BULLETIN 54

Geologic Series

Geophysical Methods of Exploration and their Application to Geological Problems in New Jersey

by

George P. Woollard

DEPARTMENT OF
CONSERVATION AND DEVELOPMENT
STATE OF NEW JERSEY

Charles P. Wilber, Director and Chief of the
Division of Forests and Parks

Meredith E. Johnson, Chief of the Division of
Geology and Topography

Trenton, N. J.

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LETTER OF TRANSMITTAL

May 20, 1941.

Mr. Charles P. Wilber, Director,
Department of Conservation and Development,
Trenton, N. J.

Sir:

It gives me great pleasure to recommend for publication the accompanying report on, "Geophysical Methods of Exploration and Their Application to Geological Problems in New Jersey" by George P. Woollard. Though busily engaged on research problems financed by the Guggenheim Foundation and the Geological Society of America, Dr. Woollard upon my urgent request consented to write this report as a contribution to the State in which he resides. I feel that we are greatly indebted to him, both for the time he has generously donated, and for this enlightening report on the uses and value of modern geophysical methods of exploration and the work already done in New Jersey.

Yours very truly,

MEREDITH E. JOHNSON,
Chief of the Division of
Geology and Topography

PREFACE

At the request of Meredith E. Johnson, State Geologist of New Jersey, the writer has undertaken to make a brief report on the various geophysical methods used at the present time in subsurface geological investigations, and the extent to which they have been applied in New Jersey.

In presenting this report a three-fold division has been made; Part I defines the term geophysics; describes its applications, and its particular use in geological work. In addition, its role in the finding and developing of the nation's natural resources is considered, as well as the relative cost of different types of geophysical work. Part II is a brief summary of the various methods of geophysical examination that are now being applied to geological problems, and Part III deals with the actual investigations that have been made in New Jersey.

As the description of techniques employed is of necessity extremely brief, a bibliography of published works describing the various methods in detail has been appended for the use of those desiring more information.

GEORGE P. WOOLLARD

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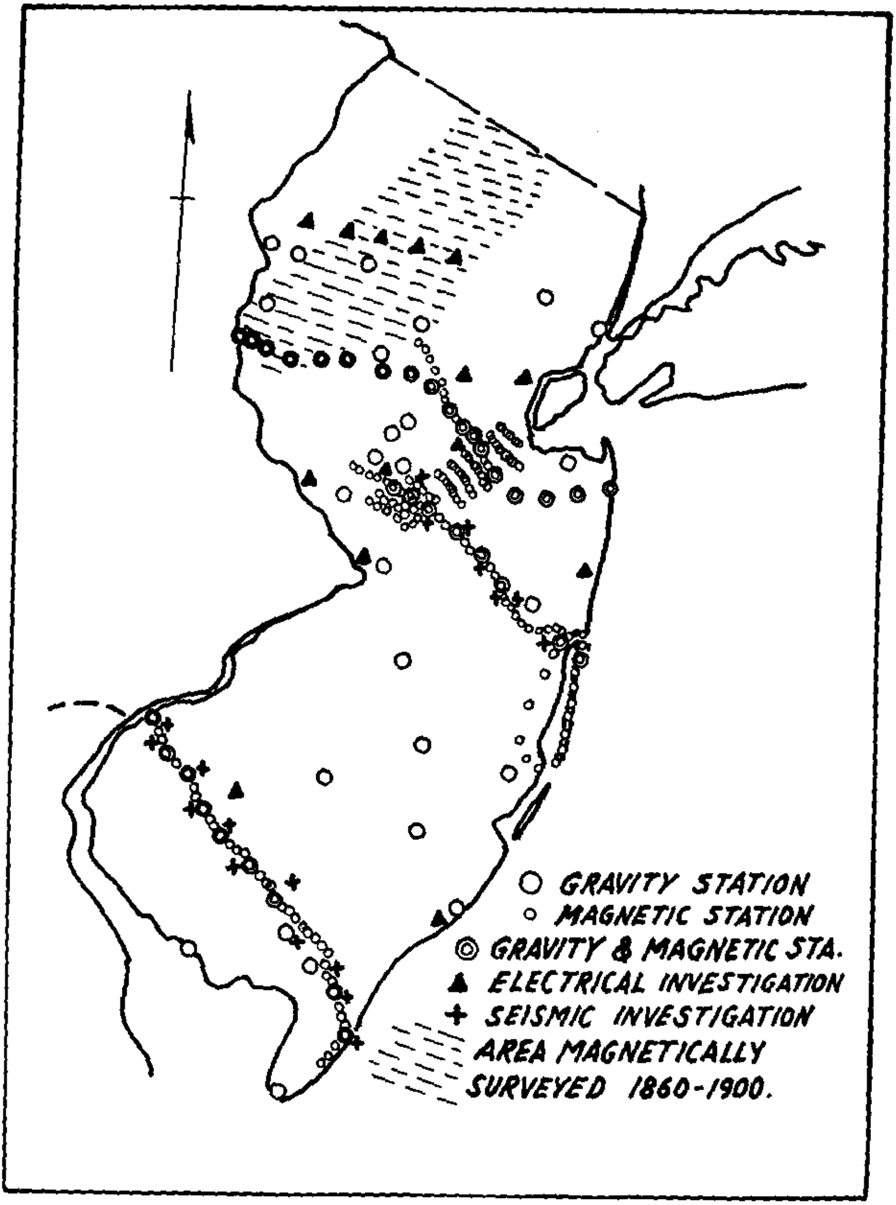


Outline map of New Jersey showing location of geophysical work done in New Jersey.

GEOPHYSICAL METHODS OF EXPLORATION AND APPLICATION TO GEOLOGICAL PROBLEMS IN NEW JERSEY

GEORGE P. WOOLLARD

PART I

GEOPHYSICS DEFINED AND ITS APPLICATIONS DESCRIBED

INTRODUCTION

Although the State of New Jersey has no official program of geophysical investigations of geological problems, considerable work has been done in various parts of the State by other agents and agencies with which the State has cooperated through the Division of Geology and Topography of the Department of Conservation and Development. The writer, both individually and in collaboration with Dr. Maurice Ewing and Mr. A. C. Vine of Lehigh University has made such investigations, as have the United States Coast and Geodetic Survey and the American Telephone and Telegraph Company. Practically all of the work which has been done to date has been of an exploratory character designed to test the latent possibilities of some of the various geophysical methods for solving some of the many geological problems presented in the State.

Thomas A. Edison was one of the first investigators to use geophysical measurements in New Jersey, and he carried out extensive magnetic measurements over some of the iron ore-bodies in the New Jersey Highlands. However, no other work was done along these lines, either on the ore-bodies where they had proved highly successful or on other geological problems, until recent years. This lapse of activity was due in part to a lack of personnel and funds by the State Geological Survey. A contributing cause may have been the attitude of the public which distrusted all things that waxed of the mysterious. The determination of the presence of ore beneath the surface of the ground without digging a shaft was a venture smacking of the mysterious and therefore not one for which the public funds were to be spent. This attitude is still prevalent in some parts of the country, but thanks largely to the oil industry which relies to a large extent upon geophysical methods in exploring for new oil fields, the public is beginning to accept their use as both normal and right. This increasing use of geophysical methods by other than the oil industry is exemplified by their world-wide use in solving mining problems, their adoption by the U. S. Bureau of Public Roads in laying out new highways; their use by the War Department in studying dam sites; by the United States Geological Survey in studying everything from water-supply problems to involved problems in structural geology; by the United States Coast and Geodetic Survey in mapping the ocean bottom off our shores; by the Navy in locating the proximity of possible enemy submarines; by the Merchant Marine in determining the depth of water beneath a ship; by the Army in locating the position of hidden artillery miles away; by the Air Corps in locating planes even when they can't be seen; by the meterological service in forecasting the flying time for planes even before they leave the ground; and finally, by our power companies, and the telephone and telegraph companies, in the less glamorous work of determining where to place repair crews to "shoot trouble" even before it happens.

It is, therefore, not surprising that through geophysics many mines formerly considered worked out and dead have been reopened, that unsuspected natural resources worth millions of dollars have been discovered in areas where the surface geology gave no clue of what lay beneath, and that other areas formerly desert are now verdant due to the discovery of buried water supplies now used for irrigation.

Since geophysics is obviously a very broad term as evidenced by the above list of its applications, we must define it so that an understanding can be had as to what is meant when the term is used.

Geophysics Defined

Although geophysics can be briefly defined as the science which treats of the physics of the earth, it includes many diverse fields familiar to us under various names. Some of these branches are meteorology, the science devoted to the study of weather phenomena which is so important to those using and working in the airways; hydrology, the science dealing with the flow of underground and surface waters; oceanography, the science dealing with ocean phenomena such as variations in salinity, currents and temperature, and which control not only the temperature of our coasts and the sea-food available, but also serve as a first line of defense for our country. This defense aspect has been brought to the notice of the public only in the last few years by the publication of maps of the ocean bottom off our shores which, used in conjunction with sonic depth-finders, permit ships to know accurately their positions even in heavy fogs. A still more recent development has been the improvement of submarine detectors as vital defense instruments through oceanographic research. Another branch of geophysics deals with terrestrial electricity and magnetism and such terrestrial and extra-terrestrial phenomena as sun spots and cosmic showers and their effects on the earth and our everyday activities. It has been found for instance that solar disturbances are apt to disrupt telephone, telegraph and radio communications, and even ruin the satisfactory operation of teletype machines. Again, it has been found that aeroplanes flying over certain areas, as in that portion of New Jersey adjacent to Wilmington, Delaware, cannot rely upon their compasses due to the strong magnetic disturbance in that area. Other areas have been found in which marked radio disturbances are always obtained. The study of all these varied phenomenon comes under this branch of geophysics.

Geodesy is another branch of geophysics devoted to the study of the shape of the earth and in detail it gives us the general configuration and elevation of the country. Seismology deals with earthquakes, their points of origin, severity and other related facts which it is necessary to know in making studies as to how to minimize their damage, determine their possible periodicity and other vital data. Vulcanology is a branch devoted entirely to the study of volcanoes, and there are still other branches of geophysics which effect our lives in varying degrees.

The examples cited serve not only to show the wide field embraced by the term geophysics, but also to show that the various branches are all part of the general study of the earth and as such also come under the head of geology, the science devoted to the study of the earth.

APPLICATION OF GEOPHYSICS TO GEOLOGICAL RESEARCH

Although it might appear from the above definitions that meteorology, oceanography, hydrology, seismology, vulcanology, geodesy, terrestrial magnetism and electricity are all a part of geology, this concept is not in accordance with that generally held by the layman. He thinks of geology as a science devoted entirely to the study of rocks and minerals and of maps showing the distribution of these rocks and minerals. The commonly accepted idea of a geologist is a man wearing boots who goes around chipping off specimens of rock with a hammer; his studies are limited to the rocks he can see and get specimens of, and although in a vague sort of way it is understood that he has some knowledge about the rocks beneath the surface, the "practical" man, faced for example with the problem of obtaining a ground-water supply, usually consults a well driller or even a water diviner rather than a geologist.

