26. S. Guttmann and R. A. Boissonnas, *Helv. Chim. Acta* **42**, 1257 (1959).
27. R. B Merrifield, *Biochemistry* **3**, 1385 (1964).
28. M. Rocha e Silva, W. T. Beraldo, G. Rosenfeld, *Am. J. Physiol.* **156**, 261 (1949).
29. For a review on the structure and function of bradykinin see *Ann. N.Y. Acad. Sci.* **104**, 1 (1963).
30. D. F. Elliott, G. P. Lewis, E. W. Horton, *Biochem. J.* **74**, 15P (1960).
31. R. A. Boissonnas, S. Guttmann, P. A. Jacquenoud, *Helv. Chim. Acta* **43**, 1349 (1960).
32. R. B. Merrifield, *J. Org. Chem.* **29**, 3100 (1964).
33. D. F. Elliott, G. P. Lewis, D. G. Smyth, *Biochem. J.* **87**, 21P (1963).
34. J. M. Stewart and D. W. Woolley, *Federation Proc.* **24**, 657 (1965).
35. ———, *Nature* **206**, 619 (1965).
36. I. H. Page and O. H. Helmer, *Proc. Central Soc. Clin. Res.* **12**, 17 (1939); E. Braun-Menendez, J. C. Fasciolo, L. F. Leloir, J. M. Munoz, *Rev. Soc. Arg. Biol.* **15**, 420 (1939); L. T. Skeggs, K. E. Lentz, J. R. Kahn, N. P. Shumway, *J. Exp. Med.* **104**, 193 (1956); H. Schwarz, M. Bumpus, I. H. Page, *J. Am. Chem. Soc.* **79**, 5697 (1957); R. Schwyzer, B. Iselin, H. Kappeler, W. Rittel, H. Zuber, *Chimia Aarau* **11**, 335 (1957).
37. G. R. Marshall and R. B. Merrifield, *Biochemistry*, in press.
38. W. Rittel, B. Iselin, H. Kappeler, B. Riniker, R. Schwyzer, *Helv. Chim. Acta* **40**, 614 (1957).
39. I. H. Page, *Federation Proc.* **23**, 963 (1964).
40. B. Riniker and R. Schwyzer, *Helv. Chim. Acta* **47**, 2357 (1964).
41. E. Sondheimer and R. W. Holley, *J. Am. Chem. Soc.* **76**, 2467 (1954); A. Battersby and J. C. Robinson, *J. Chem. Soc.* **1955**, 259 (1955).
42. M. B. North and G. T. Young, *Chem. Ind. London* **1955**, 1597 (1955); G. W. Anderson and F. M. Callahan, *J. Am. Chem. Soc.* **80**, 2902 (1958); M. W. Williams and G. T. Young, *Collection Czech. Chem. Commun. Suppl.* **24**, 39 (1959).
43. K. Arakawa and F. M. Bumpus, *J. Am. Chem. Soc.* **83**, 728 (1961).
44. E. D. Nicolaides and H. A. De Wald, *J. Org. Chem.* **26**, 3872 (1961).
45. E. D. Nicolaides, M. K. Craft, H. A. De Wald, *J. Med. Chem.* **6**, 524 (1963); H. A. De Wald, M. K. Craft, E. D. Nicolaides, *ibid.* **6**, 741 (1963).
46. E. Schnabel and C. H. Li, *J. Am. Chem. Soc.* **82**, 4576 (1960).
47. M. W. Williams and G. T. Young, *J. Chem. Soc.* **1964**, 3701 (1964).
48. B. Liberek, *Tetrahedron Letters* **1963**, 1103 (1963).
49. R. B. Merrifield and J. M. Stewart, *Nature* **207**, 522 (1965).

The Rubidium Magnetometer in Archeological Exploration

Exploration with a highly sensitive magnetometer allows use of more effective survey techniques.

Sheldon Breiner

By shining a purple light through an empty bottle, we may greatly increase our chances of finding ancient buried walls and pottery. The purple light and empty bottle in this case, however, are the working parts of a rubidium magnetometer recently demonstrated to be effective for delineating buried structures and potsherds near the possible site of the ancient Greek city of Sybaris. The application of this instrument to archeological exploration opens many new facets of magnetic search techniques, for it is more than 100 times as sensitive as the magnetometers used earlier.

The importance of developing methods for locating buried sites and objects of archeological interest is recognized even by the nonarcheologist. The cut-and-try method of excavating at random will simply not work in many areas where surface evidence is completely lacking. Several methods are available to the archeologist, however, to aid him in the search: (i) search of historic writings; (ii) systematic drilling, dredging, or trenching; (iii) analysis of aerial photographs; and (iv) geophysical methods based on seismic, electrical, or magnetic survey techniques (*1*). It is with the last method that we are concerned.

After the development in 1955 of the first directionally independent and truly mobile instrument for making magnetic surveys, the proton magnetometer (*2*), the speed and ease with which we were able to perform such surveys were vastly increased. Since that time reports have appeared describing the use of the proton magnetometer for detecting buried kilns, tombs, walls, and forts (*3, 4*). A portable instrument such as the Elsec proton magnetometer (*1*) can resolve a change of approximately 1 gamma (10^{-5} oersted) where the earth's total magnetic field intensity is 50,000 gammas. This high accuracy and mobility are achieved through use of the phenomenon of nuclear magnetic resonance known as free precession. The spinning protons in a fluid such as water behave like small, randomly oriented bar magnets. Through application of a uniform magnetic field about the sample, the protons are aligned in the direction of the artificial field. When the applied field is removed, the protons precess about the direction of the ambient magnetic field at a frequency proportional to the field intensity. The measurement of this frequency, however, has two practical limitations. First, the maximum sensitivity of a portable proton instrument is about 1 gamma. Also, in order to polarize the protons, the instrument must operate discontinuously. The portable versions require from 4 to 6 seconds per reading.

In 1957 H. G. Dehmelt (*5*) described a method for optically pumping and monitoring the energy-level states of electrons of the alkali metals. Optical pumping is a method by which electrons are caused to undergo selective energy-level transitions and to become concentrated in a particular energy sublevel of the atom (*6*). This method provided a means for monitoring the transition frequency of atoms with much greater sensitivity to magnetic field intensity than could be achieved with the proton precession method. Moreover, the process was continuous and well suited for mobile sensing of the field. These principles were applied in the development of a magnetometer in which was used, among other elements, the vapor of rubidium. The U.S. Navy and the National Aeronautics and Space Administration funded the manufacture of such instruments for geophysical applications; NASA used the principles for rocket and satellite measurements of field intensity. Instruments

