reference frequency. This results in an inverted contour map. As an example, Q100 (Figure 5) is inverted (The section A'A, Figure 5, has been corrected in Figure 8 for interpretation purposes). Q102 (Figure 6) is in the correct convention. In practice, System 1 allowed the fastest surveys. With this system a typical grid of 80 by 100 meters could be surveyed in four hours.

The accurate survey of grid Q47 was conducted with the cesium system and plotted in conventional read-out units. Later, the values obtained in the field were fed to a computer which converted these numbers to gammas and then contoured the results with an off-line plotter. This magnetic map is shown in Figure 3 and is discussed further in the section on Interpretation.

Interesting anomalies were probed immediately after contouring of the field data. A gasoline motor-powered auger was used for drilling and a probe consisting of 12 millimeter diameter connectable steel rods one meter long with a sharpened first section was used for establishing the depth of stone or tile sources. This probe, called a "spillo", could be used to a depth of 7 meters and with experience the operators could tell by the type of resistance encountered whether the material was sand, pebbles, tiles, or stonework. The drill was slower to use but afforded the added advantage of bringing up fragments of pottery, stone, roof tiles, etc., that in many instances allowed determination of the age of the material giving rise to the anomaly. The locations of "spillo" holes are shown in Figure 5. Filled-in symbols indicate probings which encountered solid resistance (tiles or stone) and the numbers associated with these symbols indicate the depth at which the obstacle was encountered. Open symbols indicate that no solid structures were detected.

Interpretation

The most significant archaeological feature inferred from the magnetometer surveys and confirmed by drilling in 1966 was the NW extent and right angle turn of the long wall. As illustrated in Figure 1, this wall was traced precisely in grids Q30, Q26, Q100, and Q102. The wall shows as a strong linear magnetic feature as seen in Figures 5 and 6. In many places along its length, positive identification was augmented by drilling.

Excavations near and within Q30 (Rainey, 1962) had revealed the existence of a wall buried in this particular location, 1 meter below the ground surface, and about 5 meters high. The wall was constructed of very weakly magnetic sandstone embedded in a matrix of slightly more magnetic silt and clay layers. The upper part of the wall was of Roman construction, but the distinctly different lower part was dated as a 4th century B.C. Greek wall. The wall was excavated as a result of data gathered from a proton magnetometer survey of the area. The wall was mapped from the excavation for a distance of more than 1 kilometer, first with a proton magnetometer and later much more rapidly by a rubidium vapor magnetometer equipped with an audio output (Breiner, 1965). The NW limit in the Parco del Cavallo was not determined precisely until grids Q100 and Q102 were made with the portable differential magnetometers. Grid Q100 was surveyed with a Rb-Rb system, while a Cs-Cs configuration was employed for a grid Q102.

In Q100 (Figure 5), the magnetic lineation is seen to strike first to the SW, and then suddenly to shift 90° to the SE. The lineation is continuous to the SE in grid Q102. This shift suggests that the wall has turned a 90° corner and then strikes towards the Crati River. A three-dimensional model of a wall structure turning 90° in a static magnetic field environment characteristic of southern Italy is shown in Figure 7. The model is based upon the "spillo" holes of Q100 which encountered the top of the wall. The various wall parameters (height, thickness, susceptibility contrast, natural remanent magnetization) were varied to produce the most satisfactory fit to the field data. The profile line A-A' of Figure 8 shows the extremely good fit between the theoretical anomaly and that actually found in the field. The North side of the wall is located directly below the steepest descending portion of the theoretical contours, and the drill data bear this out. The discrepancy of the NW corner between the model and field data is due to a strong anti-magnetic feature running NE just past the NW corner of the wall. We have interpreted this feature as a trace of an old channel of the Crati. Its features may be seen in other grids, notably Q13, Q15, and Q26, where its appearance is linear and well defined. We also note that the direction of magnetization of the best fitting model was parallel to the present direction of the earth's magnetic field. If no natural remanent magnetization is present, the data indicate that the susceptibility contrast between the north part of the wall and the surrounding silt and clay is positive, with a magnitude of 2.0×10^{-3} emu units. This indicates that an ultrabasic rock type was employed as construction material in the wall. This is in marked contrast to the antimagnetic nature of the anomaly found in Q30. Either the wall at Q100 was built of different material from that near the excavation, or the flood plain deposits were markedly different in magnetic character. One additional point seems to bear out the former observation, namely that the drill bit encountered numerous fourth century Greek pottery fragments near the top of the wall, at its western limit, which may possibly indicate that the Roman upper part is absent at this end. The SE striking portion of the wall appears to be at a slightly greater depth of burial than that portion striking SW (see Figure 9). The variation in depths to the wall as found by the "spillo" is presumably an indication of the state of ruin of the wall. In fact the general broadening of the anomaly to the South in Q100 (Figure 5) indicates a broader structure brought about either by collapse of the wall or additional structures at greater depth.

The magnetic contour map of Q47 (Figure 3) shows several typical anomalies of a less distinctive nature than the wall anomaly of Q100. This grid was made in an area of clustered anomalies in which another excavation revealed foundations and roof tiles from small dwellings. The grid is located 800 meters due North of the Masseria Lattughella shown in the location map, Figure 1. As in the anomalies of Q100 and Q102 the "spillo" holes are located precisely with respect to the contour lines, and in three out of five attempts roof tiles and stone obstructions were encountered. These types of anomalies demand the high sensitivity of the gradiometer system for the detection of inflection points, maxima etc., which is necessary for the successful location of features by drilling. These anomalies are typical of ones caused by remanent magnetization.

Summary

The city of Sybaris was not found, but this field season demonstrated that anomalies due to deeply buried archaeological features could readily be detected with high-sensitivity alkali vapor magnetometers. Also, with these light-weight portable instruments, large areas could be surveyed very quickly. The difference mode of operation afforded instantaneous cancellation of extraneous magnetic variations and permitted the use of the maximum sensitivity where needed. This, combined with the digital readout, facilitated rapid plotting and interpretation of the results.

The finding of the turning of the long wall at its southwestern limit indicates that the wall may have had a more important function than had been realized previously. Perhaps it was the outer wall of the 5th to 4th century B.C. city of Thurii or of its port. Although not "sybaritic", this may prove to be a significant find.