That geology at the present writing is neither as broad in its scope as the first definition or as limited as the second concept is the result of two opposite trends. The first, which is primarily responsible for the average layman's concept of the present status of geology, is due to the fact that about 1900 or a little later, a good deal of the United States had been mapped geologically—at least on a reconnaissance basis. That is, maps had been drawn which showed the areal distribution of the various kinds of rock at the surface and these had been classified as to their geologic age and correlated with similar rocks in other areas. As very few people had been particular about keeping an accurate record of the material encountered in drilling and digging wells, only a very sketchy idea was available as to what lay beneath the surface. True, the dip of outcrops had been observed and the thickness of stratigraphic beds beneath the surface computed, but this method could not take into account the presence of buried erosion surfaces or all the changes in dip that occur beneath the surface. Therefore it is not surprising that the citizens of many states felt that their Geological Surveys had fulfilled their purpose when the surface geology had been mapped, since obtaining a knowledge of the subsurface formations did not appear to be feasible from an economic standpoint. As a result, the appropriations made to many of the Surveys were drastically reduced and geologic research was necessarily curtailed. The result of this policy is that today people are having to spend thousands of dollars annually in unplanned and often ill-advised private prospecting to get information which is not made available to others and which usually is soon lost or forgotten. The following examples serve to illustrate the futility and waste of such a policy.

In selecting a factory site it is necessary to know the foundation conditions as well as the quantity and quality of the available water supply. That information is seldom available and has to be obtained—often at very considerable cost—by the parties interested. So, also, the foundation data needed for the construction of bridges and dams must be obtained by the individuals concerned. Towns along the coast decide without benefit of geologic advice upon municipal improvements such as deepening their yacht basins and end by ruining their water supply. People buy charming homesites in the country without knowing whether they can get water for a hundred dollars or whether it will cost them thousands. Others sink thousands of dollars in local oil wells with no real knowledge as to whether they have a chance of getting their money back or not. States set up heavily financed councils and commissions to entice industry to build plants within their borders without even knowing what potential mineral wealth they have to offer or if they can furnish the newcomer with a water supply. To be sure they tell of the railways and rivers serving various localities, the abundant labor, the cheap fuel, the low taxes; but there are few areas where the geologic factors which also enter into whether a venture will be a success or not are known with the same degree of certainty. These examples show the present need for a knowledge of what is beneath the surface of the ground as well as what is at the surface.

Formerly mineral prospects were found on the basis of surface outcrops and their subsurface extension had to be followed by a very expensive program of shafting and drilling. Similarly oil and coal deposits were located by gas leaks and outcrops, although structural geologic interpretations of surface outcrops were later applied in locating possible oil pools. Occasionally then, as now, promoters persuaded people to drill for oil purely on a hunch and New Jersey has quite a few such "oil" wells which cost thousands of dollars. Contrast these methods, however, with the present ones used by the oil industry; with the methods of development used on mineral prospects in the mining areas of Canada, and on the great gold deposits of South Africa. The work is still being done at the surface, but without drilling except as a final step. The deposits studied are from a few hundred feet to thousands of feet beneath the surface, and there are few if any surface indications of their presence. These investigations are being done cheaply and economically—in fact they cost less than the few drill holes that are sunk to verify the indications obtained by instruments which in 1900 or even 1920 were not thought of in connection with geology. These instruments have all been borrowed from the various branches of geophysics and have been adapted to the problems of geology. Magnetometers are being used to study not the broad relations of the earth's magnetic field as in Terrestrial Magnetism, but to study the many local magnetic disturbances in order to determine whether they are due to a sheet of trap rock, an area of serpentine, a gabbro mass, or a potential iron ore deposit. Seismographs are used not to study earthquakes, but rather the speed of sound through rock from man-made earthquakes caused by the explosion of charges of dynamite; and from which data the depth to various geologic horizons can be determined. These data are then used to reveal geologic structural changes which may be of value in indicating the possibility of an oil pool, the depth to an artesian water supply, or an ore-bearing horizon. Gravity instruments are not used as in geodesy to study the shape of the earth, but rather to study the relatively small variations in mass distribution which are due to variations in the sub-surface geology. These instruments measure the variation of gravity to better than one part in ten million and have been employed in both the mining and oil industry with marked success. Heavy ground current conditions and radio anomaly areas have been found to be correlated with the geology and radioactivity has been found to play an important role in solving some geologic problems. For example, in pure science, radio activity measurements have been used to determine the age of the various rocks, and in the oil fields they are used to detect porous sands that may act as reservoirs for oil and also to determine the position of old erosion surfaces. Similarly in electrical measurements of all kinds, conductivity, resistivity and electromagnetic effects have been used to help indicate oil-bearing sands in wells, heavy sulphide ore-bodies, the depth to fresh water horizons and in many other ways.

From these examples it is obvious that certain methods lend themselves more readily to one kind of an investigation than another; for example, the magnetic methods would be the ones best adapted to the study of naturally magnetic materials such as bodies of magnetite (the natural magnet, lodestone), ilmenite, franklinite, pyrrhotite, or rocks containing even a small percentage of these highly magnetic minerals such as serpentine, gabbro or trap rock. Electrical methods take advantage of the fact that there is frequently a marked change in the electrical resistivity or conductivity of two media as in the case of a change from salt to fresh water, or sand to hard rock; or rock and a metallic sulphide ore body. Similarly, the seismic method relies on the detection of a change in the speed of transmission of the sound wave caused by an explosion when it passes from one kind of rock to another. It is, therefore, seen that the success of the various geophysical methods of exploration depends upon the existence of marked differences in the physical properties of the material being investigated, or sought, and the material adjacent to and surrounding it.

As it is not always possible to hunt directly for certain materials because their physical properties do not differ greatly from the surrounding rock, an indirect approach is frequently necessary. Thus oil is not hunted directly, but instead the geologic structural conditions are sought which will permit oil, if present, to segregate into what are commonly known as pools. That is, a structural trap is hunted which involves a displacement of one or more "key" geologic horizons which are known from well data to bear a definite relation to oil reservoir sands. This same sort of technique is also used in locating the position of artesian water sands since it is difficult to work with the water directly except in special cases. Of course the information about the geologic structure obtained by geophysical methods can also be obtained from bore hole and well data, but it is generally economically impossible to sink a sufficient number of deep test wells or bore holes in an unexplored area to show what is beneath the surface for even a small area—let alone a large one—and as a result this method is generally reserved to test geophysical indications or to develop known mineralized areas.

CHOICE OF METHODS BEST ADAPTED TO EACH PROBLEM

In choosing the geophysical method to be applied to any geological problem the general nature of the problem has to be considered first. For instance, if a survey were being carried out to determine the possible iron ore reserves in the New Jersey Highlands, the magnetic method of prospecting would immediately suggest itself since these ores are known to be highly magnetic. They could also be mapped quite satisfactorily by using any of the electrical methods since the ore is largely magnetite, a mineral which is a good electrical conductor as compared with the enclosing country rock. Also, since magnetite has a much higher density than the country rock, these deposits might be mapped by gravitational methods. Electro-magnetic methods could probably be used as well. In this area, though, the first choice would be the magnetic method, since the greatest difference in instrument readings would be expected with this method. For example, the magnetic susceptibility of magnetite is 97,350 c.g.s. units, while that for the average country rock is only around 1000. In other words a factor of change of about 97 may be expected in the readings as one passes from country rock over a magnetite ore-body. In comparison, the factor of change for the electrical method would be about 8 to 1 and for the other methods mentioned it would be even less.

Consider now an artesian water supply problem: say that of finding the depth to a certain water horizon. Two geophysical methods of solution suggest themselves. One would be to take advantage of the possible change in electrical properties of the water as compared to the country rock, and the other would be an indirect method, such as the seismic, whereby some horizon whose position relative to the artesian stratum is known and could be located. Since the seismic method would require the use of dynamite as well as much more expensive equipment, the electrical method would be the cheaper and would probably be tried first; but if the locality being studied were near a city or industrial area with ground current disturbances due to power leaks or street railways, the seismic method might be the one finally adopted since bad ground current conditions might make accurate and reliable electrical measurements impossible.

Similarly in the case of an operating mine where it is desired to map the extension of some ore-body it might prove necessary to use a less favorable method than the natural one indicated due to the susceptibility of the more favorable method to external influences. For example, the gravitational method might be selected to follow an ore-body that is naturally magnetic. In this case the tracks, motors and underground mining equipment might prove as magnetic or more so than the ore-body and thus give a false picture, or fluctuating magnetic fields might be obtained due to the use of direct current in the mine. Other examples might be cited, but the above give an idea of some of the factors controlling the choice of methods other than what might be called the "natural selection".

In brief, the natural selection of geophysical methods involves the use of the magnetic method on problems involving naturally magnetic bodies, and the use of gravitational methods on problems involving changes in mass distribution such as the location of salt domes in the Gulf Coastal Plain, etc. However, there are other factors which have to be considered in making a choice of methods. For instance, in the areal delineation of subsurface bodies the gravitational method has been highly successful, but these data give very little absolute information concerning depth. Similarly the magnetic method is useful in locating magnetic bodies, gives some information on their depth, but the exact areal extent of the bodies can not always be determined because of polarization effects. Electrical methods can be used as can also the seismic methods for determining both areal and depth measurements, but both these methods are handicapped by slowness of operation and the electrical methods are also susceptible to external electrical effects. Because of these considerations it has become customary in exploring areas where little is known of the subsurface geology to use the magnetic, gravitational and some of the electrical methods for determining areas of disturbance, and other electrical methods and the seismic methods primarily for obtaining depth data. This employment of the methods therefore reflects the roles in which they can be most successfully and also most economically used.