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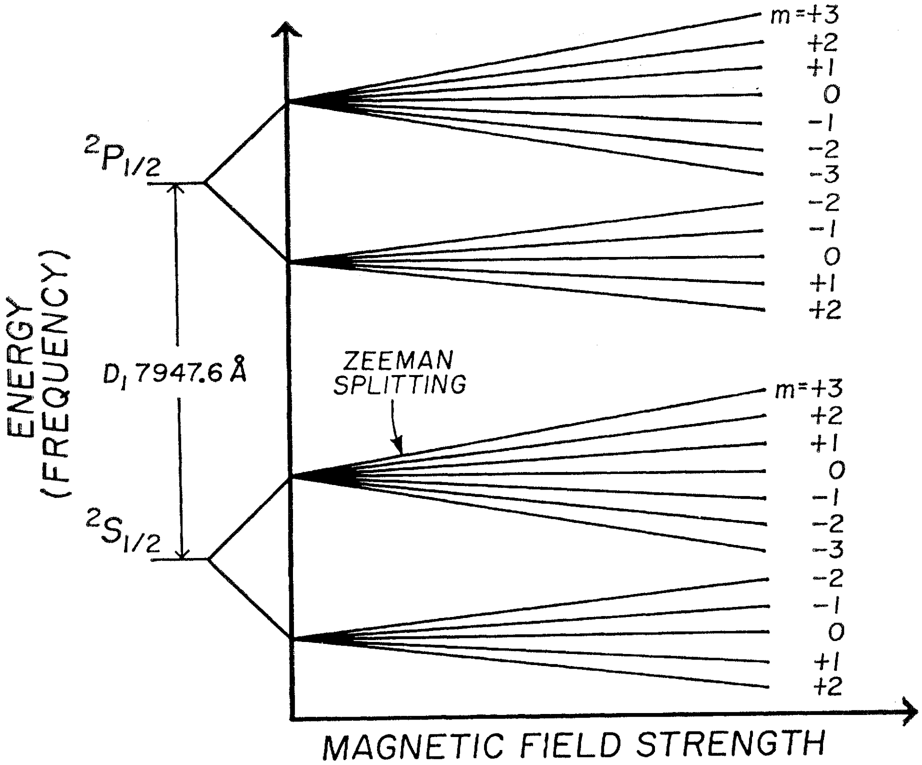

Fig. 1. Energy-level diagram for Rb^{85}.

were further developed to monitor the micropulsations of the earth's magnetic field at ground observatories around the world. Next, the rubidium magnetometer was introduced as a tool for oil and mineral exploration. Then it was ready for use by the field archeologist.

Principles of Operation

The rubidium magnetometer is just one of a set of almost identical instruments based on the principles of optical pumping and monitoring. Magnetometers based on the principle of optical pumping and using Rb^{85}, Rb^{87}, cesium, potassium, sodium, or metastable helium as the active element have been constructed and operated. Each element or isotope determines slightly different temperature, frequency, and absolute accuracy characteristics of the magnetometer. To accomplish the pumping and monitoring process in a rubidium magnetometer, a Rb^{85} light is used as an energy source of photons (wavelength, 7948 angstroms), which are focused through a glass cell containing Rb^{85} vapor. The transparency of this cell is decreased, however, when the Rb^{85} photons are absorbed by the valence electrons of Rb^{85}; this absorption raises the electron's energy, causing the electron to rise from the $^2s_{\frac{1}{2}}$ ground state to the $^2p_{\frac{1}{2}}$ excited state (see Fig. 1). The rise of the electron to the $^2p_{\frac{1}{2}}$ state must, by quantum mechanical rules, be accompanied by an increase of $+1$ in the corresponding sublevel. The absorbed photon energy is soon reradiated, and the electron drops back with equal probability to any one of the sublevels of the ground state, ready to absorb another photon. However, since there are the same number of sublevels in the ground state and in the excited state, the electrons in the highest sublevel of the ground state cannot rise to the excited state nor absorb additional photons. A large number of electrons are thus "pumped" into this highest sublevel of the ground state, and, because the photons pass freely through the vapor cell, the cell becomes transparent.

Sweeping the vapor cell with a weak alternating magnetic field disrupts this state and allows pumping to begin again. If one varies the frequency of the applied field and observes the light transmitted through the vapor cell, a sharp absorption is seen to occur when the applied field has a frequency given approximately by the equation $f = 4.667H$, where f = frequency (in cycles per second) for Rb^{85} and H is the total field intensity, in gammas. The electrons undergoing the transition between energy sublevels precess about the magnetic field at a Larmor frequency determined by the Zeeman splitting of the levels (see Fig. 1). Whereas the proton magnetometer operates discontinuously with a Larmor frequency of approximately 2000 cycles per second in a field of 50,000 gammas, with the rubidium magnetometer the Larmor frequency is continuous and approximately 233,000 cycles per second.

In the actual instrument (*7*), the modulation of the transmitted light is detected by a photocell. The current from the photocell is amplified, changed in phase, and used as a feedback signal to drive the alternating magnetic field about the vapor cell. This arrangement thus constitutes an oscillator whose frequency is proportional to the total magnetic field intensity at a rate fixed by an atomic constant, 4.667 cycles per second per gamma. The signal from this oscillator is then mixed with that from a fixed reference oscillator to obtain an audio-frequency difference also proportional to the field intensity. This audio-frequency difference can either be made audible or transformed, in a frequency discriminator, to an analog voltage for display on a paper chart recorder. The complete recording unit used in the field is shown in Fig. 2.

Magnetic Anomalies of Archeological Origin

The successful application of magnetometers to archeological exploration depends, by and large, on the existence of a distinguishable magnetic anomaly associated with a site of archeological importance. The aim is (i) to detect this anomaly and (ii) to identify it as originating in a site of potential interest. The latter problem is often the more difficult. A highly sensitive magnetometer may, in some areas, detect not too few but too many anomalies and, without interpretive aids, only cause confusion.

The literature contains very little about magnetic prospecting for archeological sites and objects, and the magnetic characteristics of only a limited number of structures have been described. Thus, before describing the method, I will describe the origin of these anomalous magnetic disturbances.

The largest magnetic disturbances (or anomalies) present in any site of human habitation are usually caused by iron, but the usefulness of the magnetometer is certainly not restricted to places containing iron. On the contrary, these sites are often of minimal importance, for they may be recent and buried at shallow depths with some surface expression, or perhaps they can be identified through a search of written records.

The more subtle magnetic disturbances are caused by a contrast between the magnetic properties of various materials associated with human occupation and those of the soil, water, or rock which covers them. The magnetic properties of the occupation materials are largely controlled by the quantity, and the mechanical and thermal history, of the magnetic minerals (especially magnetite) which the materials contain. In general, the quantity of magnetite is a measure of the magnetic susceptibility per unit volume, k, defined by the equation

$$k = \frac{I}{H}$$

where I is the intensity of magnetization in an applied field H, in this case the earth's magnetic field. Then, by definition, k is a measure of the ability of a substance to concentrate magnetic flux. Typical values of k, in metric electromagnetic units, for archeologically relevant materials are 5×10^{-6} for limestone, 1×10^{-5} for sandstone, 5×10^{-4} for granite, 20×10^{-4} for humus-rich soil (*8*), 20×10^{-4} for basalt, up to 1.0 for magnetite, and over 10 for iron (*9*). Clearly, basalt ballast stones buried in sand will cause a local increase in magnetic intensity. On the other hand, the presence of a sandstone wall covered by humus-rich soil or dark, magnetite-rich silt will result in a decrease in intensity across the wall. Since air has a susceptibility of zero, a tomb in volcanic (basalt) rock can also be detected by the mere absence of flux. These examples are representative insofar as materials are concerned, but the magnetic situations described are gross simplifications.