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Figure Captions

Figure 1. Map of the region of intensive search on the Plain of Sybaris. Its location in southern Italy is shown in the lower left-hand corner. The magnetometer grids made in this area in 1966 are shown and are labelled Q25, Q26, etc.

Figure 2a,b Calculated anomalous total magnetic field over two-dimensional hypothetical archaeological structure. The curves are plotted as functions of magnetic strike angles.

$\Delta\mu$ = permeability contrast

I = magnetic field inclination

F = total field intensity

Δx_N = half-period of anomaly

In Figure 2a the wall is at a depth of 2 meters; in 2b, 5 meters.

Figure 3. Magnetometer grid no. Q47. The contour intervals are 1 gamma. Contours were calculated on an IBM 7090-94 computer and drawn by a CalComp plotter.

Figure 4. Block diagrams of two configurations for the fixed and mobile magnetometer stations for difference mode of operation.

Figure 5. Part of grid no. Q100. Contours are in intervals of 5 difference units.

Figure 6. Grid no. Q102. Contours are in intervals of 10 difference units.

Figure 7. Anomalous total magnetic field for a wall describing a 90° turn. F = 44,000 gammas, I = 52°, susceptibility contrast = 2.0×10^{-3} emu.

Figure 8. Theoretical fit to data from profile A-A' of Q100. Magnetic parameters are the same as in Figure 7.

Figure 9. Theoretical fit to data from profile B-B' of Q102. Magnetic parameters are the same as in Figure 7.

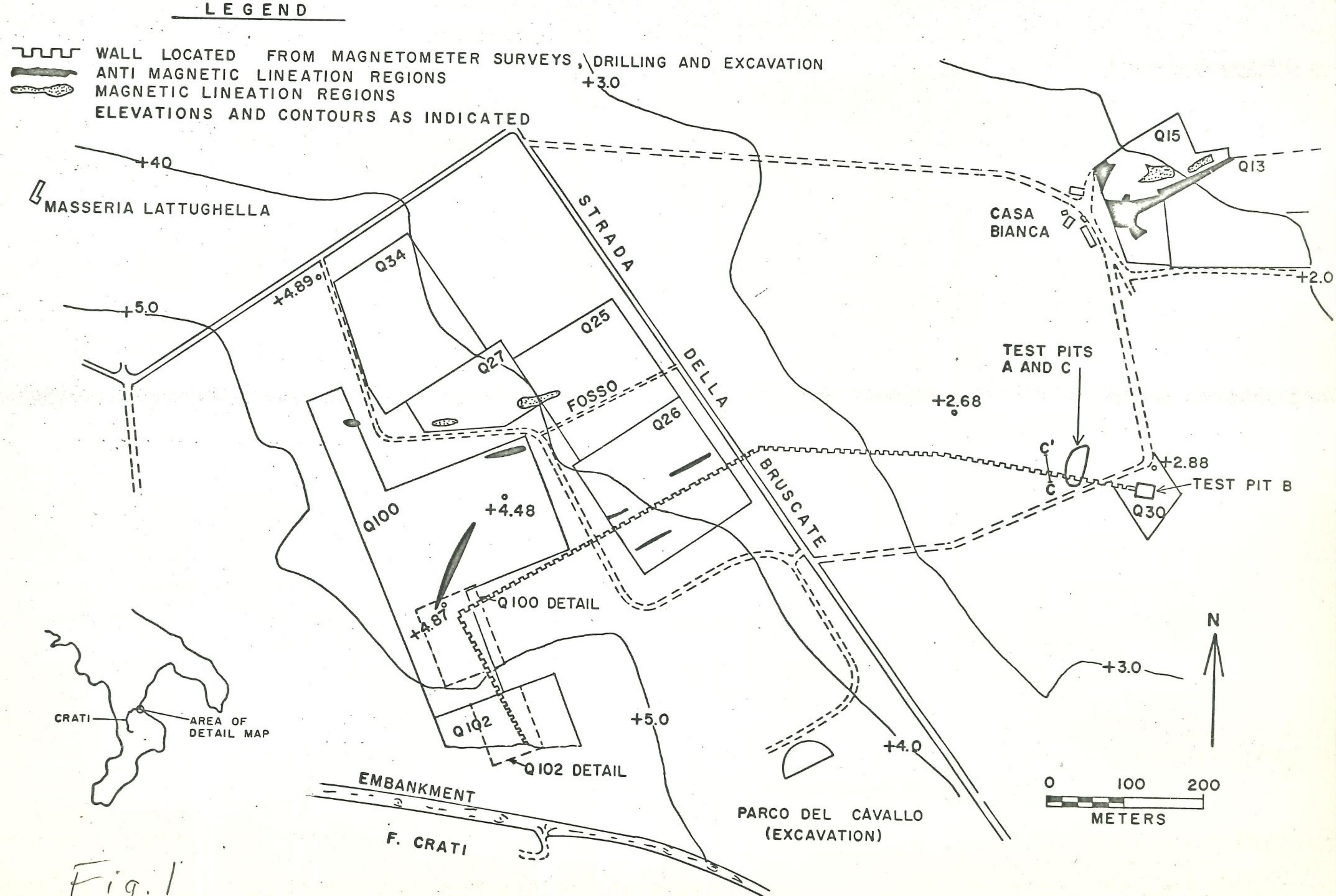
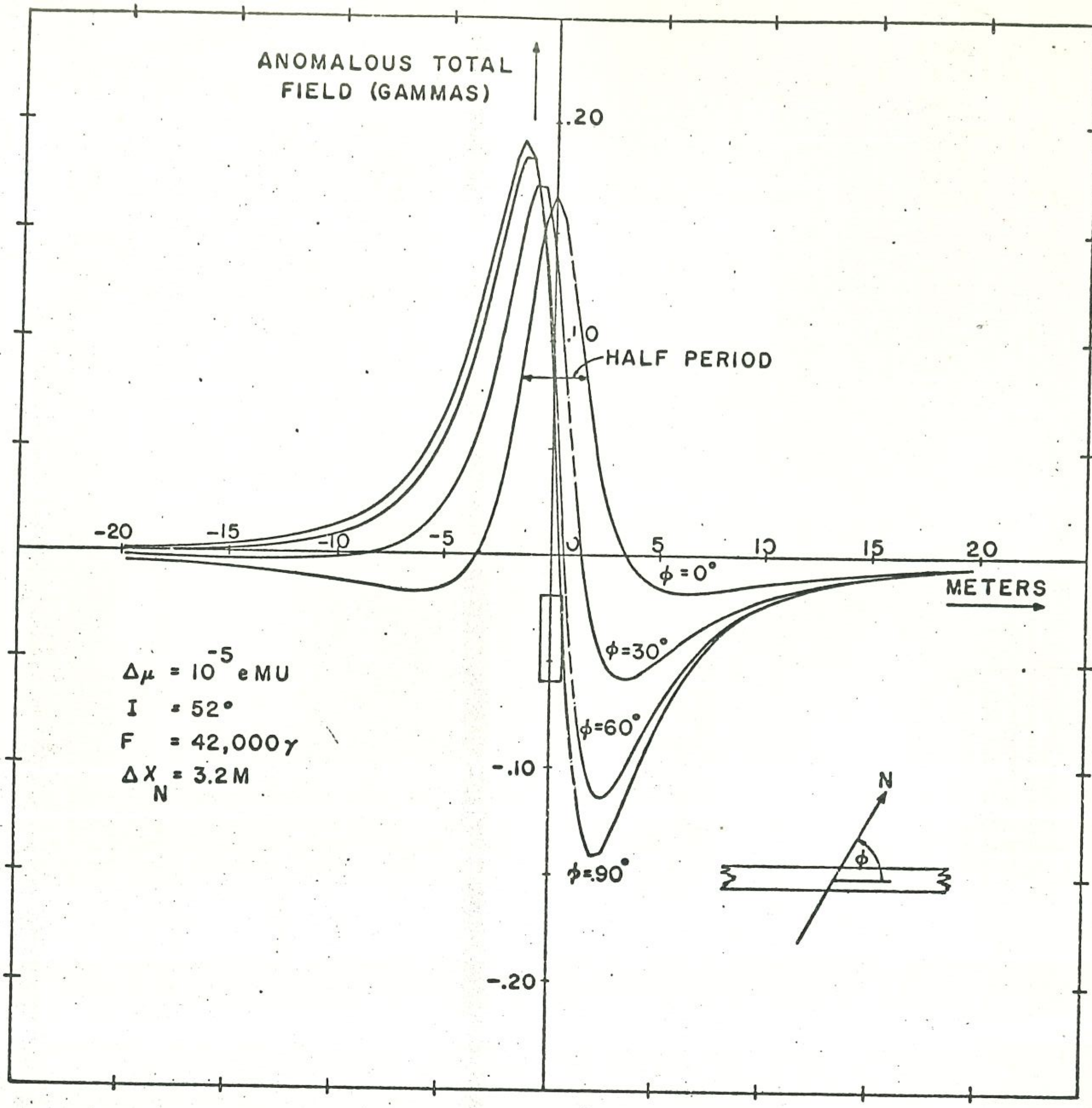