ECONOMIC CONSIDERATIONS

Economic factors in the choice of geophysical methods center on the cost per unit of area covered. For example, in gravity measurements three different types of instrument can be used. They all give reliable data and represent about the same investment. However, one can be used roughly twenty times as fast as the other two and as a result that is the instrument commonly used for general exploration. Seismic methods, as previously pointed out, require the firing of numerous charges of dynamite and as a result are more expensive than other methods which do not require the purchase of such supplies. Also, large patent royalties have to be paid in order to use the seismic method on commercial work and this also adds to the cost of the method. Magnetic instruments cost much less than those used for other methods and thus smaller amortization charges are obtained with this method. Again, some methods require a much larger field personnel than others. In deciding upon the method or methods to be employed on any problem, therefore, a balance has to be struck between the methods indicated by the geologic factors, the type of problem, the information desired, the cost of field operations, the capital investment tied up in instruments, whether the work is to be done by the parties interested or by contract with a company specializing in this kind of work, and in some areas the relative nuisance to the public of the different methods. In the oil industry the economic value of the product being sought justifies the application of any or all methods and there are numerous cases of one or more methods failing to reveal the presence of a favorable geologic structure containing oil which later was found by another method. However, in areas where one instrument has been found to yield positive results it is frequently used almost exclusively, as in the Illinois Basin where the seismic method was used almost entirely in locating the oil reservoirs of that region. Then, too, general practice has given certain instruments a reconnaissance role chiefly on account of their cheapness of operation and large areal coverage per unit of time. The magnetometer and the gravity meter fall into this class. In the oil industry, areas showing favorable structural indications obtained with these instruments are generally explored with the more expensive seismic methods before any drilling is done. However, in most other work an effort has to be made to hold down the number of methods used to a minimum and this is done through a study of the problem and all the related factors including the cost per unit of area to be covered.

The following figures give an idea of the relative cost-coverage values for the various methods. The values are only approximate and are based upon data taken from the oil industry.

Method	Cost per party per month
Magnetic	$1000.00
Gravity meter	$2000.—4000.00
Electrical	$2000.—3000.00
Seismic	$8000.—15000.00

Method	Area covered per party per month
Magnetic	500—700 square miles
Gravity meter	500—700 square miles
Electrical	2—14 square miles
Seismic	2—14 square miles

Although considerable variation in the cost of the different methods is indicated, the surprising thing is that even for seismic investigations the cost is still much less than the cost of getting the same information by drilling.

That some States feel justified in carrying out geophysical investigations as part of their general geological program is indicated by Missouri where a complete state-wide magnetic survey has been made with stations on a mile-square grid over the entire State. This work has been in progress for seven years and will be brought to completion this year. Many of the localities showing abnormal magnetic conditions have already been checked by the use of gravitational methods, and some of the more pronounced anomaly areas in the mineralized part of the State are to be core-drilled to ascertain the value of the indicated ore-deposits. In parts of the State where there is a possibility of finding oil, these magnetic investigations have already led private interests to check them further with both gravitational and seismic measurements. Here then is one example of a State that has invested heavily in geophysical work in the expectation of expanding its exploitable mineral resources even though the surface geology was well known. That the work has been a good investment is indicated by the interest displayed by oil companies in checking with more expensive geophysical methods the likely-looking areas indicated by the State's magnetic investigations; by the adoption of the magnetic method by several of the mining companies in the state for exploration work, and by the discovery of hitherto unknown and unsuspected potential ore-bodies which appear to be as large as any now known in the State.

Similar magnetic investigations have been conducted in recent years by the Alabama Geological Survey, the South Dakota Geological Survey, the Arkansas Geological Survey and the Mississippi Geological Survey; and in the last-named State drilling by a private company on a favorable structure outlined by the Survey has resulted in the discovery of the first oil pool discovered in Mississippi. This success has led to more prospecting and at the present time deep wells are being sunk in Florida and Georgia to investigate structures outlined by geophysical work and believed to be favorable for the accumulation of oil.

In Texas, Nevada, New Mexico and the Hawaiian Islands, geophysical methods have been successfully employed by governmental agencies in the search for ground-water supplies.

The indirect effect of geophysics and subsurface exploration may be illustrated by Indiana. This State had closed its geological survey early in this century since it was believed that there was nothing further to learn about the geology of the State as all the surface geology had been mapped. The recent success of subsurface exploration in adjacent Illinois, however, and the discovery of the large oil resources there has led Indiana to reopen her geological survey in order to discover something about her potential underground wealth.

The State of Illinois can also be used as an example of how a geological survey can serve the people of a State. In Illinois the geological survey has a technical staff—not counting office and laboratory help—of more than fifty specialists. It also maintains chemical laboratories, physical laboratories, and other experimental laboratories in which men work on problems concerning the natural resources of the State such as possible uses for their clays, sands, shales, limestones, coal and oil. They also work on problems relating to production, metallurgical treatment, etc.; all this being in addition to the work of mapping both the surface and subsurface geology. In Illinois if any industry has a problem in using a natural resource, the State makes that problem its own and goes to work on it on the principle that every industry kept as a going concern is an asset preserved for the State. Contrast this attitude and its beneficent results with the short-sighted viewpoint held in most other States where research is considered a luxury that can only be afforded by large private corporations. There are areas where industry has moved on leaving a desolate waste of gaping holes in only partially worked deposits; others where large factories and plants are left empty and falling into ruin and thousands of people left without jobs. The cause of such calamaties is not always the exhaustion of a natural resource, but often some ecenomic consideration such as the advent of concrete which displaced the use of brick, or lower wages in some other part of the country, or perhaps lower transportation costs. The point is: many abandoned industries could have been kept going at the original sites through research and technology.

Most people consider the possible failure of an enterprise of interest only to that concern and to the stockholders who have invested directly in it; but the State is also a stockholder, for if that industry either for want of management or cirmumstances beyond its control ceases to do business, then the State loses just as surely as the other stockholders. Property becomes idle, taxes cease to be paid, people lose their jobs and become a public burden, merchants supplying these people suffer from diminished business, other industries supplying this industry lose business and the whole vicious cycle affects the State in the form of smaller public revenue and necessarily increased public spending. It was because of this vicious cycle that the State of Illinois established a geological survey that tackles every phase of the finding, exploitation, development and utilization of that State's resources, so that the fullest possible use can be made of them and both industry and the State benefit thereby. The success of this policy is attested not only by the constant growth of the mineral industries in that State, but also by the wholehearted cooperation and backing now given the geological survey.

This discussion of the work of the Illinois Geological Survey may seem a far cry from the employment of geophysics in solving geological problems, but since only a few of the more foreward-looking States have as yet made use of such methods, I do not feel it is out of place to cite the extent of the other advances that they have made in Illinois toward making geology approach its basic definition; "that science devoted to the study of the earth".

PART II

GEOPHYSICAL METHODS OF EXPLORATION

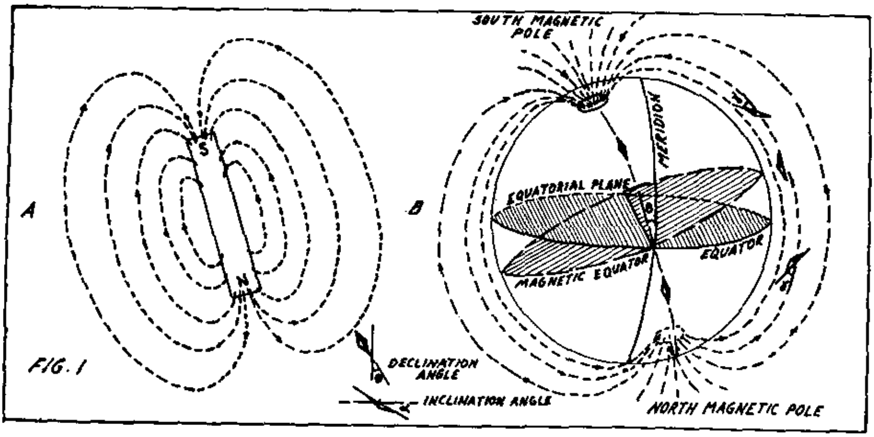
In this section a very brief outline will be given of the geophysical methods commonly employed in investigating geological problems so that the reader may have some idea as to what is involved in making such measurements, what quantities are measured, and how these measurements are interpreted in terms of geology. Examples of results obtained by some of the geophysical methods are included, showing both in plan and profile the type of change that may be expected in crossing certain geologic bodies. In plan the results are generally contoured in much the same way that topography is indicated on a map by lines of equal elevation; that is, lines are drawn through all points of equal value. For example, all points where the reading is zero are connected and the same is done for the points where the value is ten and similarly where the readings are twenty, etc., and thus the areas of high and low values are indicated.

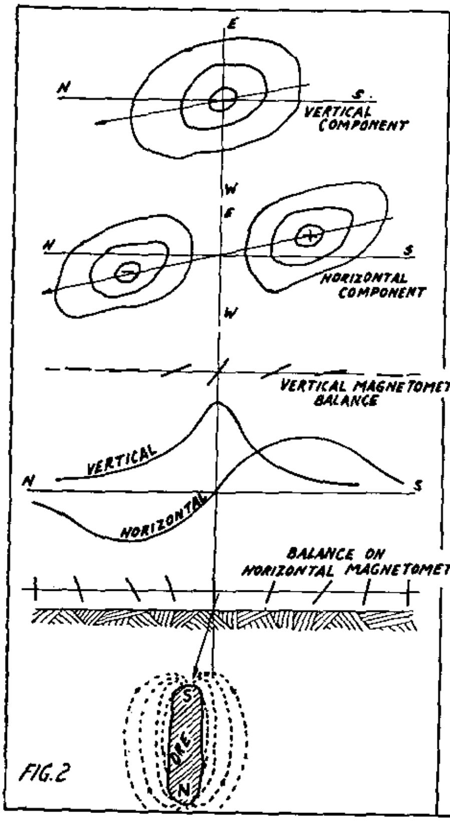
Another method of indicating these areas of change is by means of gradient vectors: that is, by arrows whose lengths are proportional to the increase in value observed, and which point in the direction of the areas of high value.

MAGNETIC METHODS

Magnetic measurements are largely dependent upon the earth itself, which is essentially a large magnet with a north and south pole similar to an ordinary bar magnet. As a result we find that freely suspended small magnets align themselves parallel to the lines of magnetic force surrounding the earth, and this fact is made use of in the compass. It is also a matter of observation that non-magnetic bodies may become polarized as when magnetic cranes are used in handling scrap iron whereby each piece of scrap becomes a magnet itself, and that the field strength of the earth is greatest at the poles just as in a bar magnet whose points of maximum attraction are at the ends, the poles, rather than on the sides.