Perhaps the most important magnetic property, causing the most prominent magnetic anomalies in surveys thus far reported, is that of remanent magnetization (*10*). In magnitude and direction it is independent of the present intensity of the field, and it is usually much more intense than the magnetization due to susceptibility alone. Pottery, kilns, hearths, and baked rocks usually exhibit this phenomenon most strongly. Remanent magnetization occurs when a material containing some magnetic mineral is cooled after being heated to a reasonably high temperature, usually above the Curie point. Within the crystals of the mineral are small, randomly oriented regions of uniform magnetization, called domains, which become somewhat mobile at high temperatures. During cooling many of the domains align themselves parallel to the ambient field (or earth's magnetic field) and are then frozen in this alignment. Since they are parallel to the ambient field, they are also parallel to each other, thus creating a net magnetic effect.

A kiln intact from the time of its last firing will create a substantial magnetic anomaly. If the fired objects are subsequently randomly reoriented and buried at a shallow depth, as in the case of roof tiles or bricks, they can still create a measurable disturbance. The objects will exhibit different magnetizations and will occur at finite but unequal distances with respect to the various points of measurement; hence, their effects will not cancel completely. The anomalous susceptibility, which is not affected by their random orientation, will also contribute to the magnetic disturbance. It is fortuitous that potsherds, bricks, roof tiles, and other types of fired clay are not only the most strongly magnetic but among the most enduring relics of civilization.

Effective Use of High Sensitivity

The rubidium magnetometer in a fixed position can resolve a change of approximately 0.002 gamma in a field of 50,000 gammas. If the instrument were used in the conventional manner, such high sensitivity would produce considerable confusion on a field record over an archeological site. This confusion, or noise, originates from two principal sources: the micropulsations from the ionosphere and the anomalously magnetic geologic formations among or underlying the archeologic strata. Thus, to utilize the full capabilities of this device we must understand the nature of both noise sources.

The magnetic field observed on the surface of the earth derives 95 percent of its intensity from relatively stable sources in the core. The remaining 5 percent originates from solar-induced currents and their associated magnetic fields in the ionosphere and in the surface of the earth (*11*). Variations from the ionospheric sources, or micropulsations, occur in periods ranging from fractions of a second to many hours and range in amplitude from zero to tens or even hundreds of gammas during magnetic storms. Their variations in form, amplitude, and frequency are similar to the variations observed by the magnetometer when it is moved over a buried disturbance. Small micropulsations such as are almost always present

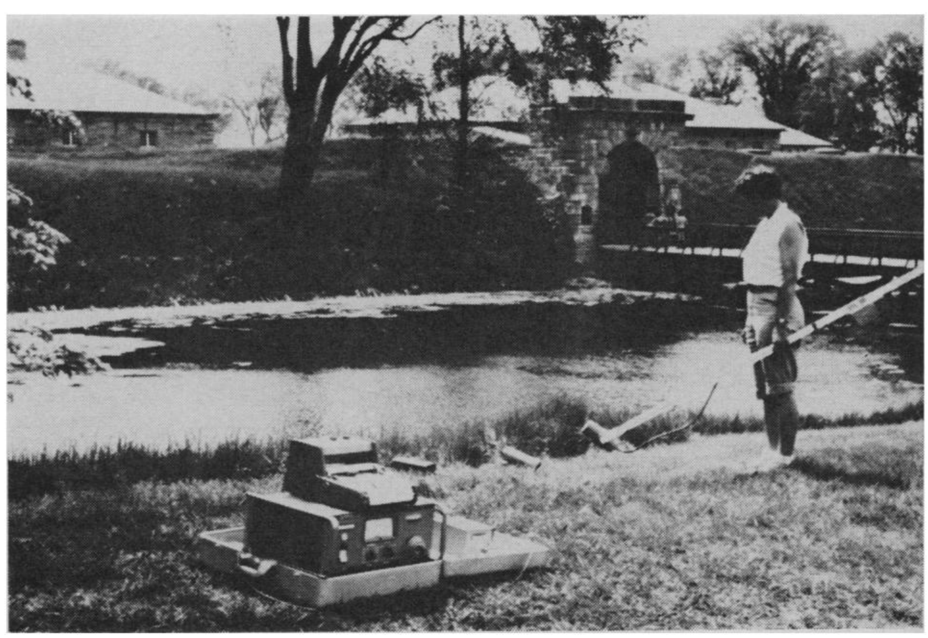

Fig. 2. A differential rubidium magnetometer in use at Fort Lennox, Quebec. The equipment at left makes recordings from the cylindrical sensors on the ground and on the hand-held staff.

during the daylight hours are shown in Fig. 3 (left) as recorded from a fixed sensor at an archeological site.

The magnetometer senses only the magnitude of the total intensity, which is a scalar (*12*); hence, it gives no directional information as to the source of a recorded magnetic disturbance. Therefore, if we observe an anomaly while traversing the ground, we do not immediately know whether it originates in the ground or is simply a micropulsation from the ionosphere.

The spatial magnetic disturbances from geologic formations are usually caused by variations in the amount of magnetite present in the underlying rock. Changes that are sharp and extremely large (up to thousands of gammas) originate in surface outcrops or slightly buried boulders of highly magnetic rock. If the changes are smooth and vary in amplitude from zero to hundreds of gammas, the sources can generally be found in the magnetic basement formations of igneous or volcanic rock at a depth of anywhere from 1 meter to many kilometers.

Either the rubidium magnetometer must operate as an ordinary magnetometer with the limitations on useful sensitivity discussed above, or it must be used in some particular manner which enables it to distinguish between interference from the ionosphere and underlying geology and interference from the sites of interest. In field operations thus far the rubidium magnetometer has proved itself valuable both when used as a single-sensor magnetometer and when used in special dual-sensor noise-cancelling configurations. First, the sensor can be used as an ordinary magnetometer, but one operating at, say, 0.1-gamma resolution. Taking advantage of its continuous-reading characteristics, we may carry it across the area of interest sufficiently fast for the archeological anomalies below the surface to be scanned faster than the low-frequency micropulsations of the same amplitude.

We can achieve a second useful mode of operation by utilizing the relatively large frequency-to-intensity (5 cy sec^{-1} $gamma^{-1}$) ratio of the rubidium oscillator. Operating only the sensor and listening to the audio analog signal, we can hear a change as small as 1 gamma in the field intensity. The resolution is limited only by the ability of the human auditory system to resolve and remember frequencies. Though this does not afford a quantitative observation, it is sufficiently sensitive for detecting bits of iron debris or isolated near-surface disturbances or for rapidly tracing out buried linear structures.