LEGEND
WALL LOCATED FROM MAGNETOMETER SURVEYS, DRILLING AND EXCAVATION
ANTI MAGNETIC LINEATION REGIONS
MAGNETIC LINEATION REGIONS
ELEVATIONS AND CONTOURS AS INDICATED
+3.0
+40
MASSERIA LATTUGHELLA
STRADA DELLA BRUSCATE
Q15
Q13
CASA BIANCA
+2.0
Q34
+4.89
+5.0
Q25
Q27
FOSSO
TEST PITS A AND C
+2.68
Q26
C'
C
+2.88
TEST PIT B
Q30
Q100
+4.48
Q100 DETAIL
+4.87
N
+3.0
CRATI
AREA OF DETAIL MAP
+5.0
Q102
+4.0
Q102 DETAIL
EMBANKMENT
0 100 200
METERS
PARCO DEL CAVALLO (EXCAVATION)
F. CRATI

Fig. 1



ANOMALOUS TOTAL FIELD (GAMMAS)
.20
.10
HALF PERIOD
-.10
-.20
-20
-15
-10
-5
0
5
10
15
20
METERS
φ = 0°
φ=30°
φ=60°
φ=90°
Δμ = 10^-5 eMU
I = 52°
F = 42,000γ
ΔX_N = 3.2M
N
φ