These conditions not only make many geologic features discoverable through the phenomenon of induced magnetism but also furnish the methods of finding them. Two of the terrestrial magnetic quantities which can be used in geologic investigations are "declination", also known as "variation", and "inclination". The first refers to the difference in degrees of azimuth between the direction of magnetic north as indicated by a compass and true north; and the second to the phenomenon of magnetic dip observed in progressing either north or south from the equator toward one of the poles. The latter is a reflection of the increase





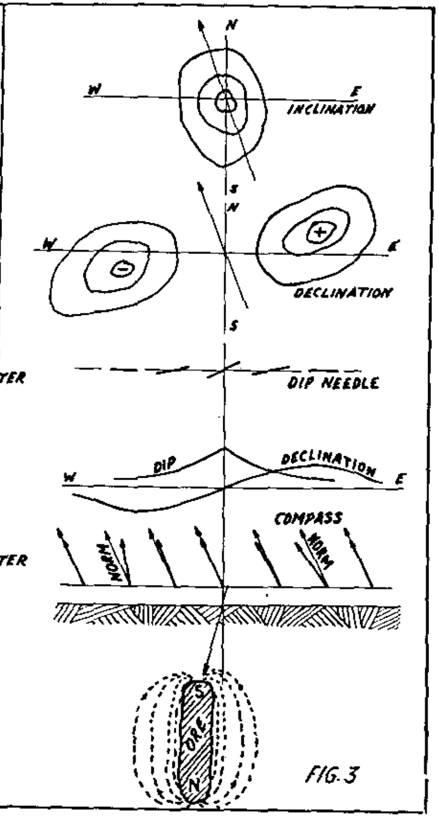


PLATE I

Fig. 1. The earth as a magnet.
  A. Magnetic field surrounding a bar magnet.
  B. Magnetic field surrounding the earth and its relation to the geographic coordinates.

Fig. 2. Anomalous distribution of horizontal and vertical components of the earth's magnetic field over a magnetically disturbed area.

Fig. 3. Anomalous distribution of declination and inclination values over a magnetically disturbed area.

in field strength as the poles are approached. When at the equator and equidistant from the two poles their respective pulls are equal and there is no dip. A move either north or south, however, permits one pole to exert a predominant effect over the other and a dip of the needle is noted. Although these two factors (see Fig. 1-A) taken *en masse* reflect the general magnetic field of the earth, when measured in detail they also reflect the presence of local disturbances due to the existence of such naturally magnetic minerals as magnetite and ilmenite and the secondary magnetic fields that have been caused by the polarization of large bodies of rock or ore containing small percentages of these minerals of high magnetic susceptibility.[1] Such bodies are evidenced in the declination by the change from an area of abnormally large to abnormally small declination, or vice versa; and in the inclination by a marked local increase or decrease in the angle of dip over the normal, the change being dependent on whether the body is more magnetic or less magnetic than the normal field of the surrounding rocks. (See Fig. 3).

Although inclination or "dip needle" studies were among the first tried in using magnetic methods on geologic problems, the dip needle has now been largely superceded by instruments which measure only one component of the angle of dip. These are extremely sensitive to small magnetic changes and because the vertical component is a great deal less sensitive than the horizontal to external magnetic influences such as sun spot activity or other cosmic disturbances we find that the former is commonly measured in exploratory geological work. Its use has an additional advantage in that the magnetically disturbed area so mapped usually corresponds very closely in position to that of the disturbing body; whereas the same body if mapped with the horizontal component will show two anomaly areas, one a maximum and the other a minimum, which flank the disturbing body. (See Fig 2). These horizontal component measurements are useful though in that the distance between the two areas of magnetic disturbance obtained reflects the depths of the disturbance.

Depth computations can also be made with the vertical component data, but they permit only a very broad estimate. The most satisfactory depth determinations are made by plotting the resultant values of both the vertical and horizontal components taken over an area as vectors and using their point of intersection below the surface as the depth of the disturbance. A similar method is also used in inclination studies where the dip is meas-

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[1] The term susceptibility refers to the ease with which a material is magnetized.

ured directly with one of the more sensitive dip needles and plotted vectorially with the normal inclination value. This depth factor is important since the size of the magnetically disturbed area is governed by depth as well as horizontal distribution of the disturbing body. For instance, it is quite possible to get the same areal magnetic disturbance from a small body of high magnetic susceptibility at great depth as from a very much larger body of lower magnetic susceptibility at shallow depth. It is also possible to obtain the same value of magnetic disturbance at any point from a small magnetic body at shallow depth as from a very much larger body at greater depth. As a very rough approximation in field work in making measurements of the vertical component the width of the magnetic anomaly may be taken as equal to the maximum depth at which the disturbance is located. Thus erratic effects produced by filled ground with lots of tin cans, old automobile frames, etc., can be eliminated or quickly tested due to the extremely narrow areal distribution of the disturbance from such causes. As already pointed out, the degree of magnetic disturbance will be controlled by the proximity of the disturbing body and also its magnetic susceptibility.

Some materials which are naturally magnetic are magnetite (the mineral known from ancient times as lodestone), ilmenite, pyrrhotite and franklinite. Other minerals range in magnetic susceptibility from the high values shown by these minerals down to the extremely low values shown by sulphur and bismuth which have magnetic susceptibilities even less than that of air. Values of magnetic susceptibility for common minerals and rocks are given in the following table.

TABLE 1.—MAGNETIC SUSCEPTIBILITIES[1]

Minerals		Rocks	
Magnetite	97,350	Basalt	600 — 15,000
Franklinite	35 640	Peridotite	12,500
Ilmenite	30 740	Diabase	80 — 4,000
Pyrrohtite	7,020	Dolerite	3,000
Specularite	3,215	Olivene Gabbro	5,600
Chromite	244	Gabbro	68 — 3,300
Limonite	220	Granite	8 — 1,500
Sphalerite	58	Norite	52 — 107
Chalcopyrite	32	Diorite	47
Dolomite	1	Serpentine	250 — 14 000
Barite	0	Amphibolite	58 — 9,000
Calcite	0	Gneiss	10 — 2,000
Fluorite	0	Phyllite	130
Galena	0	Schist	115
Quartz	0	Shale	50
Gold	— 3	Sandstone	5
Bismuth	—15	Dolomite	2

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[1] Figures given are c.g.s. units which are to be multiplied by 10^{-6}.

Other factors controlling the nature of a magnetic disturbance are the shape and orientation of the bodies of rock or ore which cause the disturbance. Just as a magnetized needle orients itself so as to parallel the lines of magnetic force surrounding a magnet, whether it is the earth or some other magnetic body, so the lines of magnetic force passing through a body tend to polarize it. For example ,in the northern hemisphere the lines of magnetic force tend to polarize near-surface bodies so that they have a south pole on their upper side and a north pole beneath. This would be the orientation of a magnetized needle (i.e. the dip needle would have the north pole dipping down). Therefore, if a lenticular ore-body was standing essentially vertical its polarization would be such that a south pole would be induced on its upper end and a north pole on its lower end; whereas, if the same ore-body were lying essentially horizontal, the poles would be induced on the respective sides rather than the ends. In this example there is no other difference than the above orientation, yet the magnetic disturbance noted at the surface of the ground would be entirely different. In the first case a marked disturbance over a small area would be noted, in the second a minor disturbance over a larger area would be found. This difference in magnetic effects for the same body may be explained as follows: Since the attraction of a magnetic pole varies as the square of the distance, the attraction measured in the first case would be primarily that of the upper pole since the lower pole is so much further away that its effect would be very small. In the second case the poles are on the sides of the body which means that they are relatively close together and although the upper one still has the predominant effect it is largely nullified by that of the lower pole of opposite sign which is only a short distance below. The difference in areal distribution of the magnetic disturbance in the two cases is a reflection of the size of the pole areas. When in the horizontal position the sides of the body were the poles and as a result a much larger area was disturbed than when the ends were the poles. When bodies occur in between these two positions the disturbance varies in intensity between these extremes and similarly in areal distribution. Magnetic profiles across the body will show an assymetric shape and it is possible from these to postulate the direction of dip of the body.

MAGNETIC CALCULATIONS

A number of corrections are necessary in the calculation of magnetic data, the importance of which varies according to the size of the area embraced by the survey and the magnitude of the anomalies encountered. These corrections can be summarized as: (1) temperature corrections, (2) diurnal variation corrections, (3) base station correction, and (4) latitude correction. The first is necessary because of slight changes in the instrument's sensitivity with temperature; the second because of changes in the earth's magnetic field during the day. The latter change is determined by either keeping one instrument at one spot during the day with an observer taking continuous readings, or else by approximating the change by returning to a base station every couple of hours to note the change in reading. The base station correction is the difference between readings at any station after taking out the temperature and diurnal corrections. This change may be due to handling of the instrument or a minor accident. Where only one instrument is in use the base correction is included in the diurnal correction. The latitude correction is only of marked importance where a large area is embraced. As the earth's poles are approached there is an increase in field strength which must be taken into account in reducing the data for all but very local areas, where all stations would be affected equally.

The method, as has been pointed out in the preceeding section, is well adapted to many mining problems and is also used for reconaissance work in oil exploration as well as on other geologic problems.

GRAVITATIONAL METHODS

Three different types of instrument have been used in gravitational methods of investigating geologic problems. The first is the pendulum which takes advantage of the fundamental physical relation that the period of swing of a pendulum bears a constant relation to the length of the pendulum divided by the acceleration of gravity. Therefore, if the period of a pendulum of known length can be measured accurately enough, and friction and other mechanical forces taken into consideration, it is possible to determine experimentally the acceleration of gravity. As generally used in physics this value is taken as a constant, but actually this is not the case. It would be constant, for instance, if the earth were a perfect sphere that stood still instead of rotating and was composed of homogeneous material; but the earth approaches an orange in shape, it does rotate and this results in a centrifugal *force that opposes the gravitational pull of the earth, and it is* made of materials of diverse densities. In addition, its surface is highly irregular, all of which results in the gravitational force varying from place to place. Corrections can be made for such factors as the effect of the general shape of the earth, its rotation, and the variations in elevations, but the variations in mass distribution due to geologic causes can only be approximated, since they are for the most part not known. As a result, geologic investigations can be made by noting the magnitude of the gravity values left after correcting for all the other known factors and interpreting the residuals in terms of the known densities of rocks and the geologic structure. These residual values are generally referred to as anomalies.

The gravimeter is another instrument used for measuring changes in the earth's gravitational field and though there are numerous different types in use they are all essentially very sensitive weighing devices which consist of a mass supported by a single spring or spring system which permits variations in gravitational attraction to be measured to one part in ten million of the earth's gravitational field. As instruments of this type require only a few minutes for an observation as compared to several hours with a pendulum, they are the ones commonly used in field work.