When the circumstance requires it, the rubidium magnetometer can even be utilized successfully as a differential magnetometer, through the use of two sensors, one fixed and one mobile, connected together by means of a cable. The micropulsations sensed by two sensors located within a kilometer of each other are almost identical since they originate primarily in the ionosphere, hundreds of kilometers away. Thus, when a mobile sensor is moved across an area and the difference between it and a fixed reference sensor is recorded, the only change that will be observed will be due to the anomalies below the ground traversed by the mobile sensor. Records obtained with such an arrangement were used in the construction of the maps during the Sybaris expedition described below. To illustrate the effectiveness of this means of removing interference, micropulsations present on the record of the single fixed sensor may be compared with the degree of cancellation that can be obtained on a differential magnetometer recording with both sensors in a fixed position (see Fig. 3).

Another variation of this differential scheme is the use of both sensors as mobile instruments connected together on a rigid staff. This configuration is usually termed a gradiometer, as it actually measures the difference of the two intensities over the distance between them—that is, the gradient. Even better cancellation of the micropulsations is achieved with this configuration than with the one just described, and the long cable link between the sensors is eliminated. But, most important of all, the gradiometer filters out some of the background magnetic anomalies that originate in

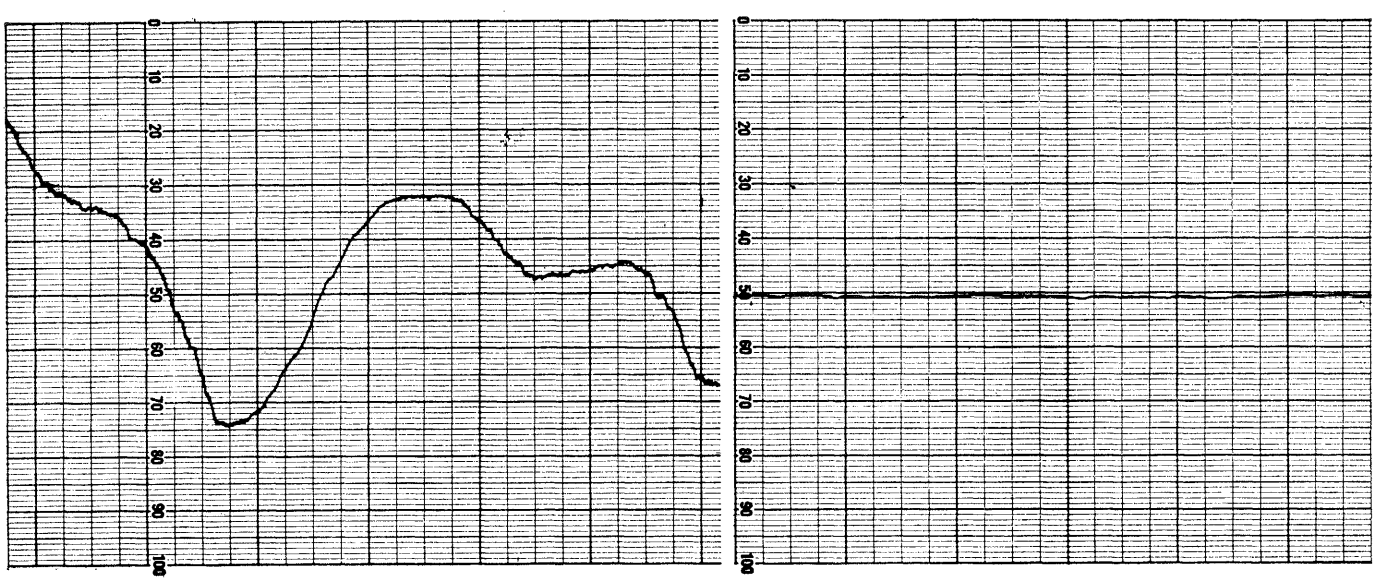

Fig. 3. Rubidium magnetometer recordings from the plain of Sybaris, made with both sensors in a fixed position. Full scale represents 1 gamma; duration of each recording shown, about 75 seconds. (Left) Single-sensor recording of typical daytime micropulsations. (Right) Differential magnetometer recording made during the same activity, with almost complete cancellation of time variations.

the deeper underlying geologic strata.

To understand the method by which it does this, we must first examine just what quantities are measured by each sensor acting alone. In general, the magnetic intensity, H, of a magnetic dipole in the form of a unit volume of, say, a wall buried in silt with a contrast ΔI in the intensity of magnetization is given by

$$H = \frac{A\ \Delta I}{r^3}$$

where r is the distance from the unit volume to the point of measurement and A is a factor determined by the size, shape, and orientation of the source. The significance of the inverse cube factor is apparent if we compare the anomalous intensity, at each of two sensors, from a buried wall with the anomaly produced by an underlying geologic-magnetic disturbance. Let us suppose that the two sensors are directly above a given part of the wall at distances of 1 and 2 meters, respectively, from it, and that the wall overlies the geologic source at a distance of 10 meters. Then, if the geologic anomaly were even as large as the wall anomaly at the site of the lower (closer) sensor, the differential anomaly of the wall would be almost 4 times that of the geologic strata. This is a somewhat exaggerated example, but the validity of the principle is borne out in its application to the search for Sybaris.

A functional gradiometer requires sensors of very high sensitivity in order to be able to measure small differences in intensity between the two ends of the gradiometer. Furthermore, the gradiometer was just shown to be very effective at resolving near-surface anomalies from the ever-present magnetic disturbances of the underlying geology. For these reasons alone, the rubidium magnetometer should prove very valuable in certain otherwise difficult areas of exploration. A description of some tests that have been made will illustrate these points.

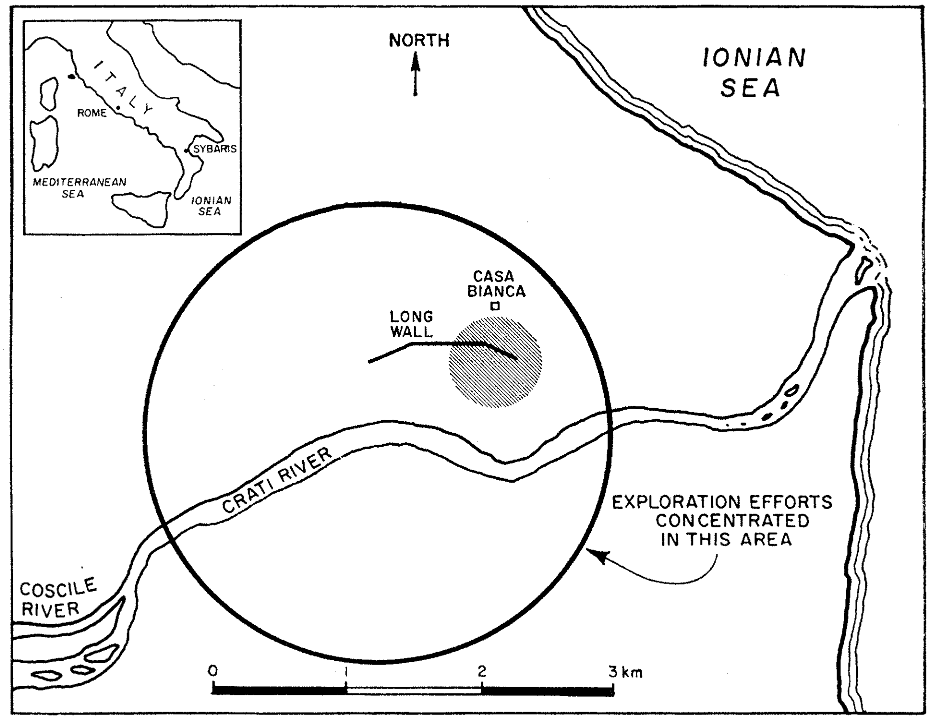

Fig. 4. Possible location of the port of Sybaris. Hatching indicates the area in which rubidium magnetometer surveys were made.