FIGURE 2a

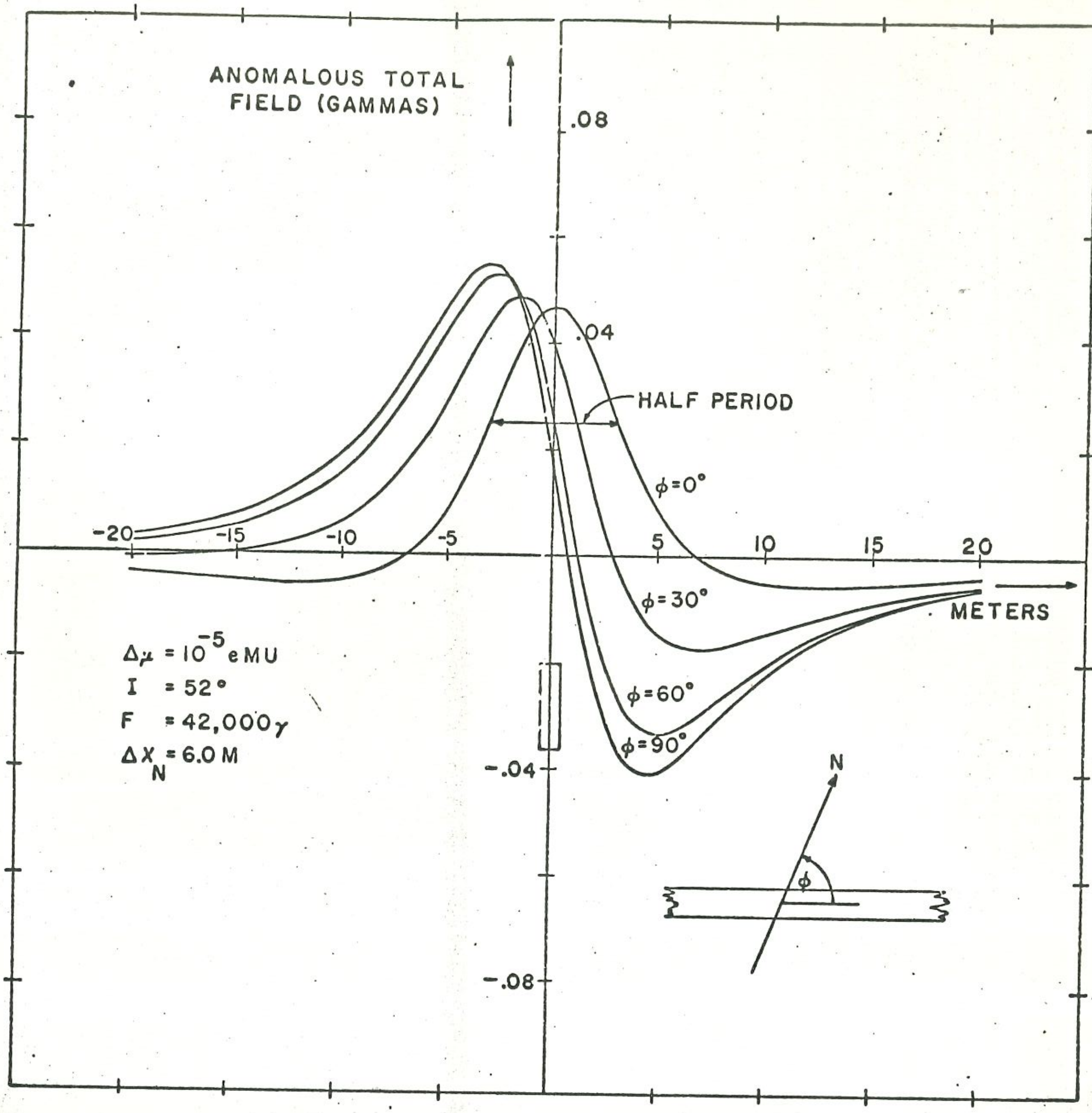

ANOMALOUS TOTAL
FIELD (GAMMAS)
.08
.04
-.04
-.08
-20
-15
-10
-5
5
10
15
20
METERS
HALF PERIOD
ϕ=0°
ϕ=30°
ϕ=60°
ϕ=90°
Δμ = 10^-5 eMU
I = 52°
F = 42,000γ
ΔX_N = 6.0 M
N
ϕ