A third type of instrument that has been used in measuring gravity is the torsion balance. This instrument is very sensitive to horizontal forces, so much so in fact that corrections must be made for the effect of trees and fence posts within a hundred feet of the station. It consists essentially of two small gold weights, either placed on an inclined boom, or attached to a horizontal boom so that one weight is at a lower elevation than the other, and the whole is suspended by a fine thread so as to be free to rotate in a horizontal plane. Due to the differential attraction of the gravitational field on the two weights, the system twists until an equal opposing torque is established and this rotation is then recorded. By taking observations in six azimuths, data are obtained which permit two gravitational quantities to be determined, the gravitational gradient and the curvature or horizontal directive force. These two quantities can perhaps best be visualized if we consider the gravitational surface as being similar to a topographic one and characterized by ridges and valleys, swells and swales, and peaks and basins. The gradient value obtained is the degree of slope in the direction of maximum positive slope. To use a topographic comparison, the value at any point might be described thus: a five per cent grade up hill in a southwest direction. The curvature value gives the direction of orientation of a horizontal boom with weights on the ends suspended by a torsionless fiber and is plotted as a vector whose length reflects the degree of change in the level surface at this point from that of a sphere. With these two values obtained at each station and plotted as vectors the direction of the gravitational highs or ridges would be shown by the gradient vector arrows,and the axes of the topographic forms (ridges, troughs, scarps) in the gravity surface by the curvature vectors. On anticlines and the up-throw side of faults the curvature vector parallels the structural axes. In synclines and on the down-throw side of faults the curvature is perpendicular to the structural axes. The relations between these various sets of data are shown in Fig. 4.

The torsion balance is very seldom used at the present time due to the large time factor involved in taking observations which consume several hours at each station. Before the advent of the gravimeter, however, it was used with great success, in locating salt domes in the Gulf Coastal Plain. The results obtained over a salt dome are illustrated in Fig. 5 for both a gravimeter and torsion balance survey.

In gravitational work it is frequently found that there are large anomalies many miles in width which because of their size cannot be related to known geologic features. Consequently in determining geologic structure it is necessary to eliminate these large effects and use only the extremely small values which are left. The significance of the large anomalies is believed to be deep-seated and perhaps due to very marked changes in the nature of rocks deep within the earth's crust, and since this region is beyond the limits of exploration we can only postulate the cause. The source is believed to be deep beause of the wide areas over which the anomalies occur and the general smoothness of the anomaly curve. For near-surface features the areas involved would be smaller and the changes more erratic, since near-surface geologic variations are extremely variable both as to size and kind of rock present. Since measurements showing a deep-seated control would embrace many kinds of rocks, the gravity anomaly would reflect the average effect of the whole crust down to the primary cause of the anomaly, this distance factor plus the inclusion of so much diverse material would smooth out the anomaly curve. An analogous effect is produced when one looks down on a range of mountains from an aeroplane. When flying low they appear quite sharp, but the higher one goes the smoother the scene below appears. Another reason for believing these large anomalies are due to deep-seated causes is the fact that they quite

FIG. 4

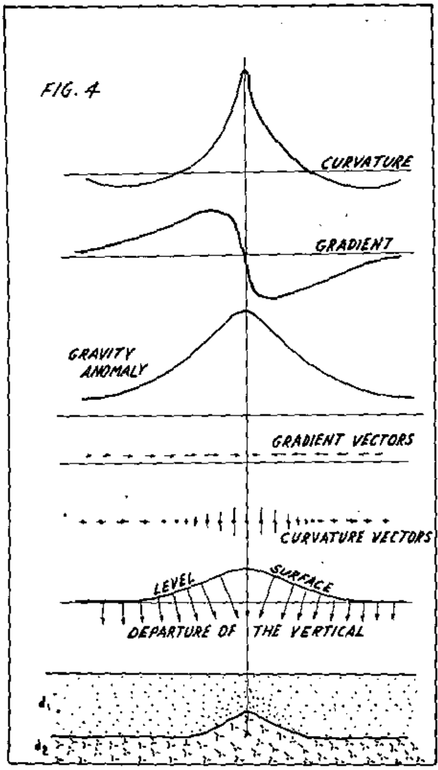


FIG. 5

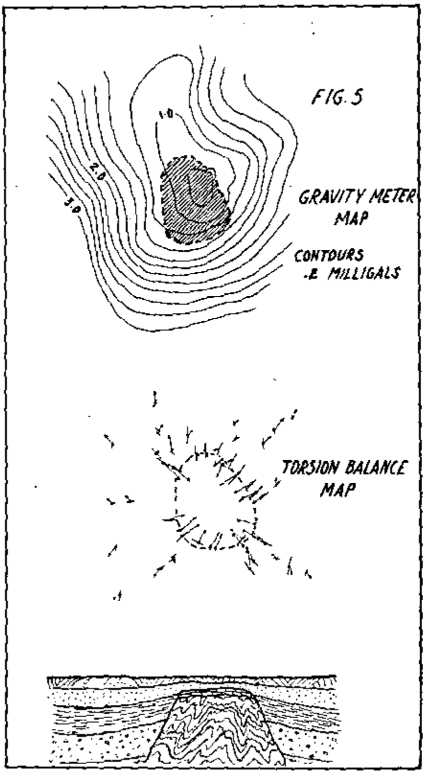


FIG. 6

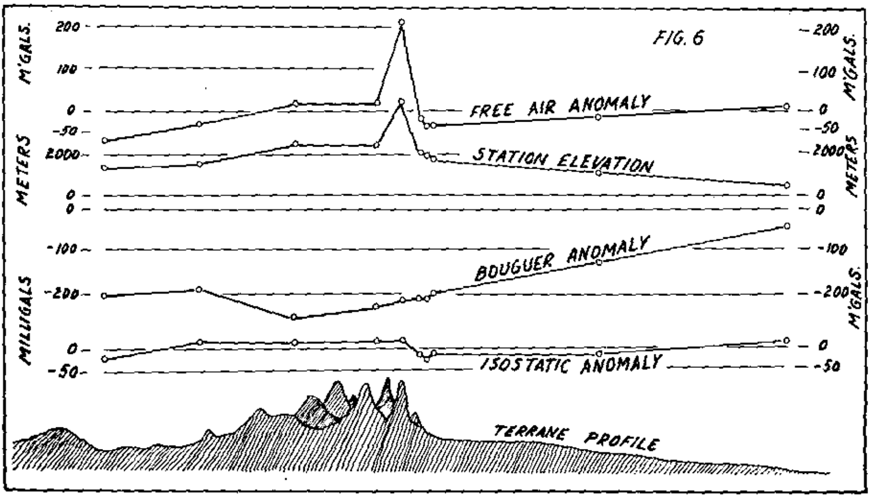


PLATE II

Fig. 4. Anomalous distribution of gravitational quantities over a gravitationally disturbed area.

Fig. 5. Effect of a salt dome on the gravitational field as shown by "A", a gravimeter map, and "B", a torsion balance map.

Fig. 6. The relation of gravimetric Free Air, Bouguer and Isostatic anomalies in crossing the Rocky Mountains.

frequently embrace areas of diverse surface geology with marked changes in density whose effects are almost completely masked by the large anomaly and only show up in the small residuals left after removing the effect of the regional anomaly.

Gravitational values therefore, like magnetic ones, reflect the combination of size of the disturbing body, its depth below the surface, and its departure in physical property from that of the surrounding material. The latter factor in this case is the density of the rocks involved rather than their magnetism. Some of the densities of the more common rocks and minerals that might give rise to anomalies are listed in the following table.

TABLE 2.—DENSITIES

Minerals	
Gold	19.4
Galena	7.6
Chalcocite	5.8
Magnetite	5.2
Franklinite	5.1
Barite	4.7
Chromite	4.5
Sphalerite	4.
Limonite	4.
Salt	2.2
Sulphur	2.

Rocks	
Peridotite	3.55
Gabbro	3.09
Norite	3.2
Diorite	2.99
Dolomite	2.8
Diabase	2.7 — 3.1
Granite	2.5 — 2.7
Serpentine	2.5
Shale	2.3
Sandstone	2.2 — 2.5
Clay	1.6
Coal	1.2

Just as with magnetic data, certain corrections have to be made to gravitational data before an interpretation of readings can be made. These include a correction for elevation, since the gravitational value varies as the square of the distance and it is thus necessary to reduce all data to a common datum; a correction for the latitude due to the fact that the earth is shaped like an orange and hence the gravitational force increases both north and south of the equator; a drift correction in gravimeter reading for errors introduced by slight changes in the elastic behavior of the springs; a terrane correction to take into consideration the effect of the mass of the material lying beneath the station and down to the reference datum (i.e. sea level); and in areas adjacent to mountains, an isostatic correction to compensate for the deficiency in mass associated with mountain ranges. The need for exact elevations is a drawback to gravitational methods since this frequently necessitates special survey parties to obtain this data and this adds to the cost of the measurements. Likewise, the terrane correction requires a knowledge of the topography surrounding the station so that the mass effects of hills rising above the station and valleys lying beneath it may be eliminated. Though this information has to be obtained in very great detail—in fact to inches of change within a radius of a hundred feet—for a torsion balance station, gravimeter work requires only a rather generalized map of the changes. In fact it is customary when working with a gravimeter to disregard elevation changes that make an angle of less than 12° with the horizontal.

The isostatic correction is based upon geodetic measurements which show that a plumb-bob in the vicinity of a mountain range is attracted toward it; yet where a correction is made for the mass of the mountains, instead of the plumbline coming back to the vertical, it is inclined away from the mountains, thus showing that they are characterized by a deficiency in density. This discovery gave rise to the theory of isostasy according to which the mountains stand high because they are light. That is, all columns of the earth's crust down to an arbitrarily chosen depth have the same mass. Therefore, if one stands higher than another and hence has a greater volume, it must have a smaller density value. Another conception of this phenomenon is that the columnar sections of the earth's crust are really like blocks of ice floating in a sea of a much denser rock. Hence changes in the relief at the surface are accompanied by correspondingly larger changes at the bottom of the columns, giving downward projections of light crustal rock in the denser medium below and thus giving rise to the phenomenon noted with the plumbline in the vicinity of the mountains. According to the first concept, the Pratt hypothesis, which is the one used in North America, all crustal sections terminate at a fixed depth beneath the surface where they come in contact with a denser substratum; and according to the second concept, the Airy hypothesis, which is the one commonly used in Europe, the crust is likened to blocks of ice with each upward projection compensated by a downward projection, thus giving an irregular contact with the dense subcrustal material. For each hypothesis the corrections based on the assumptions mentioned come out practically the same and it therefore makes little difference which is used. This isostatic correction is seldom applied in geologic exploration, mainly because most surveys are of small areas and the correction would be about the same for all stations. In regional work, however, it is important. Gravitational values other than torsion balance results (which are expressed as gradient and curvature vectors) are generally expressed as one or another type of anomaly. Free Air anomalies refer to the fact that the results have been corrected for all instrumental factors such as drift, temperature, barometric changes, etc., and in addition the latitude of the station and the elevation above sea level. Bouguer anomalies are simply Free Air values plus the correction for the terrane and the mass down to sea level. Isostatic values are the Bouguer values plus the isostatic correction for the changes in elevation relative to the standard column which is taken as having the elevation of sea level. The changes which result when the three sets of data are plotted are shown in Fig. 6.

