Technique

December 10, 1965

Dear Dr. Lieban:

This refers to your letter of December 8th, and our request for fund for the "Development of the Rubidium Magnetometer for Archaeological Prospecting". Certainly, I concur entirely in the submission of that proposal. I am sorry there was a slip-up here, so that my name did not appear on that proposal as a principal investigator.

You will note from the enclosed clipping that the rubidium magnetometer is now referred to as the cesium magnetometer. This is because the designing engineers at Varian Associates substituted cesium for rubidium in the sensor so that the instrument will be more stable and less subject to orientation. It has been a great success and we know we can continue to improve the instrument.

The other clipping from the New York Times is an accurate account of our success with the thermoluminescence method of dating pottery and hence, I enclose this also.

Very best wishes,

Froelich Rainey
Director

Dr. Richard W. Lieban
Program Director for Anthropology
National Science Foundation
Washington, D. C.

FGR/vg

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

December 8, 1965

Dr. Froelich Rainey
University Museum
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dear Dr. Rainey:

Your proposal for support of the "Development of Rubidium (or Alikali Vapor) Magnetometer for Archaeological Prospecting" does not bear your signature as principal investigator. Please send us a brief note stating that you concur in the submission of the proposal.

Sincerely,

Richard W. Lieban

Richard W. Lieban
Program Director for
Anthropology

Techniques

NSF

December 14, 1965

Dear Dr. Lieban:

With reference to our telephone conversation today, here are some comments upon our request for funds to develop the rubidium (now called cesium) magnetometer for archaeological prospecting.

We requeste $10,000 for the rental of a newly rebuilt magnetometer, rather than funds for purchase, for the following reasons. Tests of a Varian Associates rubidium magnetometer in the fall of 1964 demonstrated that this type of magnetometer was about one hundred times more sensitive than the proton magnetometer, but the instru - ment we used was not portable and not adapted to archaeology. After extensive discussions with Varian Associates engineers in Palo Alto, we decided to develop a lighter and more effective instrument for our particular purposes, particularly a very small, light readout and recorder which would be an entirely new instrument. The cost of this development was estimated at about $50,000. We agreed to share this cost with Varian Associates since we had no idea, at that point, whether the new instrument would have any practical application. Under that agreement, the University advanced $15,000 to the Varian Associates (funds raised from private sources in Philadelphia) and then agreed informally that we would advance another $10,000 or $15,000 depending upon the cost when the redesign and testing had reached a somewhat more advanced stage.

We here, at the Applied Science Center of the University Museum decided that it would be unwise to purchase an instrument which is now under development, because no one could see what kind of a rubidium magnetometer we would be using a year or six months hence. Thus, the $25,000 to $30,000 which we expected to spend to match Varian Associates' contribution would be in effect sharing the cost of development. We have not yet reached any agreement with Varian about purchase of equipment from them. It may be that part of the $25,000 or $30,000 eventually paid to Varian will be applied against the purchase of instruments, but we hope this can be delayed until we achieve a satisfactory instrument.

You will note that the development of the past year, not only achieved a satisfactory readout and recorder, but also substituted cesium for rubidium in the sensors. This was unpredictable. But the point is that working in collaboration with Varian Associates and sharing development costs, we have arrived at a very successful cesium magnetometer. Moreover, I have had requests for information about this instrument from the Harvard Observatory, the Defense Department and several engineering firms. If the instrument can be used for other types of research outside archaeology, and I expect it can be, then we can expect Varian Associates to put it into production and, of course, the price of the instrument would drop to a fraction of the cost of developing this first model. It is our hope that we can develop a light, portable and effective instrument for archaeology which can sell at about $5,000. But at this point it is not possible to get a specific estimate. I think this is a sensible way to go about such developmental research.

Finally, I should like to point out that developing these instruments is much like the original development of radiocarbon, in the sense that it is not easy to fit together the cost of electronic and physical research with the cost familiar in the field of archaeology. Nor is it easy to get the archaeologists and physicists to see eye to eye. We have been lucky here, at the Museum, with a physicist like Elizabeth Ralph and a chemist like Mark Han, who have now learned to work with several of our interested curators and field directors. Moreover, we have had quite surprising support from industrial firms like Varian Associates, Texas Instruments and Sun Oil Company.

In any case, this kind of coordination of activity is working and we are getting very good results, both with survey instruments and the dating technique.

Very best wishes,

Froelich Rainey
Director

Dr. Richard W. Lieban
Program Director for Anthropology
National Science Foundation
Washington 25, D. C.

FGR/vg

Techniques

December 16, 1965

Dear Dr. Lieban:

This is a note requested in your letter of December 8th, in which I wish to assure you that I am in complete concurrence with the proposal to the National Science Foundation for support of "Continuation of Dating Pottery by Thermoluminescence."

Apparently, the copies of that proposal were signed by Dr. Kidder, my Associate, in my absence.

Most sincerely yours,

Froelich Rainey
Director

Dr. Richard W. Lieban
Director, Program for Anthropology
National Science Foundation
Washington 25, D. C.

FGR/vg

December 16, 1965

Dear Dr. Lieban:

In regard to our awareness of Martin Aitken's work at Oxford, we regret that we did not make this clear in our grant proposal. Never before have we collaborated so closely with another organization in another country, than we have in the course of our experiments with thermoluminescence. In addition to approximately monthly correspondence and the exchange of all progress reports, the time table of visits is roughly as follows:

1962, July - Beth Ralph visited Oxford laboratory, spent one week with Aitken there and in the course of the Radiocarbon Dating Conference, Cambridge, England.

1963, July - Beth Ralph visited Oxford, for approximately five days.

1964, April 1-10 — Beth Ralph had discussions with Aitken in the course of NATO Paleomagnetic Institute meeting, in Newcastle, England.

1964, November 6 & 7 - Martin Aitken visited United States, and us.

1965, September 14 - Ralph conferred with E. T. Hall (Director of Oxford Laboratory) in Boston.

September 21 - E. T. Hall visited us.

December 2 - S. J. Fleming, graduate student now working with thermoluminescence at Oxford, visited us.

We should like to point out that Miss Ralph started experiments in thermoluminescence in September 1958, three years before Oxford began their work. Copies of threeeletters dated 1961 are enclosed in which some of our initial contacts and progress are described. A year after our Applied Science Center for Archaeology was initiated (supported by N. S. F. grants, G -13256, 1961; G-1857, 1962; GS-16, 1963; GS-294, 1964; GS-566, 1965) Mark Han was employed to work full-time on thermoluminescence under the direction of Miss Ralph.

Because of our headstart, many of the pitfalls and difficulties described by Tite & Waine (Archaeometry, 1962) had been tried, eliminated or by-passed in our laboratory. The " Note added in proof", p. 79, supports this statement - we both discovered at this time that it was necessary to make all glow curve measurements in an inert a atmosphere and that consequently most of our previous determinations and conclusions drawn therefrom were meaningless.

In regard to a few specific aspects of the technique, our comments are as follows:

Grinding: Han constructed a simple ball mill grinder (made with roller skate wheels, string, cardboard, etc.) which enables samples to be ground slowly with a minimum of friction and heating. None of the difficulties nor problems experienced at Oxford have been encountered and no luminescence is enduced.

Alpha Counting: We use a more standard method with ZnS applied to a specially shaped plexiglas holder. The same screen is used for all measurements and we have found that it can readily be decontaminated in an ultrasonic cleaner. Oxford uses ZnS on scotch tape supported by a plexiglas ring. This has the advantage that no counts are lost due to absorption by a plexiglas window, but reproduceability varies by 5%. When Miss Ralph saw the difficulty and uncertainty that this method offered while visiting Oxford, she decided that our technique was more reliable.

Various experiments, initially suggested by Miss Ralph have been carried out at Oxford. Among these are the use of blue and $CuCl_2$

solution filters for the redddtion of heat radiation; and the use of an alpha source for artificially-induced thermoluminescence.

In the Oxford reports frequent reference is made to the difficulty of obtaining uniform heating of the samples. It is for this and other reasons that our technique of mounting samples on thin aluminum foils suspended above (and not part of the heating element) was developed. Advantages are as follows:

1) Heating rate over the entire "spot" of thin powdered pottery is uniform. This has been determined with melting point lacquers of equivalent thickness.

2) Heating rate is more rapid and the whole glow curve peak (not just the upward slope) is recorded before the onset of heat radiation.

3) Since the sample is mounted firmly on the aluminum foil with silicone oil, the exact same sample may be used for the measurement of artificial as for the natural thermoluminescence. The advantages of this are pointed out in our grant proposal.

In regard to the referee's comment about decay, we find that Aitken, Tite and Reid (reference 4) are discussing a different type of decay. From p. 66 in the section labeled "Optical Bleaching" they wrote: "Measurement of the natural thermoluminescence of one sample, repeated over several weeks, showed a tendency for the glow to decrease." Then follows a discussion of the effect of exposure to sunlight, etc. This disturbing effect of sunlight has not been detected at all in our laboratory. Perhaps, our silicone oil inhibits this. Some mention is made of experiments with fluorescent light after alpha irradiation, and the following sentence is quoted (p. 70) "When stored in darkness, thermal annealing occurs in the 100-175°C region but is absent in the 250-325°C region." We find this difficult to interpret and possibly contrary to their previous and to our experimental evidence. In the section entitled "Thermal Bleaching," pp. 71-73, after a discussion of curious effects and the problems of heating samples uniformly, Atiken, Tite and Reid state (p. 73) consequently light emitted in the 300-500 °C temperature range results from traps both in this range and in lower temperature ranges; emptying of the latter therefore reduces the thermoluminescence observed in the high temperature region."

It is for this reason that we wait two weeks after x-ray irradiation before measuring the glow curves. During this time the unstable induced luminescence decays but without loss of any stable components. Naturally, we experimented with preheating at low temperatures, but we found also that the heating times, rates and temperatures were too critical for this to be a safe means of eliminating the unstable components A glance at Fig. 9, ref. 4, Tite and Waine, Archaeometry, vol. 5, p. 59, helps to verify this. The individual peaks of curve A obtained with slow heating occur at 87°C, 159°C, 223°C, and 290°C. Each peak may be thought of as a steep hill, separated one from another by deep ravines. Therefore, if one preheats a sample at 150°, one is on a very steep slope of the 159°C peak. It is seen that there is no safe plateau where one could select a temperature without extremely critical control.