FIGURE ~~51~~ 26

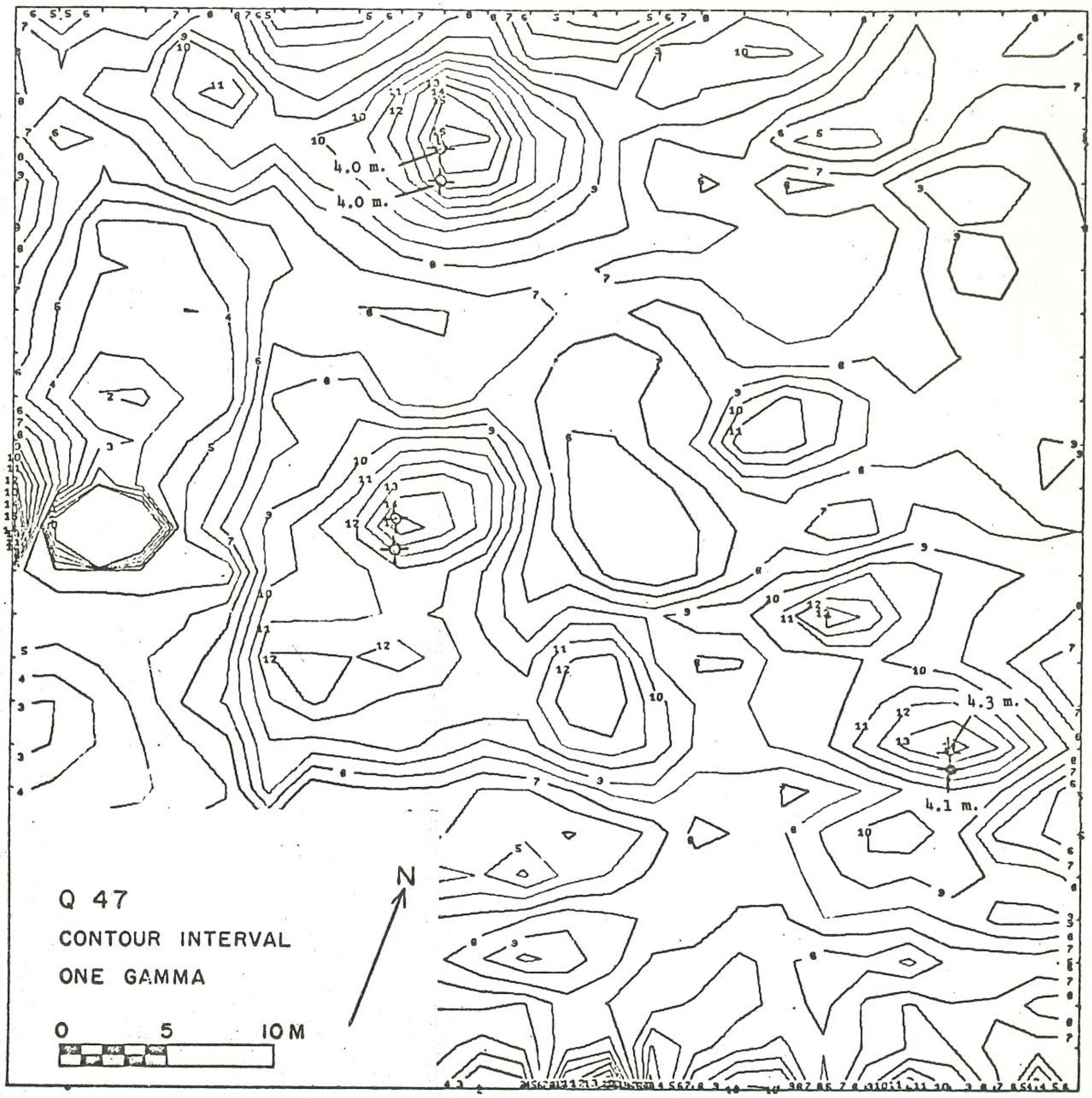


FIGURE ~~5~~ 3

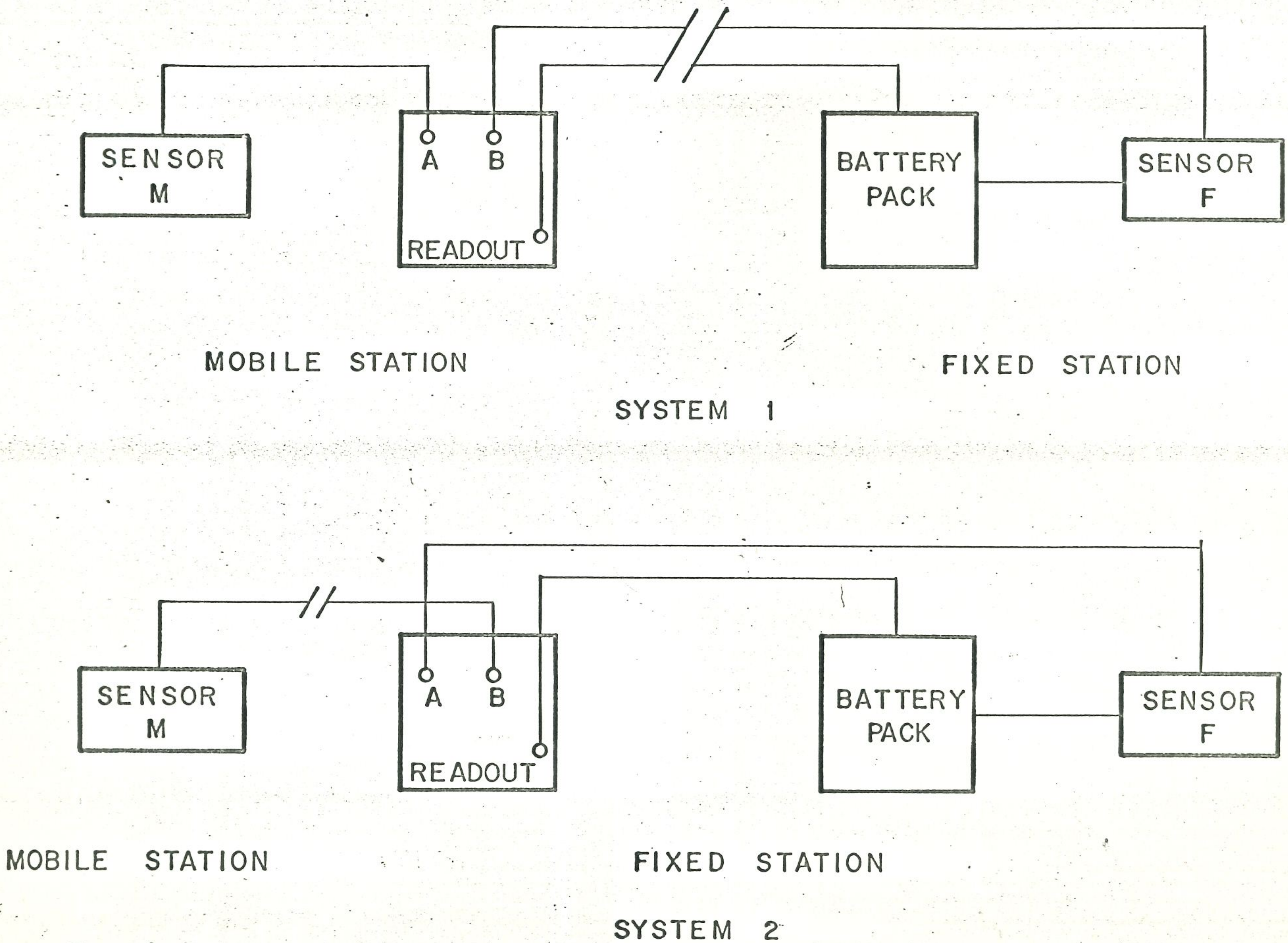

SENSOR M
A
B
READOUT
BATTERY PACK
SENSOR F
MOBILE STATION
FIXED STATION
SYSTEM 1
SENSOR M
A
B
READOUT
BATTERY PACK
SENSOR F
MOBILE STATION
FIXED STATION
SYSTEM 2