SEISMIC METHODS

The seismic methods—for there are two fundamental methods of using this technique—make use of the wave caused by an explosion which is either reflected from, or refracted along, some geologic horizon whose change in physical properties from the overlying beds is sufficient to have such phenomena take place. The fundamental physical laws involved are those of optics, and in both methods the distance to a refracting or reflecting horizon can be computed by accurately observing the time it takes for an explosion wave to go from the point of shooting down to such a surface and back to the surface of the ground where its arrival is recorded by a series of detectors called geophones. The path the wave will follow in reflections will be similar to that generally associated with light striking a reflecting surface where the angles of incidence and reflection are the same; and since these angles with the vertical are small, it is necessary to have the detectors close to the shot hole in order to record the wave arrivals on their return to the surface. In the case of refractions the condition is similar to that observed in spearing a fish where the light rays are bent as they pass from air into water giving a false impression of the actual position of the fish. In seismic refractions the wave path is bent as it passes progressively through strata of different physical properties and the wave front is thus deformed so that part of the energy travels at higher speed through certain strata and reaches the general surface ahead of direct surface waves traveling at lower speeds (see Fig. 9). Since this phenomenon is a function of the thickness of low velocity material and also the difference in velocity between the low and high speed horizons, the distance from shot to detectors necessary to get first arrivals from a deep horizon varies. Roughly it is around three times the thickness when the velocity differential is about three. The wave paths are therefore, much longer with refractions than with reflections and heavier charges of dynamite are required.

There are several other differences in the two techniques. For instance, it is customary in reflection work to place the shot much deeper than in refraction work, an effort being made to get below what is commonly termed the weathered layer, or zone affected by ground water and hence altered or weathered. This is done to avoid possible errors introduced by the poor transmission characteristics of this zone. Due to the short wave paths in reflection work, explosive charges are generally only a few pounds of dynamite; whereas in refraction work perhaps a hundred pounds and even on occasions tons of dynamite have to be used. For refraction depth investigations involving horizons about 5,000 feet deep, the writer's experience has been that about forty pounds of dynamite is sufficient except in very abnormal cases where the presence of peat or other high-energy absorbent material makes very large charges necessary in order to get a record of the explosion. The instruments and the arrangement used in both methods are very similar with the exception that it is necessary in reflection work to have a filter in the circuit which will permit only certain frequencies to pass so that the reflections can be recognized on the record. The time factor, which is so important, is determined by recording both the instant of the explosion and the arrivals of the waves at the geophones on a photographic tape. Time lines are put on this tape by the breaking of a reflected beam of light by the vibrations of a tuning fork with a frequency of 200 vibrations per second. On these are imposed traces from a series of galvanometers with mirrors attached which reflect a beam of light onto the tape. Each galvanometer is connected to a geophone which in reality is a small electrical seismograph and the small changes in current caused by the arrival of the waves is amplified and passed on to the galvanometers which deflect accordingly and cause a visual record of the arrival of the waves to be obtained. In refraction work the instant of firing is obtained by breaking the circuit of a radio transmitter at the point of firing and this break is picked up by a radio receiver at the recording end and put on the tape through another galvanometer. In reflection work a telephone line is used to transmit the firing instant to the recording apparatus. For diagrams of the apparatus and field layout see Figures 7 and 8.

The arrival times are taken off the photographic tape by counting the tuning fork time lines from the shot instant to the wave arrivals. These time data can then be plotted on a time-distance graph and the velocities of the various horizons determined (see

Fig. 9). From these velocity data the depths are then calculated using the actual wave paths followed, and the results obtained are generally within a few percent of the actual depths depending upon how regular and homogeneous the geological conditions are. In using these velocities one precaution has to be taken, however, for if the beds are dipping to any extent along the line of the investigation, excessively high velocities will be obtained when recording up-dip from the shot and abnormally low values when recording down-dip. If the dip is quite marked, an offset will be noticed on the time-distance graph; but it is generally best to make observations in both directions in order to determine the true values. Conversely, by "shooting" in both directions, the magnitude and direction of dip, if any, may be determined.

In somewhat similar fashion this method has been used for areal delineation of near-surface features involving marked changes in velocity, as would be the case with shallow salt domes, buried stream channels, etc. In this type of investigation, known as fan shooting, the procedure is to place a string of detectors along a road and shoot off to one side of the string rather than on the same line as in making depth determinations. If there are no marked subsurface changes the arrival times at the geophones would give the same velocities. However, if there are marked changes, one or more detectors will give arrival times indicating higher or lower velocities than what might be considered normal for the average geologic column. The detectors are then moved so as to extend the string in the direction of indicated change or across it on a different angle, so that by degrees the anomalous area is outlined. The velocities are generally plotted on the radii from the shot to the detectors and thus the area of change indicated (see Fig. 10).

The main value of the seismic method has been in determining the depth to certain key horizons and thus locating geologic structural changes. Its use has been adopted in road construction and investigations of dam sites as well as by the oil industry. For the former type of work a simplified set of instruments is used which can be carried around in a couple of suitcases. This eliminates the special trucks and other heavy equipment necessary in the deep explorations of the oil industry and which are desirable also for most geologic work. The method is handicapped, particularly in highly settled regions, by the annoyance sometimes created by the explosion of heavy charges of dynamite. This applies more specifically to the refraction method which re-

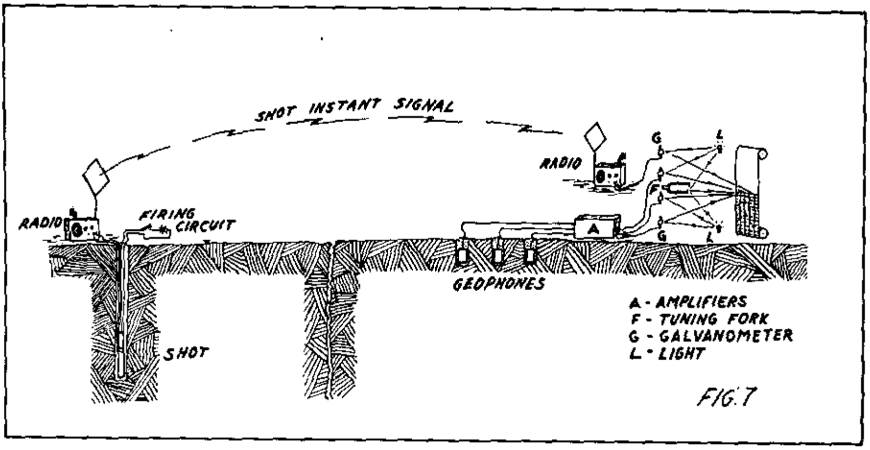


FIG. 7

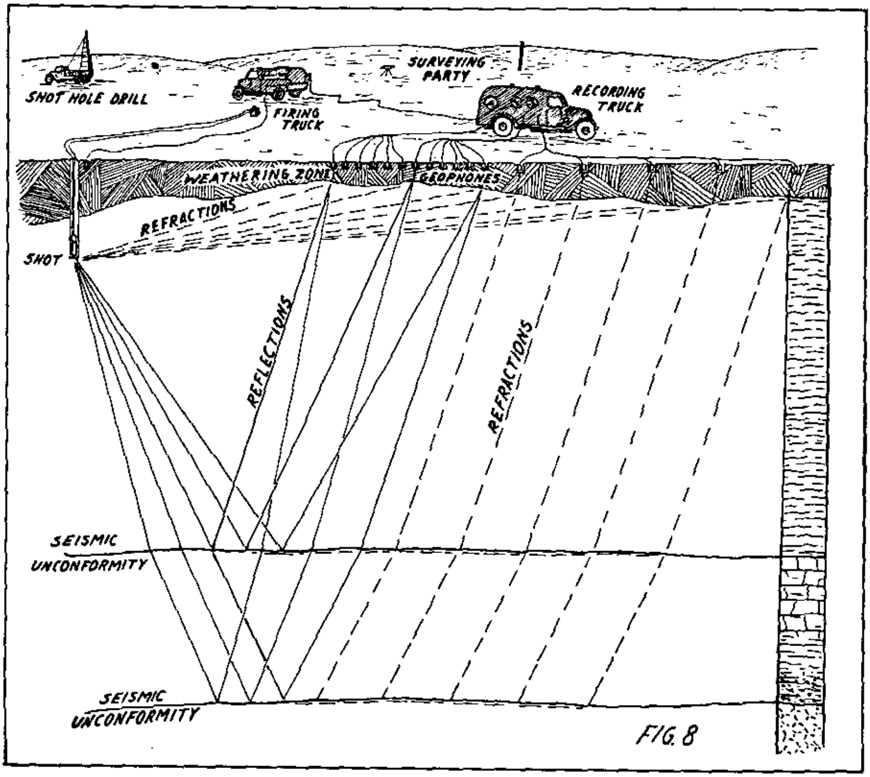


FIG. 8

PLATE III

Fig. 7. Instrumental "layout" for seismic refraction work.
Fig. 8. Diagram of field relationships in making seismic investigations.