In regard to collaboration with those engaged in more basic research in physics on our own campus, we were negligent again in not mentioning the contribution of William E. Stephens, Chairman of our Department of Physics. Miss Ralph's initial experiments were begun at the suggestion of and under the guidance of Stephens and his help and advice have been generously given ever since. At various times, Stephens has called in other appropriate members of the department for informal discussions. Among the most helpful was A. A. Braner who was a member of the department during 1963-1964. At his suggestion, Han and John Gruninger (a graduate student in theoretical chemistry and a member of our Carbon-14 and A. S. C. A. staff) visited Mordechai Schlesinger, Department of Physics, University of Pittsburgh. Both Braner and Schlesinger have been leaders in basic physical studies of thermoluminescence for many years. Among other leaders in basic research, quoted by D. R. Lewis, N. Whitaker and C. Chapman in "Thermoluminescence of Rocks & Minerals," American Mineralogist, Vol. 44, 1959, are Braner, Daniels, Houtermans, Zeller - all of whom have been consulted at least by correspondence. In addition, Takenobu Higashimura, Department of Physics, Kyoto University, spent two days here in

July 1965 and exchange visits are planned with E. J. Zeller, Brookhaven National Laboratory in January.

It is easy to understand why a reviewed of our grant proposal might quote the work accomplished at Oxford and wonder why we, if we have made as much or more progress, have not published more articles (one has recently been submitted to Nature), especially of ammore technical nature. Perhaps, the best answer is that our purposes and approaches are entirely different. At Oxford, the work has been carried on as thesis projects for graduate students - first for M. J. Tite and others, and now for S. J. Fleming. As projects for theses in physics, it has been essential for them to investigate every fundamental aspect of the process even before many of these could be measured, identified, or explained adequately. Our goal has been to develop a workable method of dating pottery to facilitate fundamental archaeological research with the hope that when accurate determinations can be made, many of the basic questions and uncertainties may be resolved. Since the Carbon-14 laboratory is an integral part of our Applied Science Center for Archaeology and since Miss Ralph has been pursuing methodological studies relatedly to the past changes in the inventory of atmospheric C-14 and their basic causes for six years, the ultimate applications of the results of thermoluminescence dating are not being overlooked. For example, we are now obtaining the first indications that this new method of dating may provide a means of assessing the change in C-14 inventory in periods prior to the range of dendrochronology.

Most sincerely yours,

Froelich Rainey
Director

Dr. Richard W. Lieban
Program Director for Anthropology
National Science Foundation
Washington 25, D. C.

FGR/vg

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D. C. 20550

FEB 16 1966

Dr. Gaylord P. Harnwell, President
University of Pennsylvania
Philadelphia, Pennsylvania 19104   GS-1040

Dear Dr. Harnwell:

It is a pleasure to inform you that a grant of $17,000 is awarded to the University of Pennsylvania for the support of a project entitled "Development of the Cesium Magnetometer." This project is to be under the direction of Froelich Rainey, University Museum. It is effective January 1, 1966, for a period of approximately one year.

The amount granted includes an indirect cost allowance of up to 20% of total direct costs, except for Rental and Development Costs, Item D of the attached budget summary, on which an indirect cost allowance of up to 10% applies.

The Foundation requires that this grant be administered in accordance with the conditions, policies, and procedures stated in "Grants for Scientific Research," June 1963 (as amended December 1963), Enclosure R-6, and the attached budget summary.

Please acknowledge acceptance of this grant under the above terms and include in your acknowledgment a reference to the grant number.

Sincerely yours,

JOHN T. WILSON
Deputy Director

Enclosures

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

FEB 16 1966

ASCA
Ralph
any comments?
for me to reply
FR

Dr. Froelich Rainey
University Museum
University of Pennsylvania
Philadelphia, Pennsylvania 19204

Dear Dr. Rainey:

This will inform you that your proposal has been approved for support by the National Science Foundation under the title "Development of the Cesium Magnetometer" in the amount of $17,000 for a period of approximately twelve months.

I am attaching some materials relating to the conditions of the grant and our administrative requirements. Please review them carefully; if you have any questions about them, or if any questions arise during the course of the grant, do not hesitate to get in touch with us.

Several points that arose in our review process may be of interest to you. One, it was suggested that the magnetic properties of the terrain are all-important and the success of the magnetic prospecting can be estimated from geologic factors. In fact, one referee commented that he could rate the project highly meritorious only if it had the advice of a qualified field geophysicist. The other point that was made is that most electrified railroads in Europe are run on direct current, which generates farflung magnetic disturbances; therefore a differential magnetometer would be essential. You may already be aware of these factors, and allowed for them or discounted them; but I felt I should bring them to your attention.

May we wish you the best of success in your research program.

Sincerely,

Richard W. Lieban

Richard W. Lieban
Program Director for
Anthropology

Enclosures (3)

NSF

Rainey

February 22, 1966

[GS 1040]

Dear Dr. Lieban:

First let me say that I am most pleased that the National Science Foundation will continue to support our development of the cesium magnetometer. We are very gratified with the success of our work in developing that instrument and I must say we have gotten quicker results in this field than with most of the intsuments we have been working with in the last four of five years.

Miss Ralph has not completed her experiments with the instrument at the Aberdeen Proving Ground with the Defense Department, because they got snowed out. But I expect this will be completed and I am hoping that that will put the instrument into production.

In reply to your comments in your letter of February 16th, as to the several points about the magnetometer and as a result of the review process, here are our comments and an attached reprint.

In the course of our surveys on the plain of Sybaris, we have paid some attention to the magnetic properties of the terrain. A few measurements made for us at Oxford are reported in the enclosed reprint. In addition to the simplified geometrical interpretation of the wall anomaly described in this article, Miss Ralph has now done some mathematical analyses of deeper anomalies which contribute to their interpretation. (One of these is included in a general article submitted to Science for publication.)

We should very much like to have an additional staff member, especially a field geophysicist, but with our dependence upon year-to-year grants, we have been unable to offer an appropriate position. However, this spring with the cooperation of Varian Associates, and thanks to your financial support toward the rental of the cesium magnetometer, we will have two graduate (Ph.D.) geophysicists assisting with our instrument surveys.

One of the best features of the new portable cesium magnetometer is that it may be operated as a differential magnetometer with two sensors. Even without extraneous magnetic disturbances, differential operation is necessary to utilize the sensitivity required to detect anomalies at depths of five to six meters. These anomalies are of the order of two to three gammas. The preliminary success with the cesium magnetometer in the fall, 1965, and the mode of operation are also described in the article submitted to Science.

Certainly we will keep you posted as to further developments. Incidentally, Mr. Friendly of the Washington Post is doing a feature story on that paper on our work at Sybaris, and since I am reviewing the piece before he publishes it, I will see that he mentions the support of the National Science Foundation.

Most sincerely yours,

Froelich Rainey
Director

Dr. Richard W. Lieban
Program Director for Anthropology
National Science Foundation
Washington, D. C. 20550'

FGR/vg

AS & A

NATIONAL SCIENCE FOUNDATION

WASHINGTON, D.C. 20550

March 2, 1966

Dr. Froelich Rainey, Director
The University Museum
University of Pennsylvania
Thirty-Third and Spruce Streets
Philadelphia, Pennsylvania 19104

Dear Dr. Rainey:

Thank you for your letter of February 22; we are pleased to have this additional information and the reprints for the grant file.

Sincerely,

Richard W. Lieban

Richard W. Lieban
Program Director for
Anthropology

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

Ralph

April 4, 1967

Dr. Froelich Rainey
The University Museum
University of Pennsylvania
33rd & Spruce Streets
Philadelphia, Pennsylvania 19104

Dear Fro:

I am sorry that I have not acknowledged receipt of your final report on GS-1040 before now, but it arrived during the busiest season of our year. It, and the accompanying papers, are interesting and informative, and we are very pleased to have an opportunity to read about your results.

Cordially,

Dick Lieban

Richard W. Lieban
Program Director for
Anthropology

UNIVERSITY OF PENNSYLVANIA
PHILADELPHIA 4, PENNSYLVANIA

Title of Proposal
Development of Rubidium (or Alkali Vapor)
Magnetometer for Archaeological Prospecting

Submitted to
National Science Foundation
Washington 25, D. C.

August 1, 1965

Principal Investigator:	Froelich Rainey	Position:	Director, University Museum
School:	Graduate School of Arts & Sciences	Department:	University Museum
Starting Date:	1 October 1965	Duration:	1 year

FUNDS REQUESTED

$24,000

Corporate Name of University: THE TRUSTEES OF THE UNIVERSITY OF PENNSYLVANIA
(A Pennsylvania non-profit corporation)

Contracting Office: OFFICE OF PROJECT RESEARCH AND GRANTS
3400 Walnut Street, Philadelphia 4, Penna.

Date:____________________

Approved:____________________
Roy F. Nichols, V.Provost

Approved:____________________
Froelich Rainey, Principal
Investigator
Director, University Museum

____
Otto Springer, Dean of the
College

____
Alfred Kidder II, Associate
Director, University Museum
(for Froelich Rainey)

Development of Rubidium (or Alkali Vapor)
Magnetometer for Archaeological Prospecting

ABSTRACT

Experiments with the Varian Associates rubidium magnetometer in 1964 indicated that a more sensitive magnetometer of this type had good potentialities for archaeological prospecting. Funds are requested for the partial support of the design and testing of a new alkali vapor magnetometer engineered specifically by Varian Associates for archaeological prospecting. Funds are also requested for minor apparatus for associated experiments.

I. Description of Research

The development and use of instruments for underground exploration continues to be one of the main projects of the Applied Science Center for Archaeology (abbreviated ASCA). Our aim is to facilitate the finding of archaeological features at known sites and to find others hitherto unsuspected or lost. Extensive surveys have now been conducted (F. Rainey and E. Ralph, New Frontiers in Archaeological Exploration, in press). with instruments already designed for archaeological prospecting - namely, the Elsec proton magnetometer (made by the Littlemore Scientific and Engineering Co., Oxford, England) and the Geohm electrical resistivity instrument (made by the Gossen Co., Erlanden, Germany)- and also with various metal detectors and seismographs. These surveys have afforded a background of experience for the evaluation of the applicability and limitation of each type at diverse sites. The most difficult features to detect are usually those which are deeply buried and are not massive. Since many of these cannot be detected with the instruments with which we have experimented, it was hoped that the development of a sonic device would fulfill this void. (Experiments with seismographs had indicated that the long wave lengths associated with the low frequencies merely bypassed the small archaeological features without exhibiting detectable refraction or reflection). The sonic device has been discussed in previous proposals. Much information about the problems involved has been obtained, but a workable device has not yet been achieved. The sonic work has been supported by $9695 from NSF grants and $62,981 from industrial sources. The project may be terminated by September 1, 1965, or, if not, will be continued with funds from industries which are interested because of other potential applications.

Fortunately, this void in detection technique may now be approached in another way because of the development of the more sensitive optical absorption magnetometers. Two of these are the Texas Instruments (Apparatus Division, P.O.Box 6015, Dallas,Texas) metastable helium magnetometer and the Varian Associates (Instrument Special Products, 611 Hansen Way, Palo Alto, Calif.) rubidium magnetometer.