Fig. 4

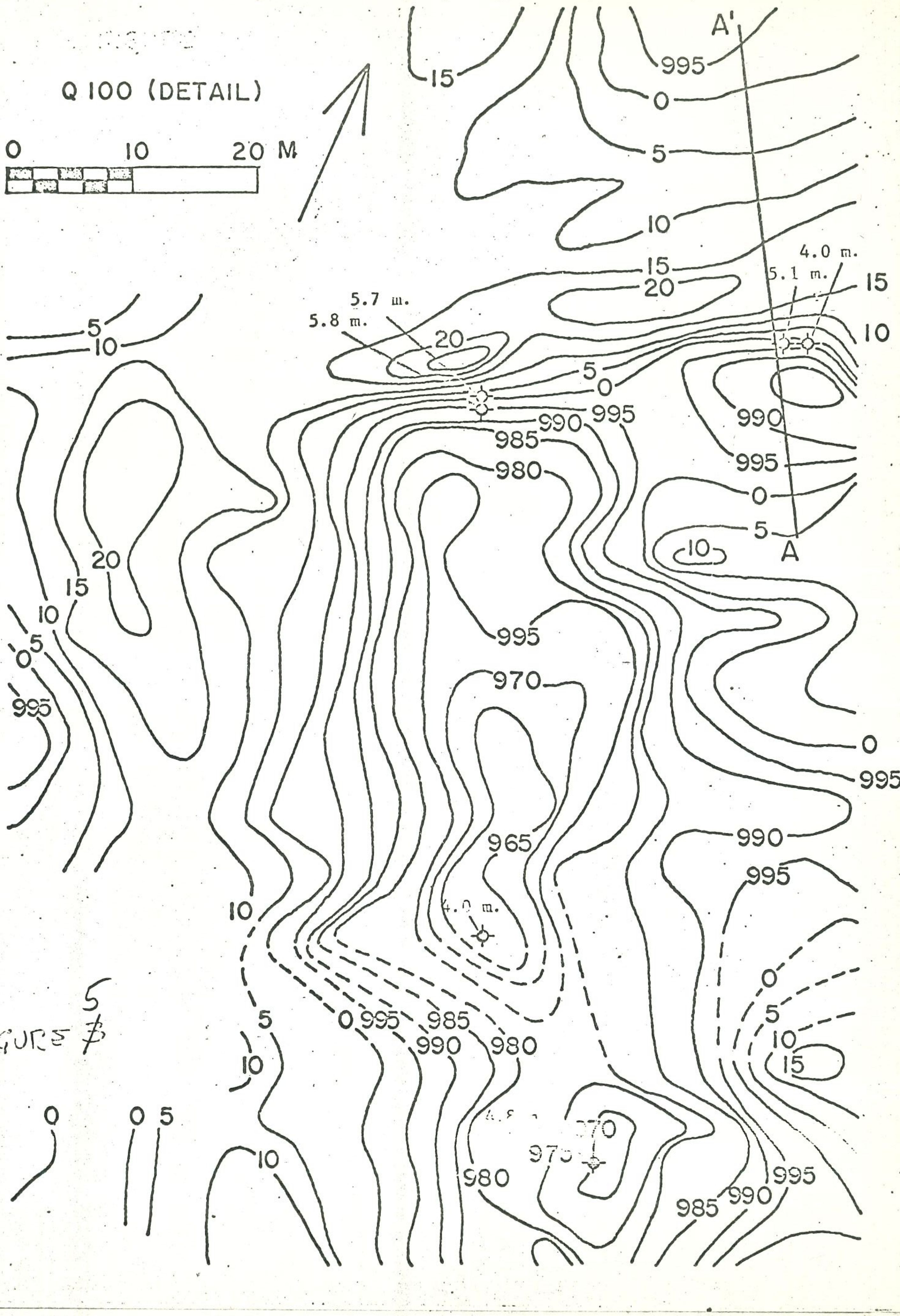
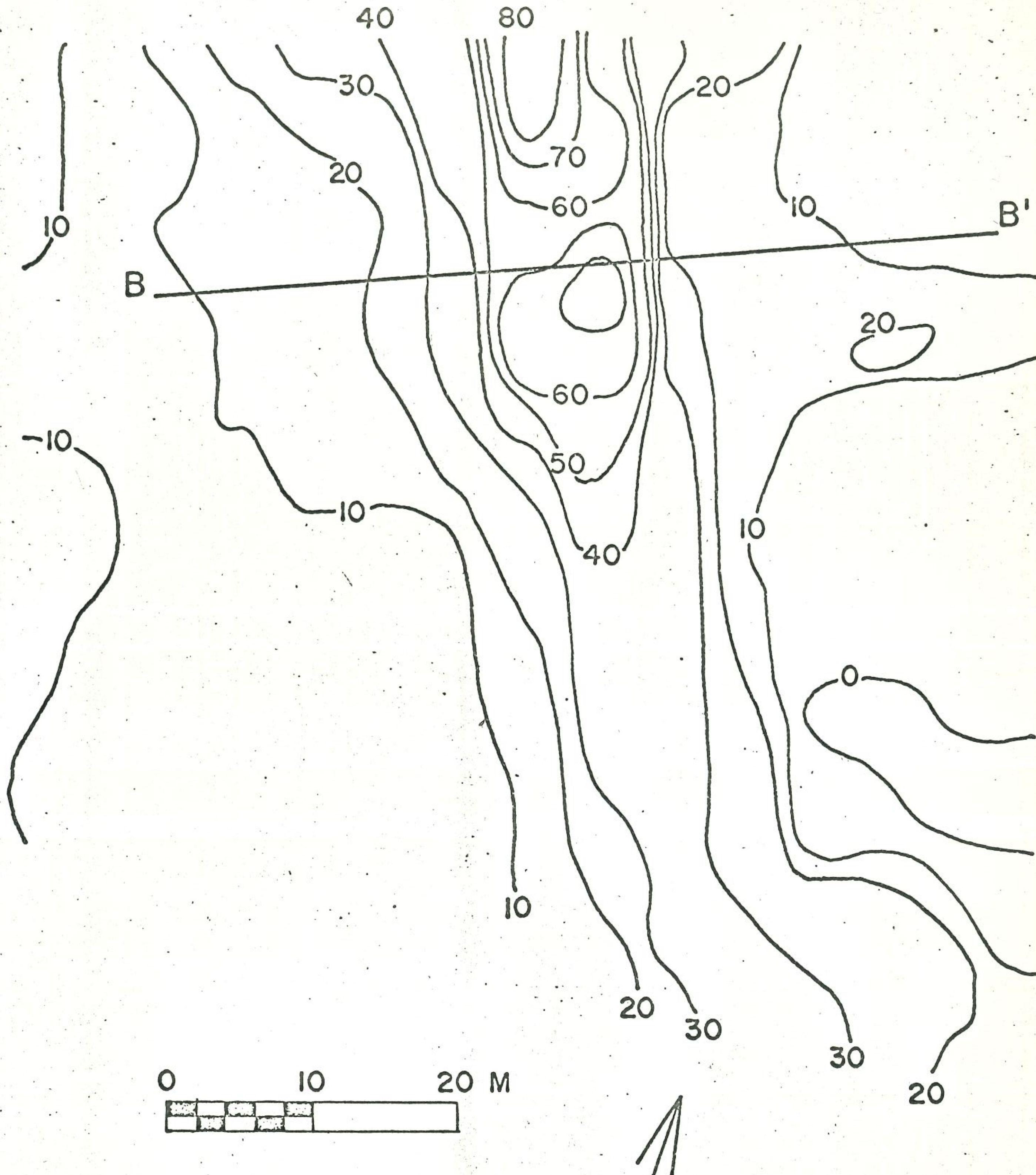

Q 100 (DETAIL)
0
10
20 M
A'
A
4.0 m.
5.1 m.
5.7 m.
5.8 m.
4.0 m.
995
0
5
10
15
20
990
985
980
970
965
975

FIGURE 5



Q 102 (DETAIL)