Sybaris

Archeological exploration with the rubidium magnetometer was first demonstrated in the course of a joint project of the Applied Science Center for Archaeology of the University Museum of the University of Pennsylvania and Varian Associates, developer of the magnetometer. This test was performed at Fort Lennox on the Ile-aux-Noix in the Richelieu River of Quebec Province, in conjunction with the Bureau of Northern Affairs of Canada (see Fig. 2). The relatively flat, silted island contained structures of historic interest. As expected, it also contained great quantities of miscellaneous iron debris. Nevertheless, the various instrumental configurations described above were tried with sufficient success to warrant a more realistic and extensive project at other sites containing more subtle anomalies (*13*).

A site was selected, and in 1964 Varian Associates was invited to participate with the Applied Science Center for Archaeology in a project on the plain of Sybaris in the province of Calabria in Southern Italy (see Fig. 4). Somewhere under this flat plain there may lie the Greek city of Sybaris founded in 720 B.C., one of the earliest settlements of Magna Graecia. Sybaris has been famed since antiquity for its wealth and luxury (our English word *sybaritic* stems from this reputation) and has been described by a number of classical authors (*14*). But, despite these descriptions of its location and despite its reputation and its importance in history, it remains buried under 3 to 6 meters of the silt and clay of the plain of the Crati and Coscile rivers. Determination of the extent and exact location of the city is extremely difficult, primarily because this region is a slowly sinking coastal plain covered by 2500 years of flood deposits which eliminate evidence that might otherwise be visible on the surface. The sinking land with its resulting malarial marsh probably accounts for the eventual abandonment of the area by the Greeks. Excavation is exceedingly difficult because the water table is very high —1 to 2 meters below the surface. Even excavation of known structures offers no guarantee that Sybaris has been found, because later Greek and Roman cities may have been constructed over the original site.

The difficulty of locating Sybaris becomes more evident when we realize that the remains of the city may occupy about 3 square kilometers in a region of over 250 square kilometers. Sample borings have been made in an effort to locate the site. This method has already met with great success, having produced the first evidence of Greek pottery contemporaneous with Sybaris (*14*). Electrical resistivity measurements have been tried, but with poor results due to the complication of the shallow water table. Magnetic surveys made with a proton magne-

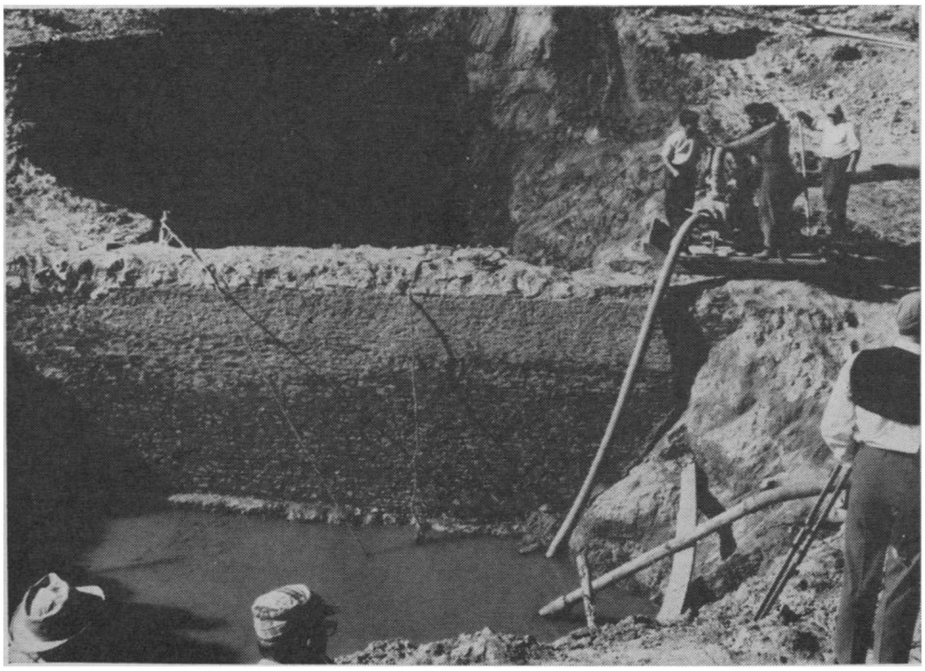

Fig. 5. Excavation of the long wall which was located with the proton magnetometer. A Roman wall was constructed on the Greek wall which appears just above the waterline. [Photograph by J. Delmege, University Museum]

tometer, however, have been extremely successful in outlining a massive buried wall over 1100 meters long with its upper surface at depths of 1 to 3 meters and its base at 5 meters (*4, 13-15*) (see Fig. 5). This massive wall was detected readily with the proton magnetometer. Since magnetic surveying had been proved useful and higher sensitivity was needed to detect the deeper (early Greek) walls and structures, it was decided that the plain of Sybaris would serve as an ideal area for testing the rubidium magnetometer.

In October 1964, under the general guidance of Froelich Rainey, director of the University Museum, a rubidium magnetometer was brought to the area for extensive tests of the various instrument configurations. Elizabeth Ralph, associate director of the Applied Science Center for Archaeology, and I conducted surveys near known portions of the previously discovered wall. In the first surveys we simply operated the sensor on flashlight-battery power, using the audio signal to drive a small loudspeaker. Within perhaps 2 hours the magnetometer bearer had traversed back and forth over a 400-meter segment of the wall, and signals from the instrument allowed us to "hear" the wall on each traverse. This was essentially what the proton magnetometer had accomplished earlier. This time, however, the measurements were made with more speed and assurance, since we were able to hear the variations continuously and to retrace areas instantly to discern possible interference from near-surface debris. On subsequent traverses of the magnetometer the anomalies were recorded on a strip chart, for compilation.

We selected an area, 90 by 120 meters, in a pasture beyond the east end of the mapped portion of the long wall as an area suitable for surveying in gridded profiles (see Fig. 4). The sensor was carried by an assistant, who walked between stakes set out in the form of a grid (see Fig. 6). A cable connected this sensor to the signal-mixing and recording apparatus 150 meters away. Another sensor, used as the reference, was placed on the ground and similarly connected. Using this scheme, we obtained results on strip charts, such as are shown in Fig. 7. These data were then compiled in the form of the contour map showing lines of equal magnetic intensity (see Fig. 8, left). Geophysical drills were later used to confirm the existence of structures inferred from the data and to show the absence of structures where there were either no anomalies or smooth contours. The drills brought up bits of bricks or roof tile, mortar, bones, glass, and decorated pottery of various kinds from depths of 3.5 to 5.5 meters (see Fig. 8).