In collaboration with Lee Langen and Sheldon Breiner of Varian Associates, experiments were conducted with various configurations of the Varian V-4938 rubidium magnetometer first for 3 days in May at Fort Lennox, Île-aux-Noix, Canada and then for 2 weeks on the plain of Sybaris, Calabria, Italy. The Sybaris project, including the reasons for the importance of this type of instrument for finding deeply buried walls on alluvial plains such as Sybaris, is described by E. K. Ralph in the attached copies of two articles entitled "Comparison of a Proton and a Rubidium Magnetometer for Archaeological Prospecting" and "The Electronic Detective and the Case of the Missing City". An article by Sheldon Breiner is in preparation.

The tests served a two-fold purpose - first, to determine the applicability of a more sensitive magnetometer and secondly, to find out what changes in instrumentation were required for this application. The detection of deeply buried structures (4 or more meters deep) which exhibited anomalies of only 3 gammas was successfully achieved (see Q#15, Ralph reports). The tests indicated that a more sensitive magnetometer and one which is incidentally also more rapid to use will afford a means of detecting and mapping out (in the form of magnetic contours) deeply buried cities such as Sybaris. The second phase is now in process - the redesign of the instrument, primarily the detection circuits, for archaeological prospecting. As described by Ralph (<u>Expedition</u> article), the instrument used last year (which had been designed for other purposes) was sufficiently workable to determine its applicability, but was not portable. Also the results obtained as graphs on the recorder were difficult to transfer to plots of magnetic contours.

Varian Associates is now redesigning the instrument to eliminate this and other difficulties experienced in the field tests.

The major changes are as follows:

1) The readout and recorder are being replaced by revised circuitry and dual digital counters. Readings may then be taken from a single sensor with one counter or simultaneously with the two counters from two sensors - either total values of each or their difference may be recorded manually. (The latter is required to negate external magnetic changes when greater sensitivity is desired). This new unit will be small and light in weight, approximately 10 lbs. where as these components previously weighed 52 lbs. and required a generator for power.
2) The sensor is being improved for greater stability, especially, in regard to ambient temperature changes. If caesium is substituted for rubidium, the instrument will probably then be called an "Alkali Vapor Magnetometer".
3) All circuits will be battery-powered with solid Ag-Cd batteries, 24 volts.

These revisions are well underway and the first tests are scheduled for August 16, 1965 in the Southwestern U.S.A. More extensive tests at more suitable sites are then planned for Italy from mid-September through October.

For this next stage of development, we are contributing $15,000 from University Museum funds. In agreement with Varian Associates, we then plan to rent this new model at a cost of $10,000 for tests and surveys. Depending upon the results of these tests, the additional $5,000 requested will either be applied toward the purchase of the instrument and/or toward the cost of subsequent redesigning. It is hoped that subsequent changes will be minor.

The total sum anticipated as our contribution to this development work ($30,000) may seem large for one instrument, but in view of the fact that it will be the first of its kind and that when industrial developmental costs are considered, our contribution is a small fraction. To our knowledge this will also be the first major contribution in instrumentation made specifically for archaeological prospecting in the U.S.A.

We are appealing to the NSF for the remaining $15,000 required because all possible Museum and private sources that we know of have been exhausted.

With the availability of one hundred times greater sensitivity for the detection of changes in magnetic intensity provided by the improved rubidium magnetometer, several new experiments may be carried out. In the course of four seasons of work with the proton magnetometer on the plain of Sybaris in Italy, we have observed that the magnitude and occasionally the positions of anomalies vary from year to year, or perhaps from season to season. We believe that this is caused by variations in natural ground currents. To verify this, to learn more about the relationships between the two types of physical changes and the interpretation of anomalies, we propose to monitor the magnetic intensity (just above the ground) and these small ground currents simultaneously.

It is possible that the measurement of telluric currents will provide a means of detection of archaeological features at certain sites. For example, at Sele near Paestum, Italy, a survey with the proton magnetometer was attempted in the spring (1965) by E. Ralph (in collaboration with Dr. Paola Zancani). Without moving the detector bottle, changes in magnetic intensity as large as

30 gammas were recorded. For various reasons, the possibilities of magnetic storms or peculiar effects from distant power lines were ruled out as the cause. The buried walls sought were expected to be between 1 to 2 meters deep, about at the ground water level, and also immediately under a layer of ash 5 to 10 cm thick from Vesuvius' eruption in A.D.79. It is possible that this ash layer just above the water table provides a path for telluric currents. The measurement of these and the finding of discontinuities may provide a simple means of detection of the buried structures.

It is for these reasons that we are asking for $2500 with which to purchase telluric monitoring or measurement apparatus.

II. Facilities

Laboratory space for ASCA is located in the University Museum. The facilities and personnel of the Electronics Shop in the Department of Physics are available for assistance with repairs and minor design changes. The University Museum is currently supporting 17 field expeditions. At the sites suitable for instrument tests and surveys such as the plain of Sybaris, Italy, guidance by archaeologists and living costs are provided. New sites anticipated for future excavations (to be supported by expedition funds) offer challenges for instrument surveys. Excavations at two sites on alluvial plains-namely Helice, Greece and Karataş-Semayük near Elmali in Lycia, S.W.Turkey would not be undertaken without previous location of buried features by instrument surveys. From what we know of these two sites, we believe that the new rubidium (or alkali vapor) magnetometer will prove to be the best instrument obtainable for pre-excavation surveys.

III. Personnel

Biographical sketches and bibliographies of F. Rainey and E. Ralph are attached.

a. Froelich Rainey, Principal Investigator, Director of ASCA (15% of calendar year time).

b. Elizabeth K. Ralph, Faculty Associate, Associate Director of ASCA (30% of calendar year time).

c. Professional Assistant, Design Engineer from Varian Associates (20% of calendar year time).

IV. Budget

Equipment

Rental of the improved Varian Associate rubidium (or alkali vapor) magnetometer designed specifically for the University Museum for archaeological prospecting	$10,000
Contribution toward the purchase of this instrument	5,000
Other electronic equipment such as battery-powered millivoltmeters and amplifiers for monitoring ground currents in connection with magnetic surveys	2,500

Travel

For ASCA physicist and Varian engineer to test sites in southwestern United States and Italy	2,500
Total, direct costs	$20,000
Univ. of Penna. overhead (20% of direct costs)	4,000
TOTAL	$24,000

V. Current Support and Pending Applications

A. Current Support

1. Field Expeditions

a. Onion Portage, Alaska, 1965 Season, NSF Grant to Brown University, approximately $30,000. (F. Rainey, Principal Investigator for summer 1965).

b. F. Rainey - directs the expeditions to Sybaris which are supported by privately raised funds.

2. Radiocarbon Laboratory

a. Univ. of Penna. annual support = $28,000. This includes salary of E. K. Ralph.

b. C-14 measurements of Known Age Samples, Dec.1964 to 1966, NSF GP-3778, $24,950 annually (E. Ralph, Principal Investigator).

3. ASCA

Dating of Pottery by Thermoluminescence, Sept.1964-1965, NSF GS-566, $20,000. (F.Rainey, Principal Investigator, E. Ralph, Faculty Associate, M.Han, Research Chemist).

4. Dept. of Metallurgy in collaboration with ASCA

Research in Metallurgy and Archaeology, Aug. 1965-1967, NSF P-17186, $12,800 annually (R. Maddin, Principal Investigator, E. Ralph, Faculty Associate).

B. Pending Applications

1. Continuation of Dating of Pottery by Thermoluminescence, Sept. 1965-1966, to be submitted to NSF, $16,826 requested, (F. Rainey and E. Ralph, Principal Investigators, M. Han, Research Chemist).

2. Development of Rubidium (or Alkali Vapor)Magnetometer for Archaeological Prospecting, Oct.1965-1966, to be submitted to NSF, $24,000 requested (F.Rainey, Principal Investigator, E. Ralph, Faculty Associate). (Present proposal).

3. Information Center and ASCA Newsletter, Oct. 1965-1966, to be submitted to NSF, $13,132 requested, (F. Rainey, Principal Investigator, E. Ralph, Faculty Associate, J. Flamm, Research Assistant).

These proposals are not being considered nor will they be submitted to other possible sponsors while they are being considered by the NSF.

The ELECTRONIC DETECTIVE and the Case of the MISSING CITY

By ELIZABETH K. RALPH

The expeditions in search of Sybaris, directed by Prof. F. Rainey (University Museum), have been conducted in collaboration with Dr. G. Foti (Superintendent of the Antiquities Department of Calabria), Eng. C. M. Lerici (Director of the Lerici Foundation of Rome), and Eng. and Mrs. E. Mueller (of Cassano Ionio). From these and from other organizations, the following persons participated actively in the 1964 program:

From the Superintendency: O. Miggiano and S. Pellegrino;

From the Lerici Foundation: F. Brancaleoni, F. Serra, B. Pastore, U. Cesarini, and D. Achilli;

From Cassano Ionio: G. Loisi, D. Falcone, and workmen;

From Varian Associates, Palo Alto, California: S. Breiner;

From The University Museum: F. Rainey, E. Mueller, D. Ridgway, and E. Ralph.

To these persons and organizations we should like to express our gratitude, and also to Mr. O. Bullitt of Philadelphia for his generous financial support.

ELIZABETH K. RALPH graduated from Wellesley in 1942. For the next seven years, she worked for an electronics firm where her duties included control of electroplating and heat treating, design and supervision of electrical inspection equipment, development of electronic apparatus and miscellaneous production engineering. During the following two years, she studied at the University of Pennsylvania for her M.S. degree in Physics. Since 1951 she has been on the staff of the University of Pennsylvania, and is now a Research Investigator in Physics and Associate Director of ASCA, University Museum. Present projects of ASCA include C-14 dating, tree-ring dating, experiments with the thermoluminescent technique of dating pottery, and the use and development of instruments for underground exploration. The latter endeavor has led to field trips in Italy.

For several years Dr. Rainey and various assistants have been looking for the ancient Greek city of Sybaris—not with eyes alone but with electronic, geophysical, and other accouterments. Now, at last, a new device has been developed, the Varian rubidium magnetometer, that may be capable of finding the city. But, even with this new assist from excited electrons, it is still not an easy job. Some of the reasons why Sybaris can not be found from an armchair with the help of the ancient references are these:

First of all, many scholars have studied the Classical sources (some have even received Ph.D.'s for their good work), and from these studies we now know about the lives, habits, habitations, and colonies of the Sybarites, but no one has been able to ascertain precisely where the city was.

Secondly, the plain of Sybaris—the region where Herodotus and others said the city should be—is very large, approximately eighty square kilometers *and* the archaic sixth century B.C. city is buried at great depths, five to six meters.

Thirdly, sites where the descendents and the predecessors of Sybarites may have lived have been found in the surrounding hills. With these included, the area of search becomes many times larger.