FIGURE 6

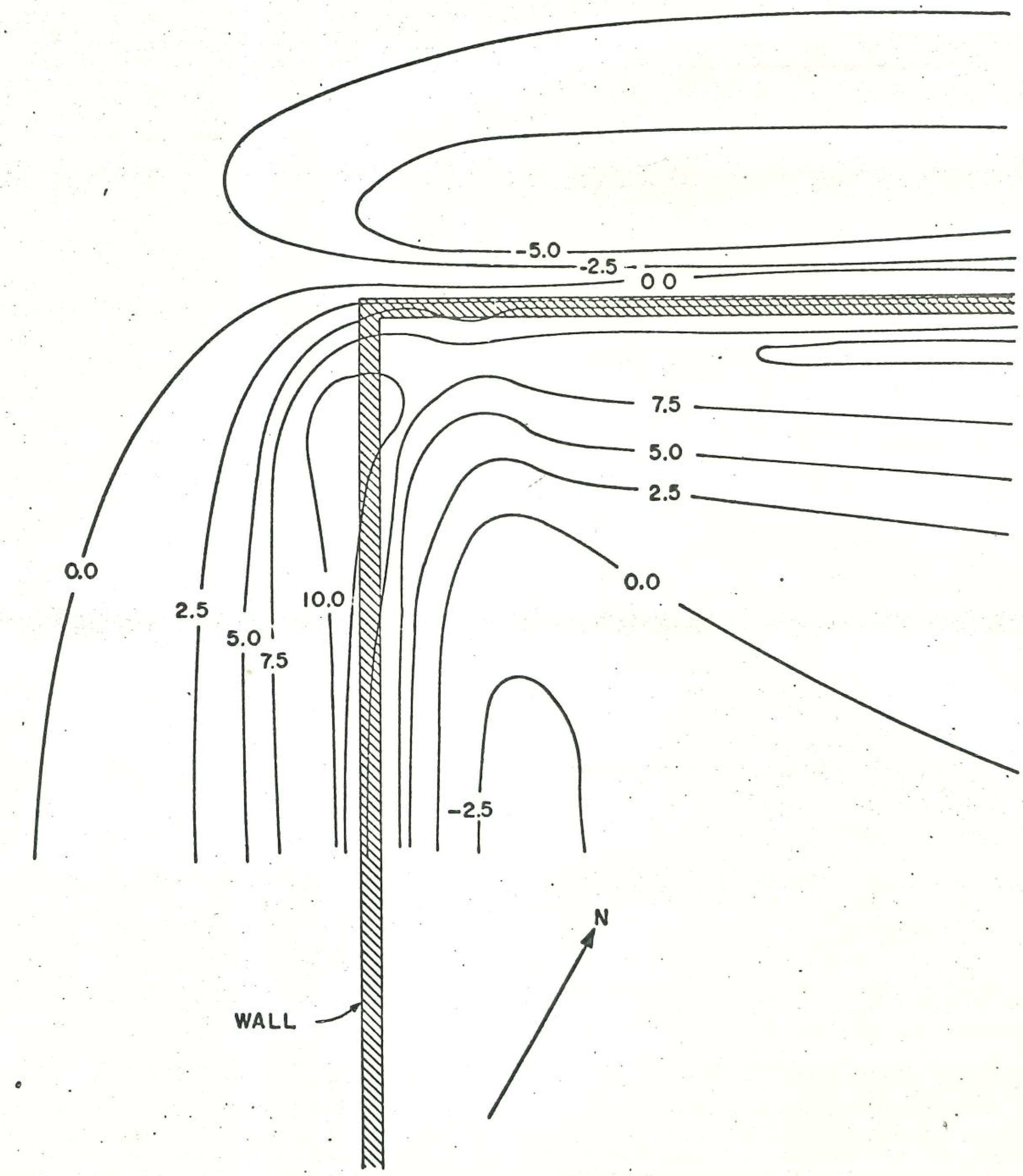


FIGURE 7

CONTOUR INTERVAL 2.5 GAMMAS
WALL DEPTH 5.0 METERS
WALL HEIGHT 4.0 METERS

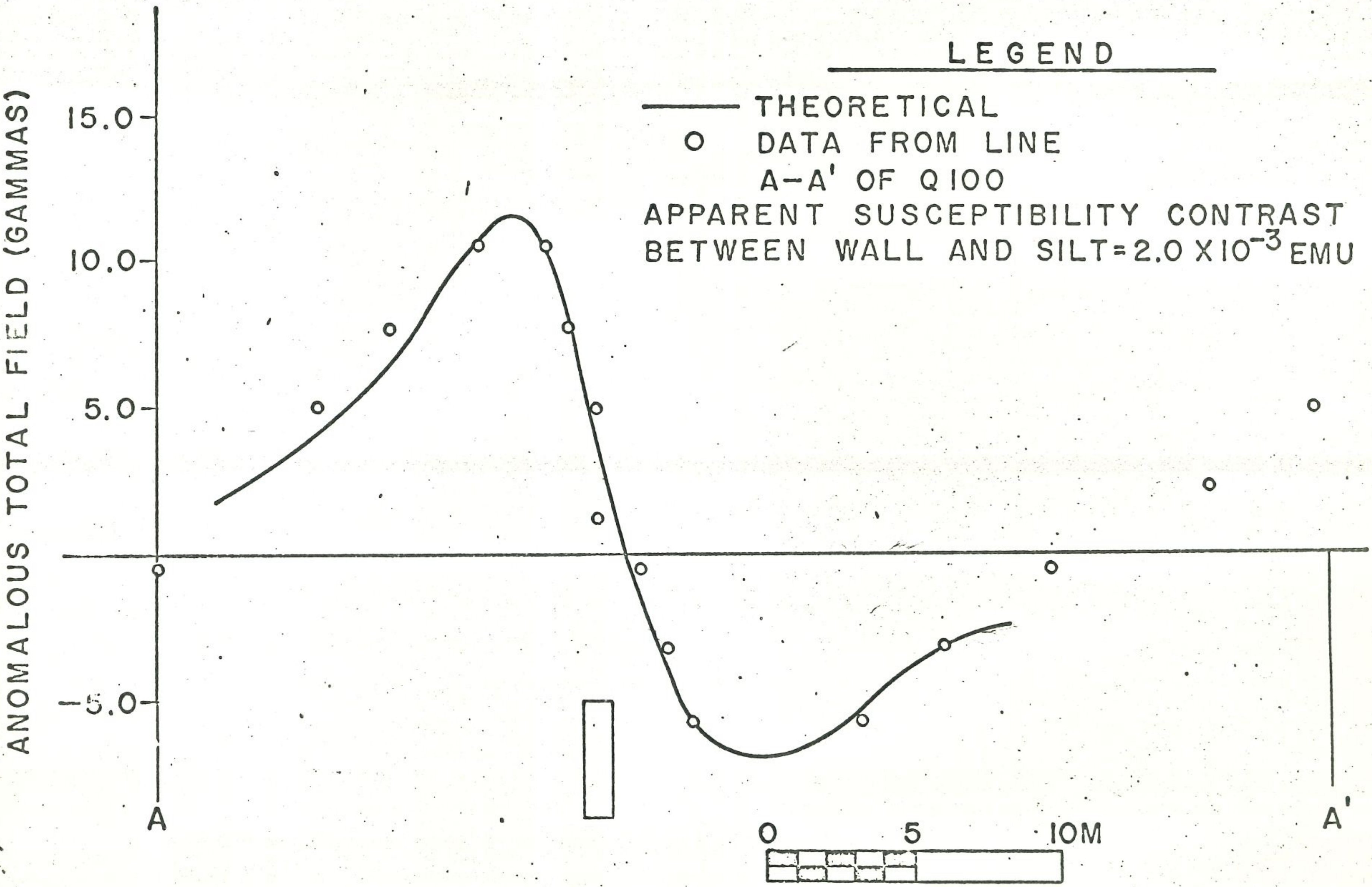

ANOMALOUS TOTAL FIELD (GAMMAS)
15.0
10.0
5.0
-5.0
LEGEND
THEORETICAL
DATA FROM LINE A-A' OF Q100