FIG. 9

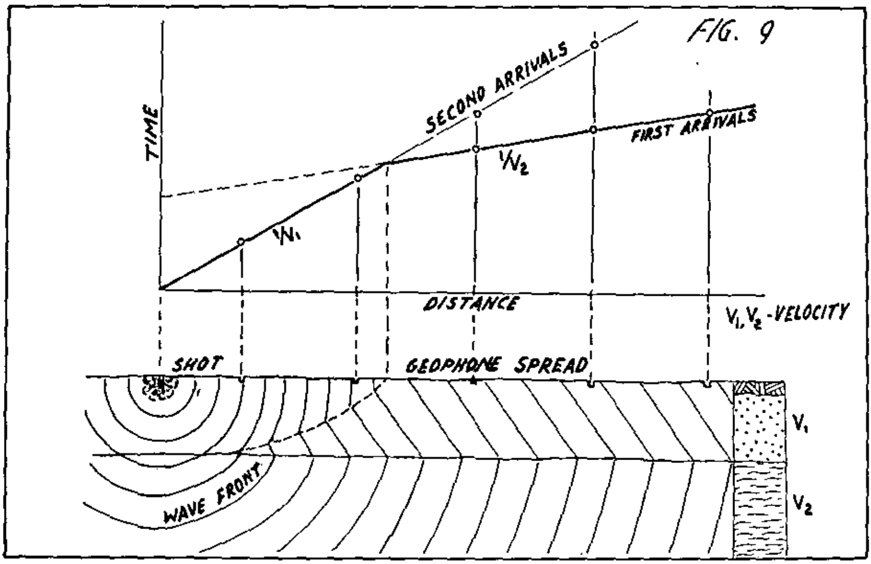


FIG. 10

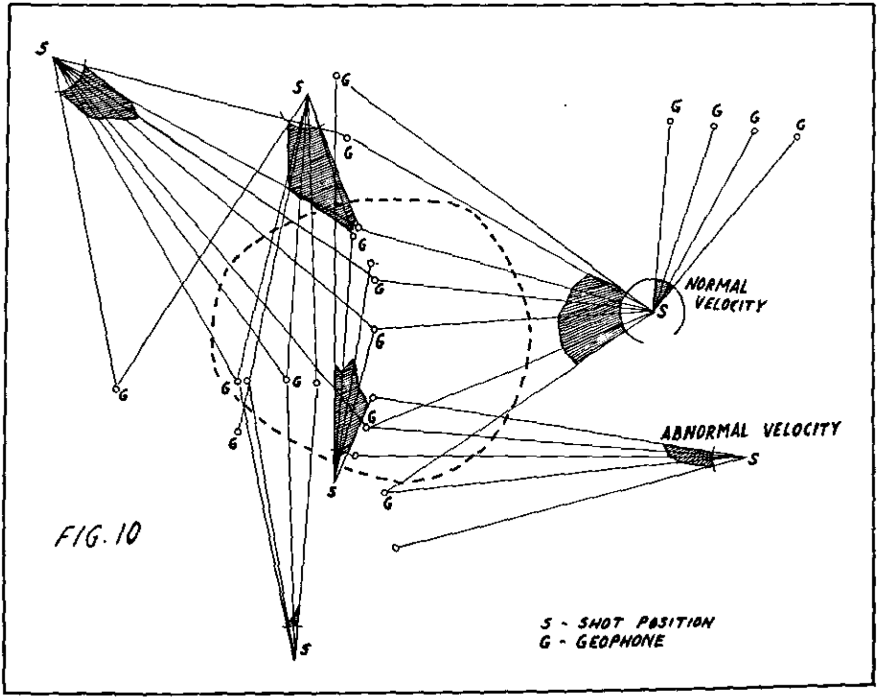


PLATE IV

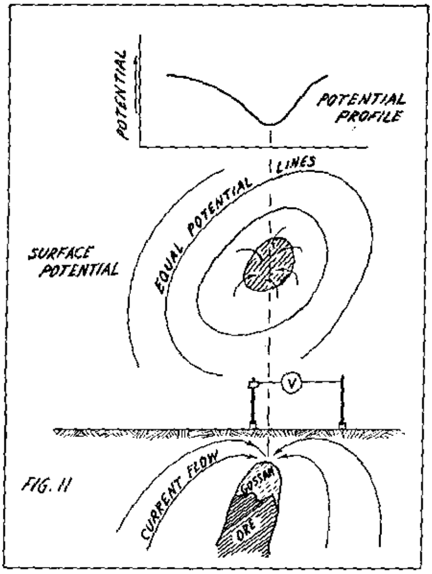
Fig. 9. Time-distance graph and its relation to the wave paths in seismic refraction work.
Fig. 10. Diagram of *Fan Shooting* Method for outlining anomalous areas such as a salt dome.

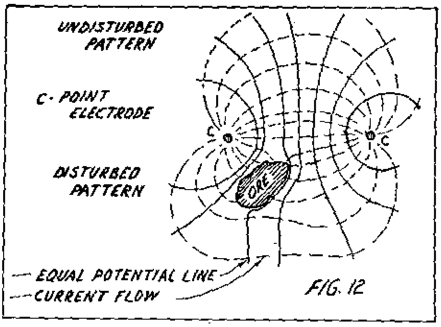
quires a spread of over half a mile for the geophones for most work, and waste land in which to explode the dynamite. Despite this handicap, however, it has been possible to carry out investigations in most areas.

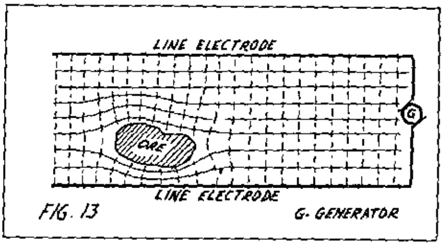
ELECTRICAL METHODS

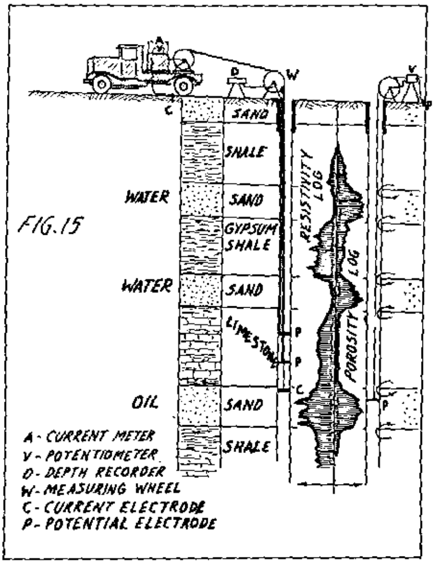
The term electrical methods embraces so many different techniques and kinds of apparatus that they have to be divided into groups. Some of the first used were the self-potential or natural current methods. Their operation depends on the existence of a natural galvanic field resulting from the action of ground water on certain metallic sulphide ore-bodies which form a natural battery and reveal the presence of the ore-body by the resulting potential field (see Fig. 11). Other methods take into account the fact that many ore-bodies are good conductors and if current is introduced into the ground so as to flow between a pair of point or line electrodes, the presence of the buried conductor can be determined by plotting the equipotential lines to see if the field between the electrodes is disturbed or not. If only homogeneous material is present a symmetrical potential field is obtained between the electrodes; but if a conductor is present, the equipotential lines deflect away from the conductor and its presence is immediately discernable. (See Figs 12 and 13).

Other methods make use of resistivity measurements: that is, current is introduced into the ground through a pair of electrodes and the difference in potential between another pair of electrodes is noted. From these data the apparent resistivity of the ground is computed by using the relation that resistance is equal to the potential drop divided by the current. In making resistivity measurements it has been found that best results can be obtained by certain arrangements of electrodes. In one of these, the Wenner configuration as it is called, the four electrodes are placed in a line and spaced at equal distances from each other. The two current electrodes are in the end positions and the potential electrodes in the center position (see Fig. 14). By moving this string of electrodes along a line with an overlap each time, it is possible to detect subsurface changes due to changes in the apparent resistivity. Since the depth of penetration of the electric field is about equal to the electrode spacing, the method is also useful for determining the depths to geologic horizons. This is done by keeping the spread centered at one spot and progressively increasing the electrode spacing until a "break" is obtained in the resistivity curve. The spacing at this point is then









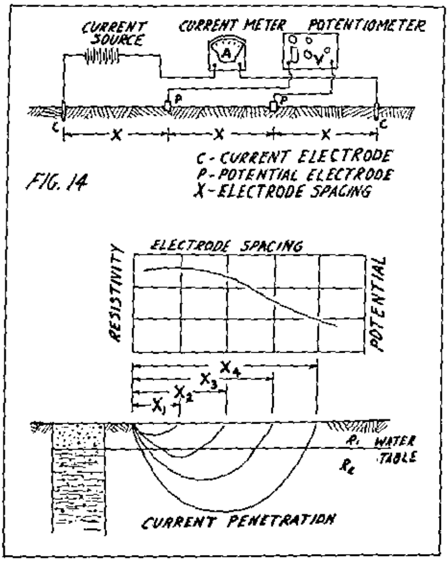


PLATE V

Fig. 11. Diagram of Self Potential or Natural Current Method of making electrical investigations and results obtained.

Fig. 12. Equipotential line pattern for an undisturbed and a disturbed area using point electrodes.

Fig. 13. Equipotential line pattern for an undisturbed and a disturbed area using line electrodes

Fig. 14. A. Diagram of Wenner configuration for making electrical resistivity measurements.

B. Resistivity curve showing the effect of ground water and relation between depth of penetration and electrode spacing.

Fig. 15. Diagram of method of electric well logging and log obtained.

taken as equal to the depth of the disturbance. This system has been used by both the Bureau of Public Roads and the War Department in making determinations of the depth to bed rock in connection with various civil engineering problems. (For a typical curve, see Fig. 14).

There are several different methods of making resistivity measurements. One called the Porous Pot method involves the use of ordinary direct current and this necessitates the use of non-polarizing potential electrodes known as porous pots. These pot electrodes are of unglazed pottery with an electrolyte of copper sulphate solution surrounding copper electrodes. They are necessary on account of potential effects that are obtained due to chemical reactions between metallic potential stakes and ground moisture when the former are driven into the ground.

Other methods, notable the Gish-Rooney and Megger, make use of a commutator which reverses the current often enough to get rid of the stake effects by reversing the polarity. Still other methods, as the Lee Partitioning method, derive their names from slightly different arrangements of electrodes. In this case three potential electrodes are used with one at the center of the spread that remains fixed while the others are moved, and observations are made of the potential drop over each potential pair. One advantage of this configuration is that it indicates the direction of change.

Electrical resistivity measurements have also been used to detect the presence of possible oil-bearing sands in drillholes. The electrodes are lowered into a well and the resistivity is measured as the system is lowered, much as in surface measurements. By measuring only the potential drop and plotting the changes, the location of porous sands can be determined due to the infiltration of the drilling mud into the sands and the resultant potential drop caused by the current infiltration at these points. The two sets of data give what is known as an electrical log. Sands or other porous horizons are thus indicated by areas of potential drop, and those sands carrying oil can be distinguished from the water sands by the high resistivity of the former. Geologic information of economic value can thus be obtained directly without the expense of cores by this method. (For an illustration of apparatus and results see Fig. 15). Some of the common resistivity values for rocks and minerals are given in the following table.

TABLE 3. ELECTRICAL RESISTIVITIES

SPECIFIC RESISTIVITY IN OHMS/CM^3

Minerals		**Rocks**	
Rock salt	10^{29}	Limestone	10^{11}
Calcite	10^{14}	Granite	10^{10}
Quartz	10^{14}	Slate	10^{10}
Sphalerite	10^{8}	Porphyry	10^{9}
Hematite	10^{8}	Coal	10^{9}
Magnetite	10^{-1}	Diabase	10^{8}
Copper sulphides	10^{-1}	Sandstone, dry	10^{6} to 10^{10}
Pyrite	10^{-2}	Serpentine	10^{5}
Galena	10^{-3}	Sand, moist	10^{3} to 10^{5}
		Clay, wet	10^{3}
		River water	10^{2} to 10^{5}

Among other electrical methods that have been used is one involving electrical transients, but these measurements have only been used to a limited extent in oil explorations, and not at all on other problems.

Although electrical methods are relatively inexpensive, they are subject to two serious drawbacks: (1) external electric effects, and (2) it is possible to obtain the same results from widely different geological phenomena. For instance, many a water-soaked fracture zone has been thought an ore body until drilled.