The anomalies were generally either much more magnetic or slightly less magnetic than the silt and clay in which they occurred. The susceptibility of the sediments was found to be approximately 4×10^{-4} electromagnetic units and that of brick or roof tile about 40×10^{-4} electromagnetic units

Fig. 6. Beginning a rubidium magnetometer traverse over grid 16 of the exploration site. The area is underlaid by a complex of structures at a depth of 3 to 6 meters.

(*13*). The more prominent anomalies —for example, the very large anomaly in the northeast corner of the grid—were probably caused by concentrations of fired clay in the form of roof tiles, bricks, or large accumulations of potsherds. The long wall itself was constructed of very weakly magnetic sandstone and is buried in more strongly magnetic uniform layers of silt, clay, and sand. This type of disturbance is recorded as a weak negative anomaly. If the Greek structures were constructed of materials more nonmagnetic than the materials used by the Romans, this type of anomaly would be of considerable diagnostic significance. Perhaps with this evidence and with depths determined from the magnetic maps and a few confirming drill holes, the magnetic surveys may aid us in distinguishing Roman from Greek structures, if the Roman structures were not exactly superimposed on the Greek.

Use of a vertical gradiometer to study anomalies in this area would be of special interest because of its high resolution and because the ground surface is particularly free of interfering magnetic debris. For reasons of instrumentation, however, it was not possible at that time to make direct observations with a gradiometer. The electronic equipment that could operate from the extremely small absolute difference in intensity of the two closely spaced sensors of a gradiometer was not available to us. In lieu of using a gradiometer, we made a second survey with the single magnetometer at a level different from that of the first, and plotted the differences in the results as though the two records had been obtained simultaneously. A portion of this plot appears in Fig. 8 (right). The increase in resolution between the left side (center area) of Fig. 8 and the right side is immediately apparent when one compares the smoothly rounded anomalies of the total-intensity plot with the more detailed contours of the difference-survey plot.

Another, smaller area was chosen near the area of Fig. 8, and a one-level survey was performed in a matter of a few hours. The plot from this site (see Fig. 9, left) was less complex than that of Fig. 8. However, there was still the question, "Where do we drill?" After a preliminary interpretation based upon the horizontal rate of change of the anomalies (the portions of the plot where the contour lines are more closely spaced), drilling areas were selected; the drilling not only revealed the wall structure inferred from the magnetometer record but even confirmed the inferred height of the wall at its central part. To obtain still higher resolution, a plot of the gradient of the gradient—that is, of the second vertical derivative—of the

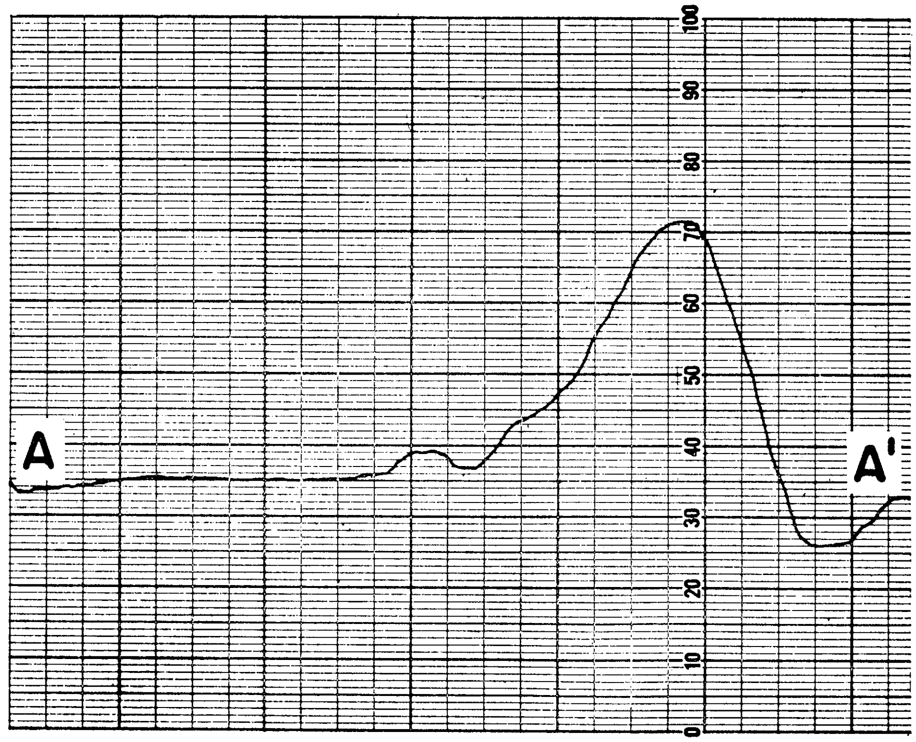

Fig. 7. Differential magnetometer profile recorded over a large anomaly of grid 16. Full scale represents 30 gammas.

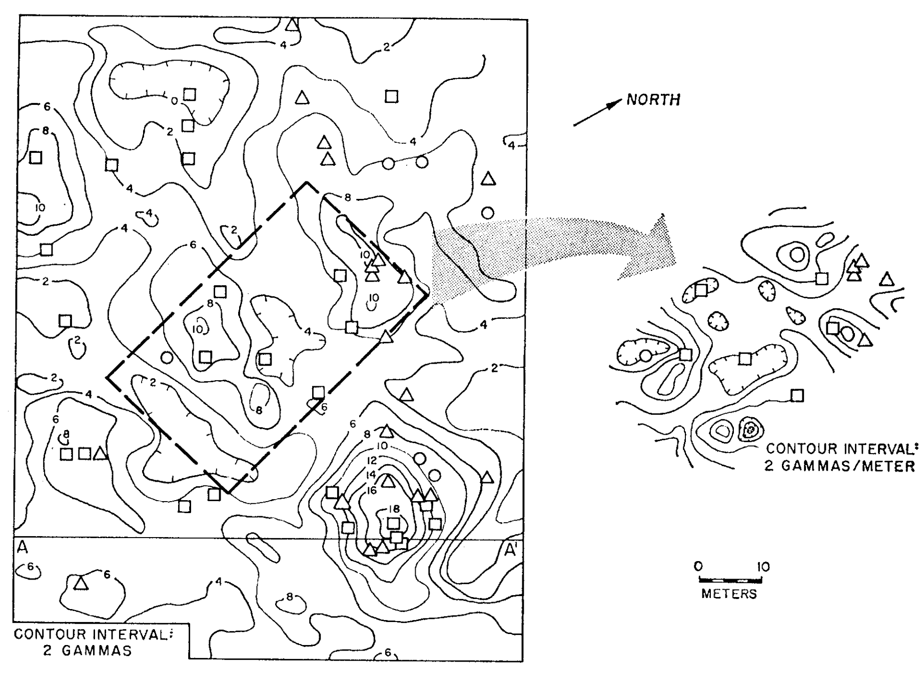

Fig. 8. Magnetic contour maps (grid 16: Zona Casa Bianca, plain of Sybaris, October 1964) over a complex of ruins, and results of drilling. (Left) Plot of total intensity. (Right) Plot of the difference between results of two surveys made at 0.5 meter and 1.5 meters above ground surface, respectively, in an area corresponding to the rectangle bounded by dashed lines in the plot at left. (Circle) No results; (squares) drill stopped by wall; (triangles) resistance from friable material.