Fourthly, Sybaris was destroyed by the unneighborly Crotoniates in 510 B.C. In that fateful year, according to Strabo, it was buried by diversion of one of the rivers, the Crati or the Coscile, but it may not have been buried completely or, if so, not deeply enough to prevent the Greeks who started building again in the fifth century from mixing up some of the evidence. Fortunately, in regard to making our task easier, these inhabitants of the fifth century B.C. gave their city a new name—Thurii. To compensate for this facileness, however, the Thurians built their city at approximately the same elevation as that of Sybaris. Even though our instruments and their operators are now well trained, it is difficult for them to differentiate between the buried walls of Sybaris at depths of 4¼ to six meters and those of Thurii which might be immediately above or, at comparable depths, resting on their own underpinnings.

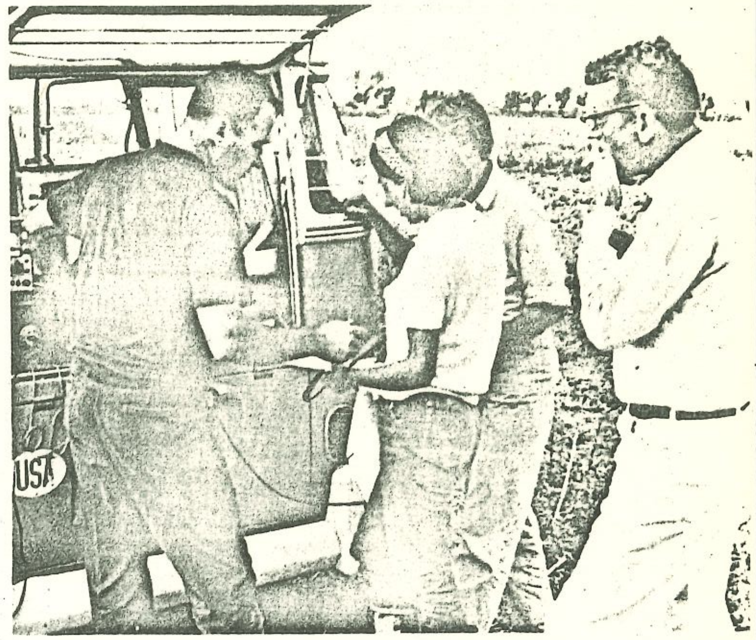
The Romans, naturally, followed along later and named their city Copia Thurii. Fortunately for our instruments, many of the Roman structures are massive and extend upward to within one to three meters of the surface. Therefore, they are much easier to detect and may be distinguished from their more elusive Greek forerunners by the magnitudes of the magnetic anomalies.

Fifthly, the elusiveness of Sybaris is increased by the high water table. The sybaritic level of occupation is at least three meters under the fresh-water table, and well below the present sea level. This may have been caused by various disturbances, but most likely from tektonic movements which initiated tilting of the land, subsequent blocking of water bodies, consequent deposition of great quantities of fine blue-gray-green clay, and concordant land subsidence.

The soil and water conditions, in combination with the depths of the structures sought, dictate the types of instruments to be used. On the plain of Sybaris the water table is higher than all but the highest remaining Roman constructions. Therefore, electrical resistivity methods are ruled out. Instruments based on wave propagation such as standard geophysical seismic detectors function well to find earth layer changes, as they are designed to do, but the long wave lengths associated with the low seismic frequencies bypass without "seeing" the comparatively small archaeological features above them. Sonic detectors, operating at frequencies higher than seismic, offer possibilities, but are not yet ready for field use. The important basic method of detection which remains and which *is* applicable for the deeply buried structures on the plain of Sybaris is that of magnetic contrast.

As a result of nuclear and other research conducted for entirely different purposes, there are detectors of magnetic intensity available that are rapid and easy to use. Proton magnetometers have now been employed for archaeological prospecting for several years and the Oxford Elsec instrument made by the Littlemore Scientific Engineering Co., Oxford, England (see M. J. Aitken, *Physics and Archaeology,* Interscience Publishers, 1961) was designed specifically for this purpose. The Oxford units are capable of measuring changes of one gamma, which is a small unit in magnetic parlance (10^{-5} oersteds), but on the plain of Sybaris, it is not quite small enough for the detection of the deeply buried archaic Greek structures where the magnetic contrast between walls and earth is comparatively small.

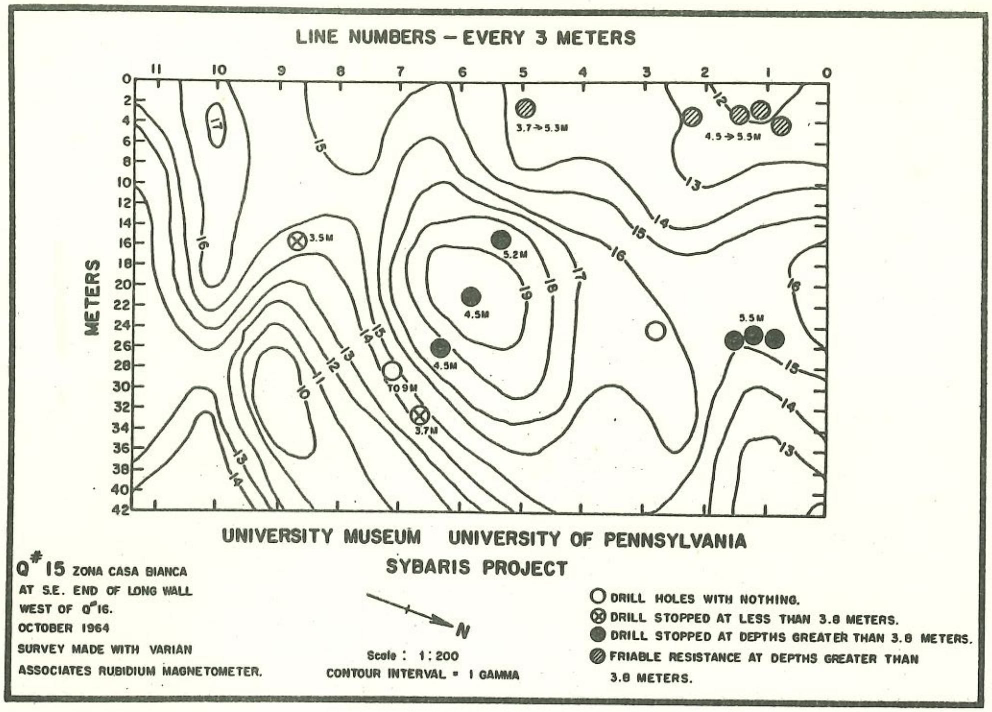
Eventually, the next step was to find or develop an instrument with greater sensitivity. But, as with many obvious things, there were complications such as natural diurnal magnetic variations of magnitudes comparable to the anomalies sought, shorter micro pulsations, variations due to uneven ground, etc. However, many of these disadvantages have been overcome or circumvented with the new Varian rubidium magnetometer. (See V-4938 data sheet, Instrument Special Products, Varian Associates, 611 Hansen Way, Palo Alto, California.)



Sheldon Breiner (left) explains the operation of the Varian Associates rubidium magnetometer to Francesca Serra, Beth Ralph, and Fro Rainey.

The Varian rubidium magnetometer was designed primarily for measuring the earth's magnetic field from planes, rockets, and satellites. Our joint tests (in Canada in May and in Italy in October) were among the first both to assess the applicability of an instrument with greater sensitivity for archaeological prospecting and to determine what arrangement of and what changes in components are needed for this adaptation.

The rubidium magnetometer is more sensitive than the proton magnetometer because of the fact that for a given magnetic change, the resultant change in frequency—the property that the instrument detects—is a hundred times greater. The two types of magnetometers detect this information in different ways, both of which, however, are based upon energetic movements within atoms. The proton magnetometer is so named because protons in the alcoholic detector bottle (after an initial "upset" with an artificial magnetic field supplied in a surrounding coil) gyrate at speeds that are proportional to the earth's magnetic field. The rubidium sensor is appropriately filled with rubidium, which, when heated above room temperature, happens to be both a vapor and to have well-defined lower energy states. The changes in energy levels, due to magnetic changes, are, therefore, more readily detected. In use, the electrons are first disturbed by a so-called



Plot of magnetic contours of grid #15 obtained with the rubidium magnetometer. (The small numbers beside the drill holes represent the depths, in meters, at which the drill was stopped by structures or encountered less resistant deposits.)

optical frequency. After this upset, the energy levels which are, in effect, the residences of the electrons, are readily "split" into sublevels and the amount of splitting is dependent upon the magnetic intensity beneath the rubidium sensor. The splitting is measured as a frequency which corresponds to the difference in energy between two particular sublevels. For the isotope Rb^{85} the resultant frequency change due to the separation between sublevels is one hundred times greater than the gyration frequency of the protons for a unit change in magnetic intensity.

Theoretically, the proton magnetometer is capable of detecting changes of one gamma, but, in practice, only a change of four gammas or more provides usable information. This could be reduced with dual detector arrangements and more elaborate circuitry, but with consequent loss of portability (i.e. my aching back!). In addition to the extra sensitivity available in the rubidium instrument, the fact that readings are taken continuously (and recorded) enables us to survey a given area about four times as fast.

It should now be easy to find the archaic Greek walls. In practice, however, in these initial tests, there were more pitfalls than progressions. The first test of the rubidium magnetometer was planned over the Long Wall, a known anomaly. The recorder and circuits were not yet battery-powered so that this was also the first test under load of a second-hand generator which I purchased in Rome. Our first problem was apparent immediately. The generator's speed, voltage, and frequency were all variable, and variable additionally when the load (that is, the instrument) was attached. This latter variation created a bad problem because it necessitated the setting of the voltage too high at the start, so that when the instrument was attached, its load would cause it to drop to the proper operating value. This was unsafe, however, for the rubidium magnetometer because it permitted the application of an over-voltage before its circuits were warmed up and drawing their usual load of current. To do it the other way around was more hazardous with this particularly bad generator—that is, to attach the magnetometer and then raise the voltage—because the voltage control was not linear nor stable. When varied, it tended to jump suddenly from minimum to maximum voltage, a jolt certain to wreck the magnetometer.

One way around this was to preset the voltage, as suggested, and to attach additional loads which could then be removed as the magnetometer warmed up. This we did, but since this was our first day of field tests and we had not brought with us every possible spare part, our subsidiary loads of soldering irons were insufficient. Result: Bang! Fuse blown in magnetometer. Another try —fuse blown again! (which indicated that the problem was more serious than just a fuse). Our volt-ohmmeter, or "tester" (a small handy gadget for trouble shooting) revealed that there was no impedance in the input circuit. Obviously, with our over-voltage we had burned out something—a component possibly as serious and specialized as the main power transformer.

The generator then ceased temporarily to be the black monster because, with it, we had power for a soldering iron and could disconnect wires—vital for trouble shooting. With great relief we soon found that the bad actor was a diode in the rectifier—not quite so irreplaceable in Italy. Still some question of whether we could find a similar diode, a small semiconductor that is quite a modern electronic component. We were lucky for, in the radio and TV supply shop in the small town of Trebisacce, there was one.