APPARENT SUSCEPTIBILITY CONTRAST BETWEEN WALL AND SILT = 2.0 X 10^-3 EMU
A
A'
0
5
10M

FIGURE 8

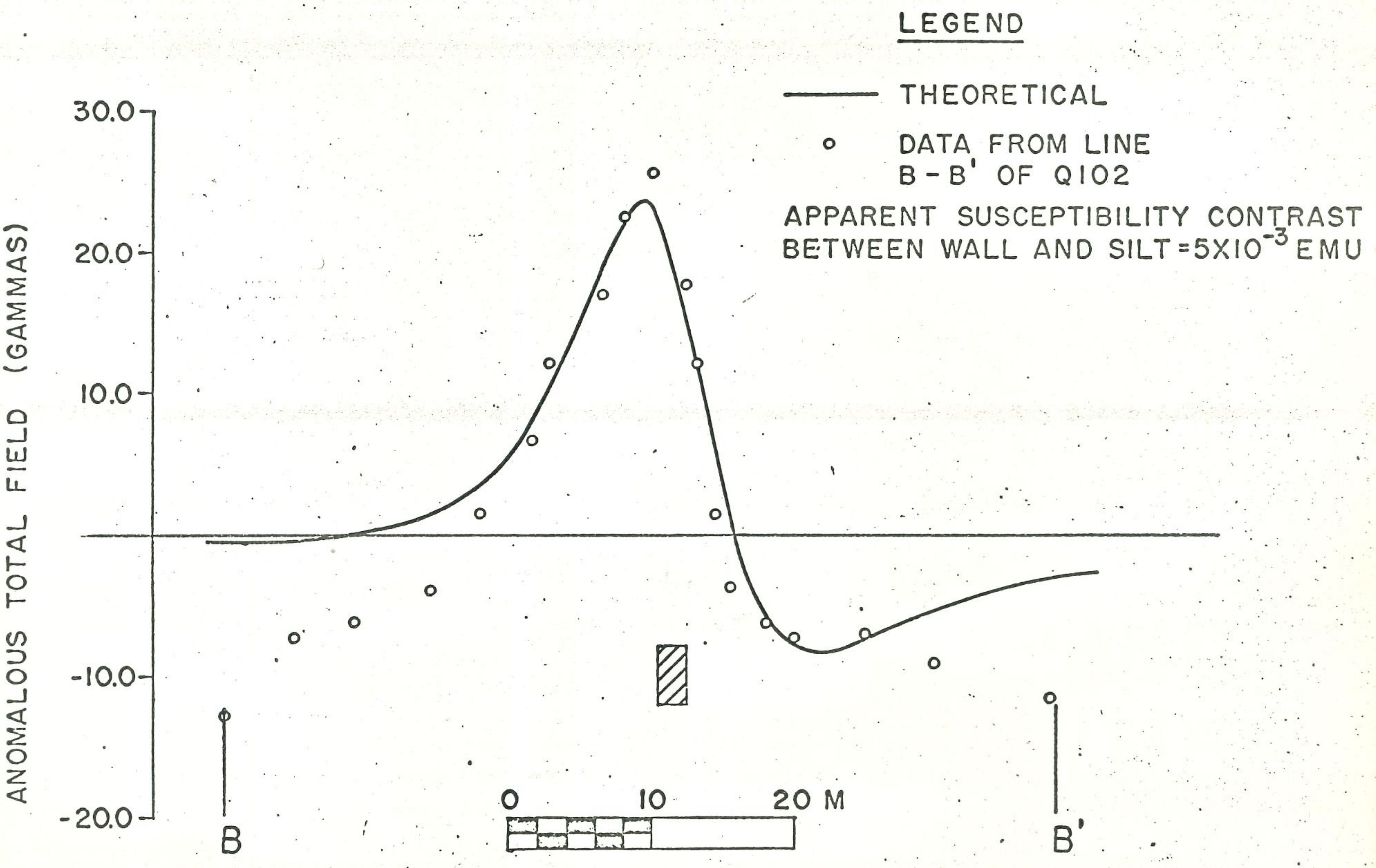

LEGEND
THEORETICAL
DATA FROM LINE
B - B' OF Q102
APPARENT SUSCEPTIBILITY CONTRAST
BETWEEN WALL AND SILT = 5X10^-3 EMU
ANOMALOUS TOTAL FIELD (GAMMAS)
30.0
20.0
10.0
-10.0
-20.0
0
10
20 M
B
B'

FIGURE 9