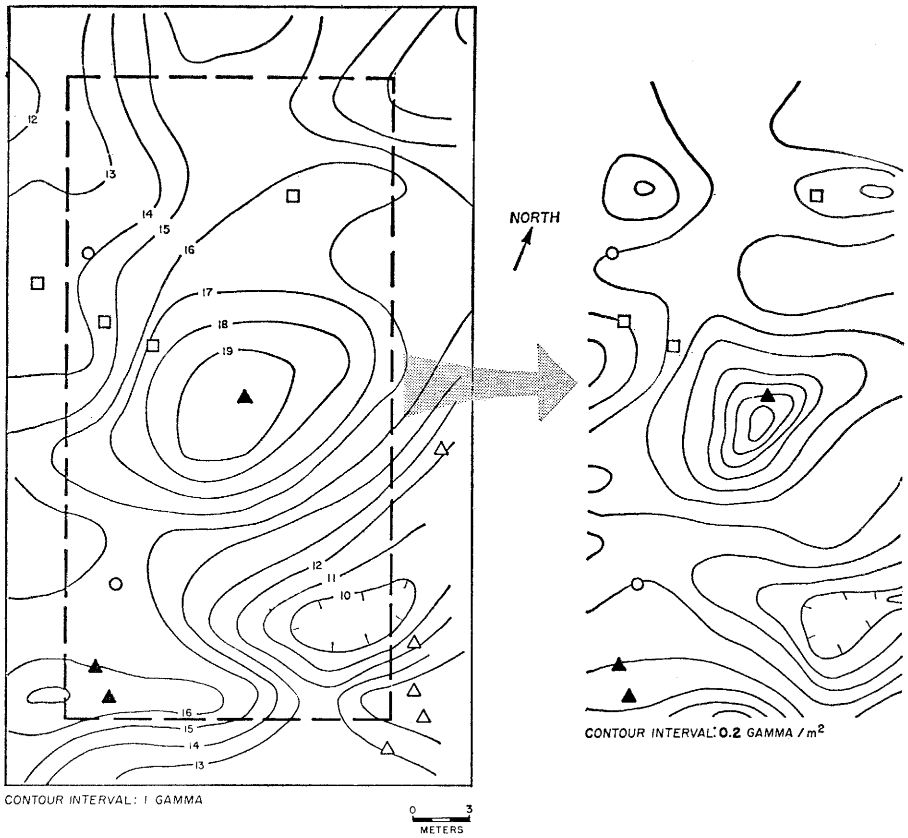

Fig. 9. (Left) Plot (grid 15: Zona Casa Bianca, plain of Sybaris, October 1964) of total magnetic intensity over ruins buried at depths of 3.5 to 6 meters, and results of drilling. (Right) Plot of computed second vertical derivative for the area outlined by dashed lines in the plot at left. (Circles) No results; (squares) drill stopped by wall; (open triangles) resistance from friable material (potsherds); (solid triangles) drill stopped, many potsherds.

total field intensity was computed from the original map (see Fig. 9, right) (*16*). Such a plot is similar to the vertical-gradient map of Fig. 8 (right) and, in fact, could have been obtained in an analogous manner from a three-level survey by plotting the difference of the vertical gradients obtained from the lower two and the upper two surveys. By this means the broader anomalies are further resolved into their separate sources, as evidenced by the distinct presence of at least three anomalies subtly hidden in the original total-intensity map.

Examples of an inverse method of interpretation were given by Linington (*4*) in reporting a magnetic survey over buried Etruscan tombs. In his analysis he represented each inferred tomb in a complex of tombs by a dipole of equivalent area, summed the effects, and compared the results with the map of magnetometer observations. It was evident from his results, as it is from the plain-of-Sybaris maps, that the magnetic field above miscellaneous magnetic structures can indeed be extremely complicated in form but can, with appropriate approximations, be made interpretable.

After successful completion of the tests at the plain of Sybaris, we were

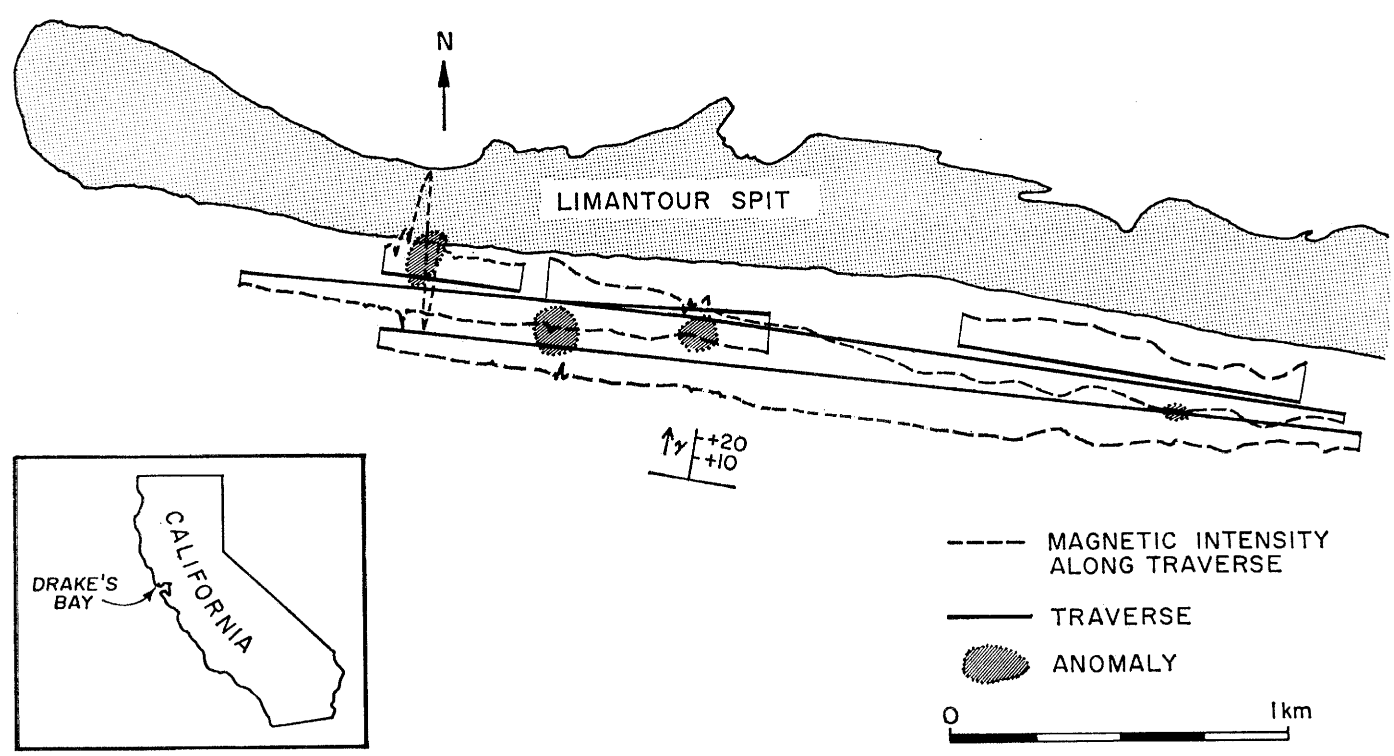

Fig. 10. Profiles of total magnetic intensity in Drake's Bay, off the coast of California; the bay contains remains of at least a few modern shipwrecks. Measurements were obtained from a rubidium magnetometer towed from a boat. [Diagram courtesy of John Huston, Council of Underwater Archaeology]