On the next day we were more cautious and attached electrical loads of light bulbs and more soldering irons before connecting the magnetometer. We included also a voltage regulator in the power line but, by some mischance, we managed to burn out the regulator before it proved its usefulness. With the voltage now under control, we resumed our initial tests over the Long Wall. It soon became apparent, however, that the frequency of the voltage that the miserable generator grudgingly produced was not right for the recorder. With a rapid instrument such as this, a requisite is a lively recorder, but, on the contrary, ours was "lentissimo." It took us a while to find out how to adjust the speed of the generator, mostly because the control was broken. When this was realized, and after another half-day's delay while a new part was made in Candido's excellent machine shop, some adjustment of the frequency could be made which enabled the recorder to have some "life"—not optimum, but operable.

On the third day, therefore, with the new rubidium magnetometer, we detected our first anomaly—a large peak in the recorder graph which appeared as the movable sensor was carried perpendicularly over the Long Wall. (This was easy to find since this wall is sufficiently massive to have been located previously with the proton magnetometer.) This was encouraging, however, because, if the recorder paper had been wide enough, the anomaly might have appeared a hundred times larger than with the proton magnetometer. Since the paper was of limited width, the needle, of course, went off-scale until the gain (or amplification) of the instrument was reduced by about one twentieth of maximum.

We were then ready for the first real test. Could the less massive, more deeply buried walls be located with the rubidium magnetometer? Two logical places to start the search were the "ends" of the Long Wall, that is, the regions where it was "lost" by the proton magnetometer. Before we had collected all of the pieces, parts, and apparatus that we had strewn around the field at our first test site however, rain descended. It does *not* rain in Calabria in October but *this* was an unusual year. In fact, it had already been raining off and on in September—an occurrence that *never* happens. Therefore, we felt the need to make ourselves and the equipment both more portable and more rainproof. We, therefore, arranged the main part of the instrument on the back shelf of our Volkswagen Microbus so that the operator could recline on the back seat inside and be protected from both wind and rain. More important, the most expensive part of the apparatus was protected and we did not lose the results which the recorder plotted as graphs in water-soluble ink. Remaining outside were the generator (noisy, odorous, and of less value), the two sensors, and the squawk box: This last consisted of a small but forceful amplifier and speaker which broadcast the resultant rubidium frequencies audibly for the benefit of the man who moved the sensor, who had necessarily to be at a distance from the rest of the apparatus which was not free of iron and other makers of magnetic anomalies. The sensor man could then hear the anomalies as he passed over them and, by hearing the changes in frequency as well as a steady signal from regions without anomalies, he could both be sure that he was carrying the sensor at the correct angle and keep his attention on the job by knowing when he found anomalies. Unlike the proton magnetometer, the rubidium sensors are somewhat sensitive to orientation with respect to the magnetic north pole. There are certain solid angles in which they work and others in which they do not.

After more rain, during which Breiner adjusted the sensors, the vital rubidium-filled detectors, which had the bad habit of being either too hot or too cold, we were ready for serious work on the fifth day. The procedure was then as follows:

1) Drive Microbus into edge of area to be surveyed.
2) Unload generator and its special "loads," lay out 400 feet of cable for the movable sensor, and unload sensors and squawk box.
3) Put gasoline and oil in generator (like an old car, it consumed both).
4) Start generator with "loads."
5) When warmed-up and stable, connect instrument and recorder. As voltage drops, remove loads as needed to reach proper operating voltage (some loads remain to help stabilize things).
6) Wait 15 to 30 minutes for sensor heaters—necessary items to vaporize the rubidium—to warm up. (When all is in order

one hears a distinctive frequency from squawk box.)

7) Everything ready—rain begins.
8) Wait 1 to 2 hours.
9) Repeat steps 1 to 6.
10) Ready again. Lunch time.
11) One hour later—ready again.
12) Generator runs out of gas—forgotten.
13) Repeat steps 1 to 6.

By mid-afternoon a few trial lines were run in a cow pasture beyond the southeast "end" of the Long Wall. These were interrupted, at last, only by the passage of the cows who naturally selected the spot where we were to pass en masse on their way to the barn. We had selected this pasture because it was one of the fields that wasn't too muddy to drive into. (Even so, after one particularly rainy morning, the Microbus had to be pushed out by six men.) The pasture, however, proved to be a fortuitously good hunting ground because we began to detect anomalies of both small and large magnitude. The next step was to make measurements on a grid, a series of parallel lines equal distances apart, so that the results could be plotted in a quantitative way.

Franco Brancaleoni kindly surveyed and staked out a large grid, 90 x 120 meters, for this purpose. With lines run three meters apart, we then ran measurements along 40 lines, each 90 meters long. As the sensor was moved over each line, a graph, representative of the 90 meters covered, appeared on the recorder. This large grid was completed in two days and only two Volkswagen "stations" were required—that is, one more after the initial location. Without breakdowns, rainstorms, etc., it could be completed in less than a day and, at least four times faster than with the proton magnetometer. Unfortunately, when the final plot of the results was made (as it happened, six weeks elapsed; but much less time will eventually be required for this) it was found that a shift had occurred within the instrument at some unknown time in the course of doing this large grid. Therefore, the grid could be plotted only with contour intervals of two gammas rather than one or less. In other words, some of the extra available sensitivity, one of the big advantages of the rubidium versus the proton magnetometer, had been lost.

This fault did not occur, however, for Grid #15, a much smaller one. It is seen in the plot of this grid that anomalies (the circular patterns such as the one of 19 gammas maximum in the center of the figure) represented by changes as small as three gammas were detected. These more or less circular shapes have been found, in many cases, to be representative of buried structures. This deduction is confirmed for the central anomaly by the drill results. (The use of drills has been reported by D. F. Brown, *Expedition*, Vol. 5, No. 2, 1963.) It is not clear why a structure was found also in the north central part of the grid not coincident with the center of the anomaly nor with the magnetic contour gradients. One possible explanation is that this structure was found at a depth of 5.5 meters, whereas that in the center of the central anomaly was struck at 4.5 meters, that is, one meter closer to the surface. The fact that these regions have positive magnetism may indicate also that they are caused primarily by concentrations of roof tiles (magnetic materials). It is unfortunate that the central portion of the larger non-magnetic anomaly represented by a lowering of the magnetic intensity to ten gammas (southeast corner of the grid) was not tested by drilling. From previous experience with the proton magnetometer and also from the drill results at the base of the anomaly, one might guess that this non-magnetic disturbance represents a structure of stone buried less deeply.

One may wonder why we do not use drills alone instead of bothering with such fastidious electronic apparatus. The answer is mainly that, if a drill misses a wall by one centimeter, it says: "No wall," but the sensor of the rubidium magnetometer may miss the wall by three meters and still detect the anomaly caused by it. In other words, for the particular application on the plain of Sybaris, the rubidium magnetometer affords a means of plotting the buried structures in the form of a magnetic map of the region of interest *without* drilling or excavating every square meter of earth. To accomplish this for an area of nine square kilometers, a year of continuous work might be required but this, even so, is a small amount of time for mapping a city of the fame of Sybaris.

How do we know whether the anomalies are representative of Greek or Roman times? In most cases, those from Roman structures are very much larger because they are generally massive and closer to the surface. Here again, a few test drill holes made in strategic spots after the anomaly is located, will indicate the depth and, by the pottery nearby, the age of the level of the top of the wall. Since the difference in levels between Sybaris of the sixth and Thurii of the fifth century B.C. is not great, a few test excavations may be required.

When this survey has been made, and when we, therefore, know the extent and location of the zone of deep structures, it may then be possible to answer the question: *WHERE IS SYBARIS?*

Submitted to Archaeometry 1/18/65

COMPARISON OF A PROTON AND A RUBIDIUM MAGNETOMETER FOR ARCHAEOLOGICAL PROSPECTING

by

E. K. Ralph
University Museum
University of Pennsylvania

During the past four years, surveys with the Elsec portable proton magnetometer[1] have been conducted by members of the ASCA (Applied Science Center for Archaeology) staff of the University Museum, University of Pennsylvania, Philadelphia. These have been carried out at both archaeological and historical sites, 15 in all, in 6 different countries[2]. Among these the most comprehensive program has been the search for the ancient Greek city of Sybaris in southern Italy[3,4]. In addition to the challenge of finding this site of former luxury and fame, the plain of Sybaris affords an ideal testing ground for instruments based on the principle of magnetic detection. Remnants of the classical periods -- that of the 6th century B.C. Sybaris, the later Greek Thurii, and the subsequent Roman Copia Thurii -- have been buried by meters of homogeneous alluvial clay that is very slightly magnetic.

As a result of the surveys conducted in 1961, 1962, and 1963, it was apparent that buried structures of sufficient mass which extended upward to within one to three meters of the surface could readily be detected with the proton magnetometer. Drilling and test excavations have revealed, however, that these are Roman, or, in some cases, Roman on top of Greek structures. In the course of six and one-half months of work and an additional three months in the autumn of 1964, very few definite finds of less massive, deep, and presumably, Greek walls were made with the proton magnetometer. The reason for this is demonstrated in Fig. 1. In the top part of this figure are shown curves calculated by the method of Vacquier et al.,[5] in which the horizontal components of magnetic intensity are neglected and the magnetic anomalies in the vertical direction are assumed proportional to the difference in solid angles subtended to the tops and bottoms of the walls as the detector of the instrument is moved over them. For the case of the massive wall on the plain of Sybaris where the clay is magnetic and the wall has negligible magnetism, the observed anomaly will be a decrease from the normal magnetic intensity. As shown in Fig. 1, after matching for peak height (with the measured one), the calculated curve has roughly the same shape as the measured one. The latter curve is shown also in gammas for comparison later with the rubidium data. It is apparent, however, that with this small magnetic contrast between walls and clay, the anomaly produced by the small deep wall is only 2 P.M.U.* (approximately 2 gammas) -- too small to be differentiated from natural, instrument, and other variations with a single sensor proton magnetometer.

The magnetizations of the clays, which are given in Fig. 1 in arbitrary units of relative magnetism, were confirmed by later measurements with the spinning magnetometer in the Research Laboratory for Archaeology and the History of Art, Oxford University[6]. These measurements indicated that our sample of 2 to 3 arbitrary units had a susceptibility of 0.7×10^{-4} emu/cc and one of 6 units, a value 1.0×10^{-4} emu/cc. A brick from a

---

*P.M.U. is the abbreviation used for proton magnetometer units.

Roman wall, in Test Pit D (to be mentioned later) had a susceptibility of 10.4×10^{-4} emu/cc or 130×10^{-4} emu/gm. These susceptibilities were measured at 2000 c.p.s. As suggested by Aitken, an estimate of the actual magnetization existing in the ground is best obtained by multiplying the above susceptibility values by a factor of 4.

The anomaly caused by the massive wall of Fig. 1 is typical of those found with the proton magnetometer on the plain of Sybaris. The majority were negative anomalies, that is, anti-magnetic and were caused by massive non-magnetic structures buried in slightly magnetic clay. One exception was a large Roman villa (Test Pit D, 1962) which was built mostly of bricks, materials which are more strongly magnetic than the clays. One of the few anomalies, representative of a deep structure, that was detected with the proton magnetometer is shown in Fig. 2. This is the pronounced magnetic anomaly in the upper left hand section of Grid #16. Since this is a strong positive anomaly, and as indicated by the drill records (7), is apparently more than 3.8 meters deep, it is presumed that it may have been caused by concentrations of roof tiles or other fired materials. (At this depth our guess is roof tiles rather than Roman bricks.) Even though other deeply and several less deeply buried structures were encountered by the drills, the plot of magnetic contours throughout the rest of this grid does not indicate their presence with certainty. The need for an apparatus capable of detecting the deeply buried structures and shallower ones of less magnetic contrast with greater sensitivity was indicated. Therefore, our attention was directed toward the more sensitive optical absorption magnetometers.

With the kind cooperation of Lee Langan and Sheldon Breiner of Varian Associates, experiments were conducted by Breiner and Ralph with various configurations of the Varian V-4938 rubidium magnetometer[8]. Preliminary tests were made at Fort Lennox, Ile-aux-Noix, Canada[2] in May 1964 before the more extensive ones on the plain of Sybaris in October.

The basic principle of the rubidium and of other optical absorption magnetometers is that, due to the Zeeman effect, the energy levels become split into various sublevels whose separations are dependent upon the total intensity of the ambient magnetic field. To detect this proportional splitting, optical pumping is required. The operation of optical pumping involves the excitation of electrons into metastable states by the absorption of appropriate electromagnetic radiation. When "pumping" is completed, redistribution of the pumped electrons to lower levels is accomplished by stimulation from a radio frequency corresponding to the difference in energy between the split levels. For the isotope Rb^{85} the separation between sublevels is approximately 4.667 cycles per second per gamma. In comparison, the change in precession frequency of the proton magnetometer is approximately 0.04 cycles per second per gamma. This is the basic reason why the Rb^{85} and similar optical absorption magnetometers are capable of detecting changes in magnetic intensity with approximately one-hundred-fold greater sensitivity. The specifications of the two types of magnetometers are shown in Table 1.

Experiments were conducted with both single and dual rubidium sensors. For the single sensor arrangement, the circuitry was reduced to a minimum, in a way somewhat similar to that adapted for detection of persons buried in snow avalanches.(9) It was battery-powered and the signal indicating a change in magnetic field was heard directly. With a single sensor and consequently no means of cancelling out background variations, sensitivity greater than that of the proton magnetometer could not be used effectively. With only an audio signal it was not readily apparent whether an anomaly was "positive" or "negative" and it was very difficult to assess its magnitude. In order to obtain greater sensitivity for the anomalies only, a dual differential sensor arrangement and recorder were tried. With this complete assembly of Varian V-4938 components, only the differences between a fixed and the moving sensor were recorded. (This assembly may be considered somewhat similar to a proton gradiometer or "bleeper", but with the differences that the sensitivity may be 100 times greater, one sensor is in a fixed position, the results are recorded, and readings are continuous. With this arrangement, external variations are nullified; and due to the fact that readings are continuous and that the moving sensor may be carried at a regular rate over the terrain, the speed of operation was approximately four times faster than that of the proton magnetometer (from one particular station). For these preliminary experiments a battery-powered recorder was not available and consequently, portability was reduced by the need of an A.C. generator. With the instruments mounted on the back shelf of a Volkswagen Microbus, the generator just outside; and 400 feet of cable leading to the movable sensor, a considerable area was covered from one station, and not much time was lost in moving to the next.

It is tempting to write that success in the location of many deep walls on the plain of Sybaris was achieved. In these initial experiments, beset by breakdowns, an unstable generator and other "growing pains", this was not fully accomplished. However, certain deep walls gave an anomaly of the order of three gammas. The first tests were made over the Long Wall (see cross section in Fig. 1) which was known to produce a sizeable anomaly. With a fraction of the available gain of the rubidium magnetometer in use, the expected 20 gamma anomaly was strongly observed. This was a satisfactory beginning.

Tests were conducted next in the region of the southeastern "end" of the Long Wall. Preliminary sweeps indicated that anomalies could be found in this region, and two small grids were made. As is seen in the plot of one of these Q #15 (Fig. 3), the results were encouraging. Magnetic contours could be plotted at intervals of only one gamma with sureness, and a magnetic anomaly of only three gammas in magnitude (central part of figure) and of such shape as to be representative of a buried structure was detected. This observation was confirmed by the drill results. Since this anomaly is positive, that is, it represents an increase over the normal magnetic intensity, it may also have been caused by a concentration of roof tiles. A structure found in the south central part of the grid was also coincident with a gradient of magnetic contours.

This structure was found at a depth of 5.5 meters, possibly below the magnetic clay, whereas the wall in the center of the central anomaly was struck at 4.5 meters. It is unfortunate that the central portion of the larger non-magnetic anomaly represented by a lowering of the magnetic intensity to 10 gammas (southeast corner of Fig. 3) was not tested by drilling. From previous experience with the proton magnetometer and also from the drill results at the base of the anomaly, one might guess that this anti-magnetic disturbance represents a structure buried less deeply.

The larger grid, Q #16, was surveyed also with the rubidium magnetometer, but, unfortunately, a shift in sensitivity occurred within the instrument at some unknown time, and the data could not be plotted with much greater detail than those of the proton magnetometer. The resultant magnetic map is, therefore, very similar to that of Fig. 2.

These experiments with the rubidium magnetometer were conducted for two weeks only, and needless to say, much of that time was spent in making repairs and mistakes. Even though the large grid was inconclusive, it was found that areas could be covered with the rubidium magnetometer, at least four times as fast, and that it may be possible to detect more deeply buried structures. Considerable information was obtained in regard to changes and improvements to be made with the rubidium apparatus for archaeological prospecting.

References

1. The Elsec proton magnetometer is made by the Littlemore Scientific Engineering Co., Littlemore, Oxford, England.

2. Rainey, F. and Ralph, E., in press: New Frontiers in Archaeological Exploration.

3. Rainey, F., 1962: Electronics to the Rescue in Search for the Lost City of Sybaris: Discoveries by a joint U.S. - Italian Expedition - Part I. Illustrated London News, 241, no. 6436, 928-930; and Engineering Devices used in the Excavation of the Lost City of Sybaris: Discoveries by a joint U.S. - Italian Expedition - Part 2. Illustrated London News, 241, no. 6437, 972-974.

4. The expeditions in search of Sybaris, directed by Prof. F. Rainey (University Museum) have been conducted in collaboration with Dr. G. Foti (Superintendent of the Antiquities Department of Calabria), Eng. C. M. Lerici (Director of the Lerici Foundation of Rome), and Eng. and Mrs. E. Mueller (of Cassano Ionio). From these and other organizations, the following persons participated actively in the 1964 program:

From the Superintendency: O. Miggiano and S. Pellegrino.

From the Lerici Foundation: F. Brancoleoni, F. Serra, B. Pastore, U. Cesarini, and D. Achilli.

From Cassano Ionio: G. Loisi, D. Falcone, and workmen.

From Varian Associates, Palo Alto, California: S. Breiner.

From the University Museum: F. Rainey, E. Mueller, D. Ridgway and E. Ralph.

To these persons and organizations we should like to express our gratitude, and also to Mr. O. Bullitt of Philadelphia for his generous financial support.

5. Vacquier, V., Steenland, N.C., Henderson, R.G., and Zietz, I., 1951: Interpretation of aeromagnetic maps. Geol. Soc. Amer. Memoir, No. 47.

6. We wish to express our gratitude to Dr. M. J. Aitken for these measurements and for his helpful advice during his visit to the plain of Sybaris in May, 1962.

7. The drilling program on the plain of Sybaris is described by Brown, D.F., 1963: In Search of Sybaris: 1962. Expedition 5, No. 2, 40-47.

8. Address inquiries to: Instrument Special Products, Varian Associates, 611 Hansen Way, Palo Alto, Calif., U.S.A. for V-4938 Rubidium Magnetometer data sheet and other literature.

9. Avalanche victim detection with rubidium gradiometer, Geophysics Technical Memorandum No. 16. Instrument Special Products, Varian Associates, 611 Hansen Way, Palo Alto, Calif., U.S.A. Note: In this memorandum the instrument described consists of two sensors. Its operation, however, is more similar to the battery-powered single sensor arrangement with which we experimented briefly than to that of the complete dual differential assembly of V-4938 components which we have described.

Figure Captions

Fig. 1. Wall Anomalies, Plain of Sybaris. Left to Right:

1) Relative magnetism of soil layers in arbitrary units.
2) Description of soil layers on the north side of the Long Wall.
3) Cross section of the Long Wall as revealed in Test Pit A (1962) with construction lines for the calculated anomaly shown above it. Actual magnetometer anomaly in P.M.U. (proton magnetometer units) and in gammas is shown also above the wall.
4) Cross section of a small deep wall with construction lines for the calculated anomaly, shown above it.

Fig. 2. Plot of magnetic contours from data obtained with the proton magnetometer for Grid No. 16, Plain of Sybaris. The round circles indicate the locations of drill holes. The notations "drill stopped" in the lower right-hand corner signify that structures were encountered at the depths indicated.

Fig. 3. Plot of magnetic contours from data obtained with the rubidium magnetometer for Grid No. 15, Plain of Sybaris. The round circles indicate the locations of drill holes. The notations "drill stopped" in the lower right-hand corner signify that structures were encountered at the depths indicated.

Table 1. Comparison of Specifications of Elsec Proton and Varian Rubidium Magnetometers

Characteristic	Elsec Proton Magnetometer	Varian Rubidium Magnetometer
Range	24,800 to 70,600 gamma	Any 6100 gamma interval from 15,000 to 80,000 gamma
Sensitivity	± 1 gamma for H = 50,000 gamma Varies between ± 0.25 gamma for H = 25,000 gamma to ± 2.0 gamma for H = 70,000 gamma	± 0.01 gamma
Information Rate	1 per 6 secs (standard)	Continuous and essentially instantaneous
Power Requirements	Two 6 volt, 8 AH batteries	Magnetometer: 105-125 volts or 210-230 volts ac, 50 to 1000 cps or 24-30 volts dc, 40 watts maximum with one self-oscillator. (Recorder is not included) Self oscillator: 24-30 volts dc, 12 watts

Weights and Dimensions	Weight	Length	Width	Height	Weight	Length	Width	Height
Detector Bottle	5½ lbs.	5½"	3½" cylinder					
Instrument without battery pack	12 lbs.	13"	4-3/4"	8-3/4"				
Instrument with battery pack and in case	21 lbs.	13½"	5½"	14"				
Coaxial Cable, 200' long	8 lbs.							
Sensor					2½ lbs.	7"	3" cylinder	
Sensor Electronics					3½ lbs.	7½"	3¼"	3¼"
Readout					38 lbs.	15½"	17"	7"
Recorder					14 lbs.	13½"	9½"	7¼"
Coaxial cable, 200' long					8 lbs.			
Total Weight	29 lbs.				66 lbs.			