invited to try the magnetometer techniques in another area of archeological interest, the Etruscan tombs and necropoli of central Italy. At the request of C. M. Lerici of the Lerici Foundation of Rome, we used the techniques to study a complex of ruins at Cerveteri and Tarquinia, Italy. Our results confirmed results reported earlier by Linington (*4*) in an extensive study of these sites.

Underwater Archeology

In an attempt to demonstrate the effectiveness of the rubidium magnetometer in underwater archeological exploration, an instrument was operated by a diver over a Roman shipwreck near Campo Marina on the Ionian coast of Italy (*17*). The goal, not yet achieved, was to find potsherds or amphora in the silt near an already known wreck and to locate additional marble sarcophagi known to be present in the silt.

A more extensive underwater test was later performed in Drake's Bay, off the coast of California, on a project sponsored by the Council of Underwater Archaeology. The Council and the National Park Service desired more information on the existence, if any, of historic wrecks in the bay, most notably of the *St. Augustine* (which ran aground in 1595), or possibly some evidence *in situ* of the visit of Sir Francis Drake to that point on the California coast. The sensor was enclosed in a watertight housing and either towed behind a boat on the surface or operated by a diver underwater at a depth of 8 meters. The results of a few longshore traverses indicate the existence of what is probably iron debris, perhaps recent ships, in the surf near the profiles (see Fig. 10) (*18*).

Although proton magnetometers have been successfully used in archeological exploration since 1958 to locate disturbances associated with baked materials, tombs, and buried walls, it appears that many sites can be mapped more thoroughly or with more meaningful resolution by means of the rubidium magnetometer, an instrument of continuous output and high sensitivity. Some areas require other techniques, involving use of a gradiometer or differential magnetometer to resolve very subtle anomalies. Even after the data have been plotted, some geophysical techniques can often be applied to make them more meaningful. In exploration of the plain of Sybaris the magnetometer technique is especially useful—in fact, economically necessary—as it may allow the archeologist to make a more meaningful appraisal of the general plan of the city before making extensive excavations.

Recently a more portable version of the rubidium magnetometer than that used in the investigations described has been developed by Varian Associates for archeological work (*19*). Better maps of more areas and more diagnostic techniques are certain to result from more extensive use of magnetics in archeology. Unfortunately, most sophisticated instrumentation such as the rubidium magnetometer, seismic instrumentation, and other geophysical equipment used in archeology has had to prove itself in allied fields before being used for archeological exploration. Perhaps the next innovation will be designed specifically for archeology.

References and Notes

1. M. J. Aitken, *Physics and Archaeology* (Interscience, London, 1961), p. 2.
2. M. E. Packard and R. H. Varian, *Phys. Rev.* **93**, 941 (1954).
3. M. J. Aitken, G. Webster, H. Rees, *Antiquity* **32**, 270 (1958); R. B. Johnston, *Prehist. Res. Ser. Indiana Hist. Soc.* **4**, No. 11 (1964).
4. R. E. Linington, *Quaderni Geofis. Appl.* **22**, 12 (1961).
5. H. G. Dehmelt, *Phys. Rev.* **105**, 1487, 1984 (1957).
6. For more information on the principles of optical pumping and monitoring see R. L. de Zafra, *Am. J. Phys.* **28**, 646 (1960); A. L. Bloom, *Sci. Am* **1960**, 72 (Oct. 1960); ———, *Appl. Opt.* **1**, 61 (1962).
7. Varian Associates, *V-4938 Rubidium Magnetometer Data Sheet* (Palo Alto, Calif., 1963).
8. E. LeBorgne, *Ann. Geophys.* **11**, 399 (1955).
9. J. J. Jakowsky, *Exploration Geophysics* (Trija, Los Angeles, 1950), p. 165.
10. This particular kind of remanent magnetization is called thermo-remanent magnetization; see, for example, T. Nagata, *Rock Magnetism* (Maruzen, Tokyo, 1961), p. 144.
11. S. Chapman and J. Bartels, *Geomagnetism* (Oxford Univ. Press, Oxford, 1962), vol. 1, p. 194.
12. The rubidium and proton magnetometers measure only the magnitude of the total field intensity, a scalar, thus the orientation of the sensor is not critical.
13. E. K. Ralph, *Archaeometry*, in press.
14. D. F. Brown, *Expedition* **5**, No. 2, p. 40 (1963) (bulletin of the University Museum, University of Pennsylvania).
15. E. K. Ralph, *Expedition* **7**, No. 2, p. 4 (1965). (Note that the plot of the drill holes on the rubidium magnetometer map is in error.)
16. The second vertical derivative was calculated from the values on the contour map by means of Laplace's equation relating the second derivatives in the three coordinate directions, or
$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} = 0$$
The first two terms were calculated for each point on a 3-meter grid from the values at the appropriate grid intersections. Similar results can be obtained by using the mean-value theorem as a theoretical justification. Variation of the grid size produces filtering effects which act on different size anomalies. These methods should prove to be very promising for studying areas such as the plain of Sybaris. See, for example, R. G. Henderson and I. Zietz, *Geophysics* **14**, 508 (1949).
17. The exploration was under the direction of Peter Throckmorton [see *Expedition* **7**, No. 2, p. 1 (1965)].
18. S. Breiner and R. G. MacNaughton, "The application of magnetometers to underwater archaeology," paper presented at the 2nd Conference on Underwater Archaeology, Toronto, 15 Apr. 1965, in press.
19. L. Langan, "Use of new atomic magnetometers in archaeology," paper presented at a symposium entitled "Prospezioni Archaeologiche," Rome, 13 Apr. 1965, in press.

20. I thank Dr. Froelich Rainey and Elizabeth Ralph of the University Museum, University of Pennsylvania, for their part in enabling us to perform the work at the plain of Sybaris and at Fort Lennox under such splendid circumstances. I also appreciate the cooperation and stimulating discussion with Engineer C. M. Lerici and Dr. R. E. Linington of the Lerici Foundation of Rome, and the kind invitation to Varian Associates from John Huston of the Council of Underwater Archaeology to participate in the Drake's Bay exploration effort.