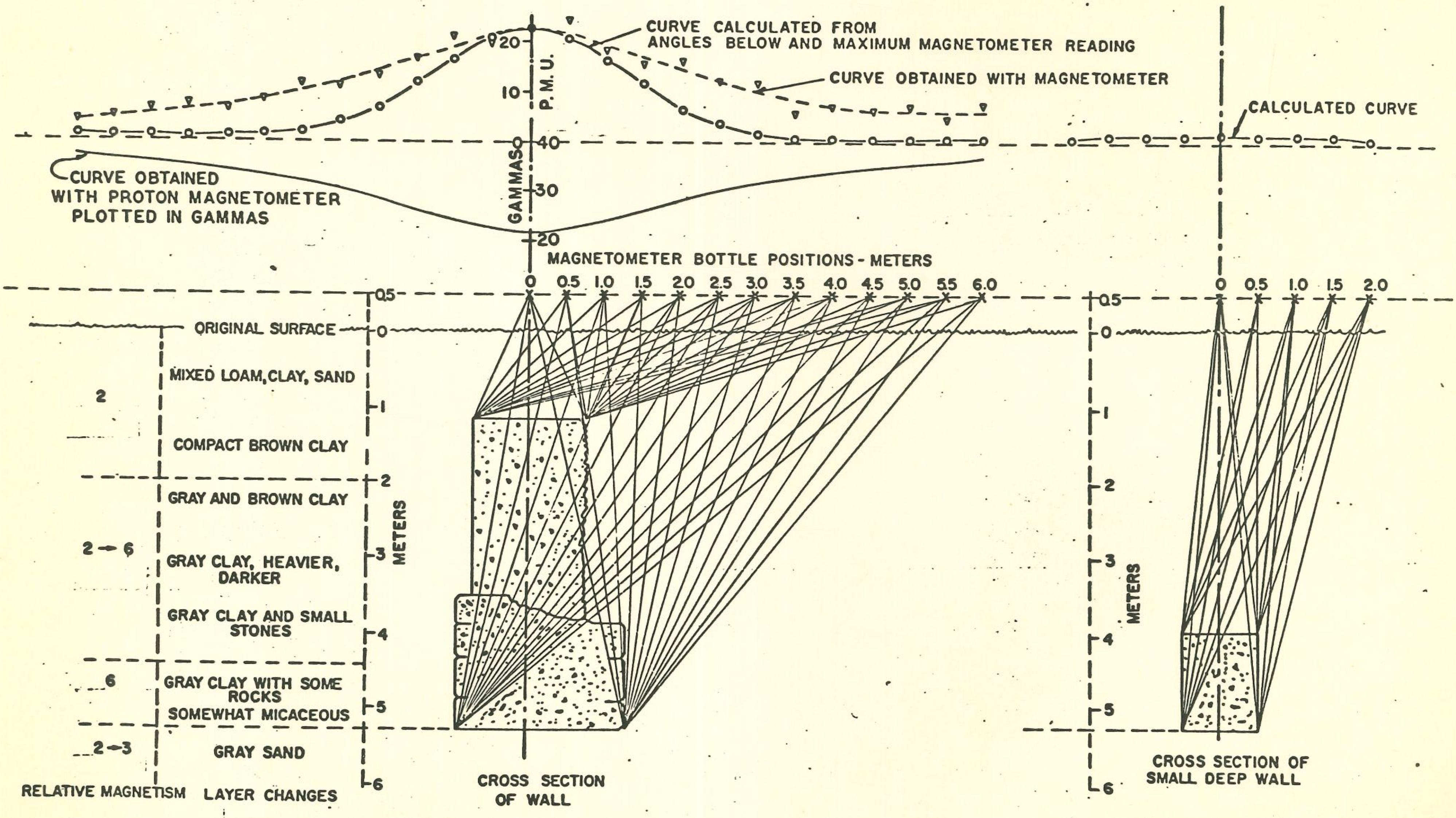
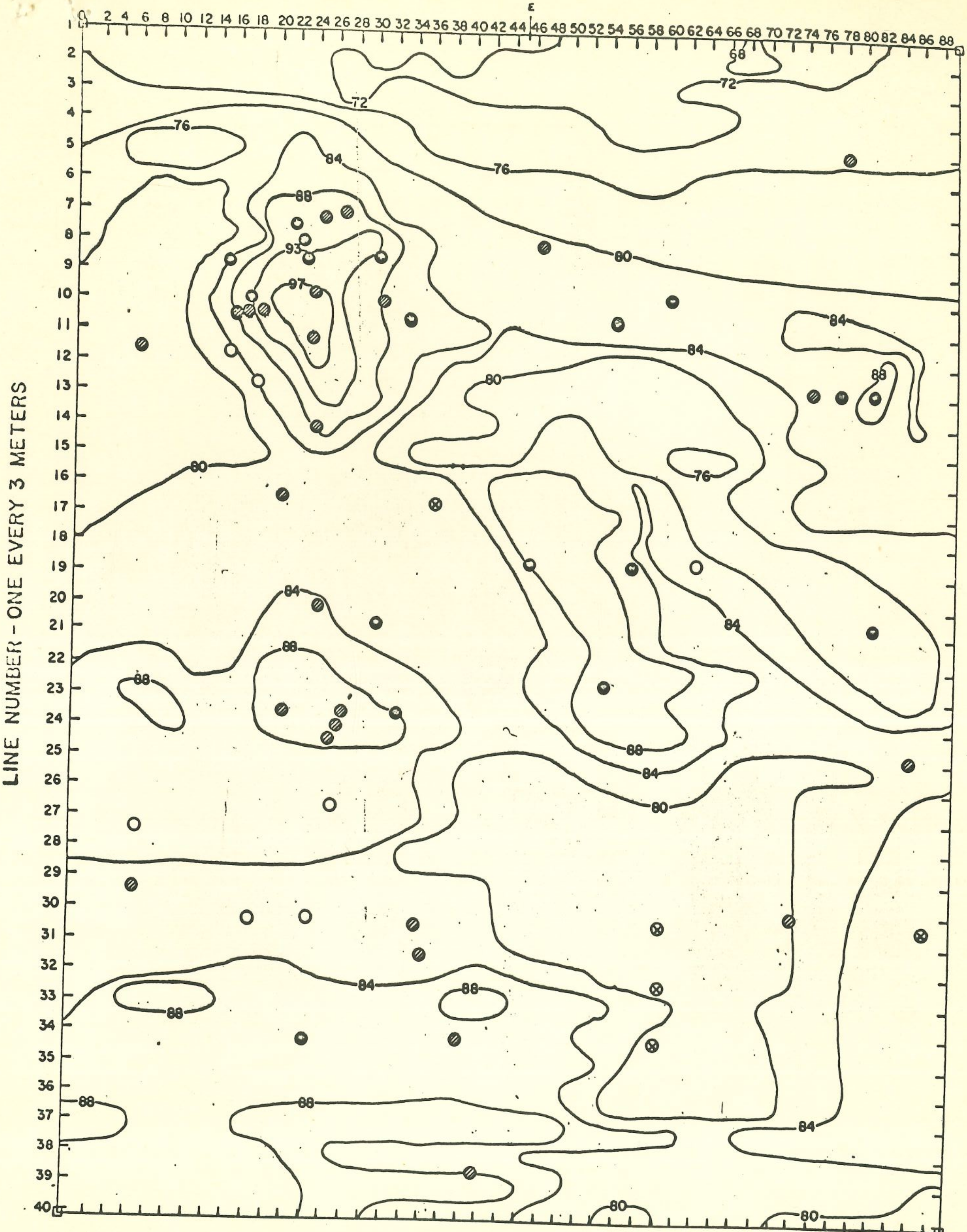

CURVE CALCULATED FROM ANGLES BELOW AND MAXIMUM MAGNETOMETER READING
CURVE OBTAINED WITH MAGNETOMETER
CALCULATED CURVE
CURVE OBTAINED WITH PROTON MAGNETOMETER PLOTTED IN GAMMAS
P.M.U.
GAMMAS
20
10
0
40
30
20
MAGNETOMETER BOTTLE POSITIONS - METERS
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
0 0.5 1.0 1.5 2.0
ORIGINAL SURFACE
MIXED LOAM, CLAY, SAND
COMPACT BROWN CLAY
GRAY AND BROWN CLAY
GRAY CLAY, HEAVIER, DARKER
GRAY CLAY AND SMALL STONES
GRAY CLAY WITH SOME ROCKS
SOMEWHAT MICACEOUS
GRAY SAND
2
2 → 6
6
2 → 3
RELATIVE MAGNETISM
LAYER CHANGES
METERS
0.5
0
1
2
3
4
5
6
CROSS SECTION OF WALL
CROSS SECTION OF SMALL DEEP WALL

FIGURE 1.



UNIVERSITY MUSEUM UNIVERSITY OF PENNSYLVANIA SYBARIS PROJECT

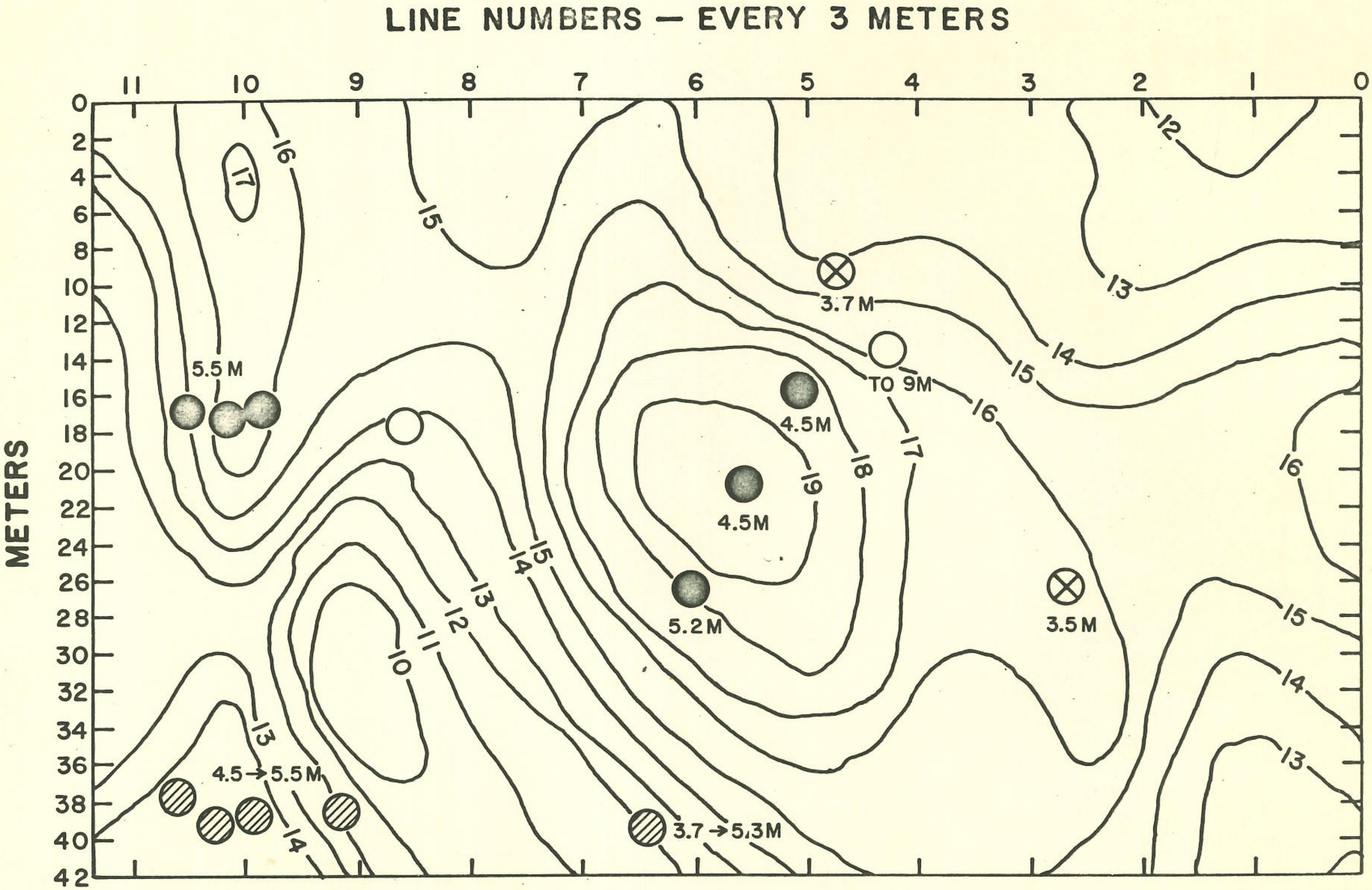
Q#16 ZONA CASA BIANCA
AT S.E."END" OF LONG WALL
OCTOBER 1964
PROTON MAGNETOMETER

N

Scale: 0.5cm = 1M
or 1:200

BASE READING = 44500 GAMMAS
CONTOUR INTERVAL =
APPOXIMATELY 4 GAMMAS

- ○ DRILL HOLES WITH NOTHING.
- ⊗ DRILL STOPPED AT LESS THAN 3.8 METERS.
- ● DRILL STOPPED AT DEPTHS GREATER THAN 3.8 METERS.
- ◍ FRIABLE RESISTANCE AT DEPTHS GREATER THAN 3.8 METERS.



N

Scale : 1 : 200

Q 15

1964

○ DRILL HOLES WITH NOTHING.

⊗ DRILL STOPPED AT LESS THAN 3.8 METERS

● DRILL STOPPED AT DEPTHS GREATER THAN 3.8 METERS.

▨ FRIABLE RESISTANCE AT DEPTHS GREATER THAN 3.8 METERS.

AS cA

OFFICE OF PROJECT RESEARCH AND GRANTS

Digest of Terms of Grant from National Science Foundation

GRANT NO: GS-1040
ACCOUNTING CODE: 4-10100-3-6431
TITLE: "Development of the Cesium Magnetometer"

PRINCIPAL INVESTIGATOR: Dr. F. Rainey
UNIVERSITY DEPARTMENT: Museum
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
NSF GRANT: $17,000
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

DURATION: 1/1/66 - 12/31/66

OVERHEAD: ~~XX%~~ 20% * of Salaries and Wages - $2,000

REPORTS: Financial - Annual and final to be submitted 90 days after termination. Scientific - Annual report and final 90 days after termination.

TRAVEL: To be authorized by Dr. Rainey (If included in above budget.) Allowance to cover transportation plus subsistence if support receipts accompany claim. Automobile reimbursement at rate of ten cents a mile. Foreign travel requires prior approval.

BUDGET: A University budget showing the source of these funds should be prepared and submitted through regular channels. 9% of salaries and wages should be budgeted for Employee Benefits.

REBUDGETING OF FUNDS: Funds may not be transferred from other categories and used for the following purposes without prior approval of the National Science Foundation:

1. Purchase of office equipment, furniture, air conditioners and motor vehicles.
2. Purchase of equipment in excess of the amount listed in the approved budget.
3. Purchase of major equipment not listed in the proposal.
4. Foreign travel when not listed in the proposal.
5. Salary of Principal Investigator or other senior personnel in excess of that provided in the approved budget.

USE OF UNEXPENDED FUNDS: Unexpended balance reverts to the Foundation.

PUBLICATIONS: Copyrighted material shall carry byline acknowledging sponsor's support and shall grant to the Government royalty-free right to reproduction.

PATENTS: Four (4) reprints of each publication to be forwarded to the sponsor. Any patentable invention or discovery shall be reported to the National Science Foundation.

PROPERTY: Title to property purchased with grant funds rests with the University.

OTHER: * 10% on Rental and Development Costs.

DISTRIBUTION: Comptroller, Attn: Mrs. Shoemaker, w/cy award
Principal Investigator Dr. Rainey
Dean
Purchasing
File

AAB:mg 3/4/66

GS-1040

UNIVERSITY OF PENNSYLVANIA

RAINEY

BUDGET

SOCIAL SCIENCES

ANTHROPOLOGICAL SCIENCES

TWELVE MONTH BUDGET

A. SALARIES		
Senior Personnel:		
(1) Principal Investigator	$ -----	
(2) Faculty Associate	-----	$ -----
Other Personnel:		
Technical Assistance		-----
		$ -----
B. PERMANENT EQUIPMENT		2,500
C. TRAVEL		
Foreign		2,500
D. OTHER (Rental & development costs)		10,000
TOTAL DIRECT COSTS		$15,000
Indirect Costs (20% of Direct Costs except for "Other" on which a 10% rate applies)		2,000
TOTAL		$17,000

S6-0026

NSF - GS - 1040

Development of Rubidium (or Alkali Vapor) Magnetometer for Archaeological Prospecting

Final Report

by

Froelich Rainey, Principal Investigator
Elizabeth K. Ralph, Faculty Associate
February 1967

In accordance with the plans outlined in the proposal for this grant, a new portable magnetometer was designed and two prototypes were constructed by Varian Associates. The new instrument is called a Model 4920 Precision Portable Magnetometer. The instrument, which consists of three parts - readout, battery back, and one or two sensors - is completely portable and when used in the differential mode, has a maximum sensitivity of 0.05 gammas. The differential mode of operation (with two sensors) afforded instantaneous cancellation of extraneous magnetic variations and permitted the use of the maximum sensitivity where needed. This, combined with digital readout, facilitated rapid plotting and interpretation of the results.

The majority of the funds in this grant was expended for the rental of the two prototypes. It is expected that one of these along with two cesium sensors will now be donated by Varian Associates to the University Museum.

Field surveys were started by Ralph in March on the plain of Sybaris where she was joined in May by Frank Morrison and Douglas O'Brien, geophysicists from the University of California. From May through July, two instruments were in continuous use. One was equipped with two cesium sensors and the other, with rubidium. The cesium system proved to be more rapid to use because the sensors were much less sensitive to orientation and therefore, the roving one could be moved and readings taken much more quickly. (This is a minor detail, but it is mentioned here to clarify the reason for the change from rubidium to cesium. Unfortunately, only one cesium system was available).

During this 1966 season, 82 grids were surveyed on the plain of Sybaris. Twenty-seven of these were made in the Parco del Cavallo area - the zone of intensive search in previous seasons. This year the plan was to find the northern, western, and southern limits of this zone of archaeological deposits and structures. (The eastern limit had been delineated in 1965). This was accomplished, but few anomalies that might be representative of the archaic Greek city of Sybaris were detected, with the exception of the area north of Lattughella where a previous excavation revealed the presence of a crude and insignificant archaic structure. The major find was the detection of the turning of the long wall. From the plot of magnetic contours (in grids 100 and 102), one sees clearly that the wall makes a right angle turn from its southwesterly direction to the southeast. This western limit of the wall had not been found before with proton magnetometers. In this region it is at depths of 4 meters or more. This find serves to demonstrate the great improvement in detection and in precise delineation that can be obtained with the more sensitive alkali vapor magnetometers operated in the differential mode. Also, data may be taken and plotted, at least, five times more rapidly than with proton magnetometers.

Outside of the Parco del Cavallo area, grids were made all over the large plain of Sybaris at half-kilometer intervals. The hope was that another archaeological zone might be detected which had been missed previously in proton magnetometer surveys and by drilling. On the fringes of the hills some anomalies due to geological features were detected, but none representative of archaeological deposits was found.

The surveys made are summarized in the attached report by Rainey and Ralph entitled, "Magnetometer Surveys and Text Excavation, Plain of Sybaris, 1966." A more detailed and technical discussion of the instrument surveys and anomalies found in the Parco del Cavallo area is presented in the preprint by Ralph, Morrison, and O'Brien (Reprints will be sent when this article has been published, if accepted).

In another region in Italy, a short survey was made at Sele (near Paestum) in collaboration with Dr. Paola Zancani. At this site, however, no anomalies were found. The reason may be that the structures sought did not present a sufficient contrast in magnetism or that there are no more there to be detected.

In Greece three new sites were investigated - Heliki (Helice), Porto Cheli, and Katsaba in Crete. All three were found not to be appropriate sites for magnetometer surveys. At Heliki and Katsaba there was too much magnetic clutter from modern civilization; and at Porto Celi, there were underlying outcrops of bedrock which made greater anomalies than the walls sought.

In the U.S.A., fruitful results were again inhibited by magnetic bedrock. In the Harvard Forest, Mass. the possible magnetic effects of soil conditions and changes could not be studied because of the highly magnetic bedrock immediately below the surface. Also, in Arizona at a site near Twin Buttes, Indian fire pits and dwellings were not found because of the presence of weathered porphyric and biotite granites - both of which were much more magnetic than the features sought.

Trails at these various sites have made us appreciate the limitations of magnetic surveying. While the new portable cesium magnetometer is the best yet developed for use on alluvial plains, uncluttered with modern civilization, sites with less homogeneous geological configurations present a challenge for the development of instruments based on other principles of operation.