ELECTRO-MAGNETIC METHODS

Numerous methods come under this head and they all involve the general principle of setting up an electro-magnetic field which, if a conductor is present, will cause a current to be induced in it and that in turn will establish a secondary magnetic field. The presence of the conductor is then derived by noting whether the primary electro-magnetic field has been distorted by the formation of a secondary field.

The methods can be divided into two groups; (1) those in which the primary field is established by passing current through conductors laid out on the ground similar to line or point electrodes in ordinary potential measurements, and (2) those in which the ground is energized by broadcasting an electro-magnetic field from an insulated loop. In both cases the disturbance can be located by using a search coil with several hundred turns of wire and an amplifier. Telephone headsets are frequently used to determine the null position of the coil — the position in which the coil is perpendicular to the resultant of the exciting field and the secondary field. This resultant may also reflect the effect of other conductors, which means that the position of silence cannot always be used directly to indicate the direction of an ore-body. There are numerous modifications of these methods, one of which is used to locate points of equal potential and thus outline the subsurface body much as with electrical potential measurements. The methods have met with their greatest success in locating sulphide ore-bodies, and another common use has been in locating buried pipe lines.

Radio-active Measurements

The radioactive methods all depend upon natural radioactive emanations, particularly gamma rays, by certain minerals or collections of minerals which are more radioactive either naturally or through secondary concentration than the adjacent material. The instrument used has been the Géiger Counter which is an ionized chamber containing two electrodes between which there is a discharge whose frequency varies according to the external ionization caused by the proximity of radioactive material. For instance, in prospecting for radioactive ores such as the carnotite deposits in the petrified forests of Arizona, the Counter will discharge more frequently as a mass of this mineral is approached. It has been used similarly in prospecting for the pitchblende deposits in the northern part of Canada. Another more recent use has been in locating the position of sands and also old erosion surfaces in wells by lowering such an instrument inside the casing. In this respect it has proven superior to electrical logging since cased wells cannot be examined by the latter method. This technique is commonly referred to as Gamma Ray logging and in general it is found that sands are characterized by a low gamma ray count as compared with shales and this permits their definition as well as with a potential log.

Considerations which Determine the Choice of Geophysical Methods

The methods described are the ones most generally used in subsurface geological exploration. It frequently happens though that the geophysical data obtained in areas where there are no well data cannot be adequately interpreted without such data and the cost of the bore holes needed to clarify the geophysical findings has to be added to the exploration cost. This cost is trivial though as compared to that of a complete drilling program and such a combination of drill hole and geophysical data gives a knowledge of a large area which would not be economically possible if this same data had to be obtained entirely from wells. The wide adoption of geophysics and its successful application to so many geological problems has marked it as one of the greatest steps forward in the study of geology; however, there have been many instances of the complete failure of geophysical techniques in solving problems, particularly those dealing with mining. Some of these failures could not have been anticipated in view of the complete absence of knowledge on other factors, both geologic and artificial, that entered into the results; but many others could have been prevented. Just as every mining problem is unique unto itself and is recognized as such by all competent mining men and geologists, so the geophysical problem at every mine is an unique one. It is absolutely essential that something be available to calibrate against if a lot of cut and try work is to be eliminated. Many mining companies interested in having ore-bodies extended have called in geophysical companies to work on their problems and yet have refused to allow them to calibrate against known ore-bodies on the assumption that if there was anything to the methods they would show up the ore. As a result ore has been predicted where there was none, and ore has actually been found at places denoted by some geophysical company as being least favorable. Frequently a company has tried a method with negative results that had proved highly successful at another mine with apparently the same sort of mineralization.

These examples serve to call attention to the fact that it is absolutely necessary to have available all the geologic information possible if geophysics is to be employed satisfactorily. Even with the benefit of all available geological knowledge it frequently happens that certain methods cannot be used successfully. For example, in involved structural areas where there is much folding and faulting, the seismic method is impractical since the records are too involved to be interpreted. This method works best in areas such as the Coastal Plain where the geologic structure is relatively simple and the stratigraphic changes quite marked. The gravitational method on the other hand has been used successfully in locating ore-bodies in areas of involved geology.

The magnetic method has been used with marked success only where the presence of bodies of large magnetic susceptibility has given rise to large changes in the magnetic field. Its use is handicapped by the fact that it is affected by stray currents and the presence of mining equipment. Similarly, the electrical methods have been used successfully in some areas of involved geology and in making depth determinations; but they have failed to give satisfactory results in others because of unknown factors, external currents, or the lack of a sufficient differential in electrical properties between the material being investigated and the country rock. However, if the limitations of the various methods are kept in mind and tests conducted on small calbiration areas in any one locality to find which of the apparently favorable methods gives positive results, there is no reason why a large percentage of successful investigations should not be obtained. Furthermore, in those areas in which geophysics is not applicable, such calibration tests would determine this at minimum expense.

Despite these many limitations, the fact remains that the employment of geophysics has played a more important role in the advancement of geologic knowledge and the economic development of our natural resources than any other single factor in the last twenty years.

PART III

GEOPHYSICAL INVESTIGATIONS IN NEW JERSEY

Instead of presenting the geophysical investigations made in New Jersey under the captions of the various methods employed, the writer will discuss the work done in individual areas since several geophysical techniques have been applied in these in order to obtain comparative data over the same geologic formations.

New Jersey Highlands

Magnetic investigations.—In this part of northern New Jersey there are extensive deposits of magnetite, the naturally magnetic iron ore, that have been mined since 1685, or earlier. These deposits occur in both banded gneiss and the Franklin limestone. The deposits worked commercially have for the most part been in the gneiss where the ore occurs as mineralized sheets which range from non-commerical thin lenses to rich pod-shaped bodies running over 90 percent pure magnetite. As a result of these concentrations of magnetite, the adjacent magnetic field is disturbed to a marked extent. In fact, where the ore is close to the surface as on the old Canfield property on Mine Hill, west of Dover, a swing of nearly 180° in the compass reading may be observed within a horizontal distance of a hundred yards, and disturbances in the declination of 25 degrees or more are commonly associated with the ore deposits. Similarly, changes in magnetic dip readings have been noted from minus fifty degrees to plus seventy-five degrees in a horizontal distance of only a few feet. These data indicate that the magnetic bodies are both strongly magnetic, since the compass needle is drawn towards them, and also polarized, since the reversal in dip indicates that a magnetic pole has been crossed. These facts were appreciated as early as 1868 when George M. Hopkins made a map of the iron deposits in the vicinity of Dover and in addition indicated the position of areas of marked magnetic attraction. In 1879 W. H. Scranton made a magnetic declination and dip-needle survey over the Washington Mine near Oxford and a portion of this map is shown in Fig. 16 as being typical of the results to be expected from a survey of the magnetite ore-bodies of this district. The most complete work, however, was done around 1890 by Thomas A. Edison who formed a company which prospected much of the iron district with both declination and dip-needle surveys. The surveys for the most part appear to have been done in the vicinity of known workings and were unquestionably instrumental in prolonging the life of several mines by indicating the presence of new ore-bodies. The amount of new ore indicated can only be surmised from the report of William S. Bayley[1] who was given the opportunity to examine the Edison maps which unfortunately now appear to be lost: "An inspection of these maps shows that the areas over which high dips have been observed

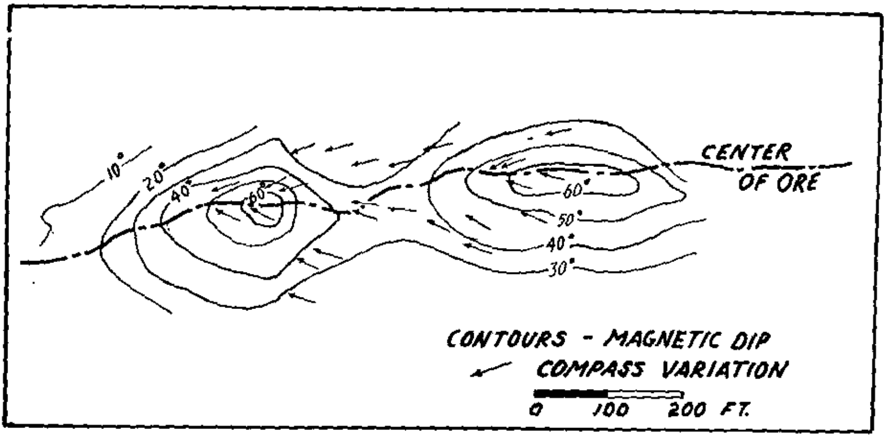


Fig. 16. Magnetic dip and compass variation measurements on a magnetite ore body at the Washington Mine.

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[1] Bayley, William S., Iron Mines and Mining in New Jersey: N. J. Geol. Survey, Final Rept. VII, 1910.

are in the aggregate very large, thus indicating a considerable reserve of ore which has not yet been touched."

Although mining companies have removed more than 27,000,000 long tons of ore from New Jersey's developed iron ore deposits, and in 1940 alone produced 1,292,794 long tons, the prospective ore-deposits outlined by Edison's surveys have remained untouched and are still awaiting development. Perhaps this will be accomplished by iron-mining companies on their own initiative, but if the State of New Jersey wishes to insure the continuation of its mining industries, it would seem to be a wiser policy not to leave this development to chance, but to point the way to assured reserves of ore by a resurvey of the entire iron ore belt with modern geophysical equipment to be followed by enough core-drilling of the best prospects to show indisputably that these are large enough and the ore of good enough quality to interest any company in need of ore.

In this same area lie the Franklin Furnace zinc deposits, but as far as the writer is aware no geophysical measurements have been made there. However, the amount of franklinite present in the ore would indicate that ore-bodies could be found with the magnetic method providing there were no other complicating factors, since franklinite has a very high magnetic susceptibility.

In connection with absolute magnetic measurements over the United States the U. S. Coast and Geodetic Survey has established several magnetic stations in the Highlands, and although these serve to show the regional variations in the earth's magnetic field, they show little relation to the local geology.

Gravitational measurements.—A few gravitational stations have also been established in the Highlands by the U. S. Coast and Geodetic Survey as part of their general network covering the country, but they have not carried out a detailed gravitational survey. The region lies on the flank of a marked gravitational trough which extends into Pennsylvania and New York, and any geologic interpretation of gravitational work in this area would have to depend upon the residuals left after removing the effect of this regional variation. (For the areal gravitational relations in New Jersey see Fig. 17).

Electrical measurements.—Probably the first attempt at geophysical prospecting by electrical methods in New Jersey was an investigation of five dam sites in the Highlands area conducted by the Schlumberger Electrical Prospecting Methods in the winter of 1929-1930. Of the sites examined three were on

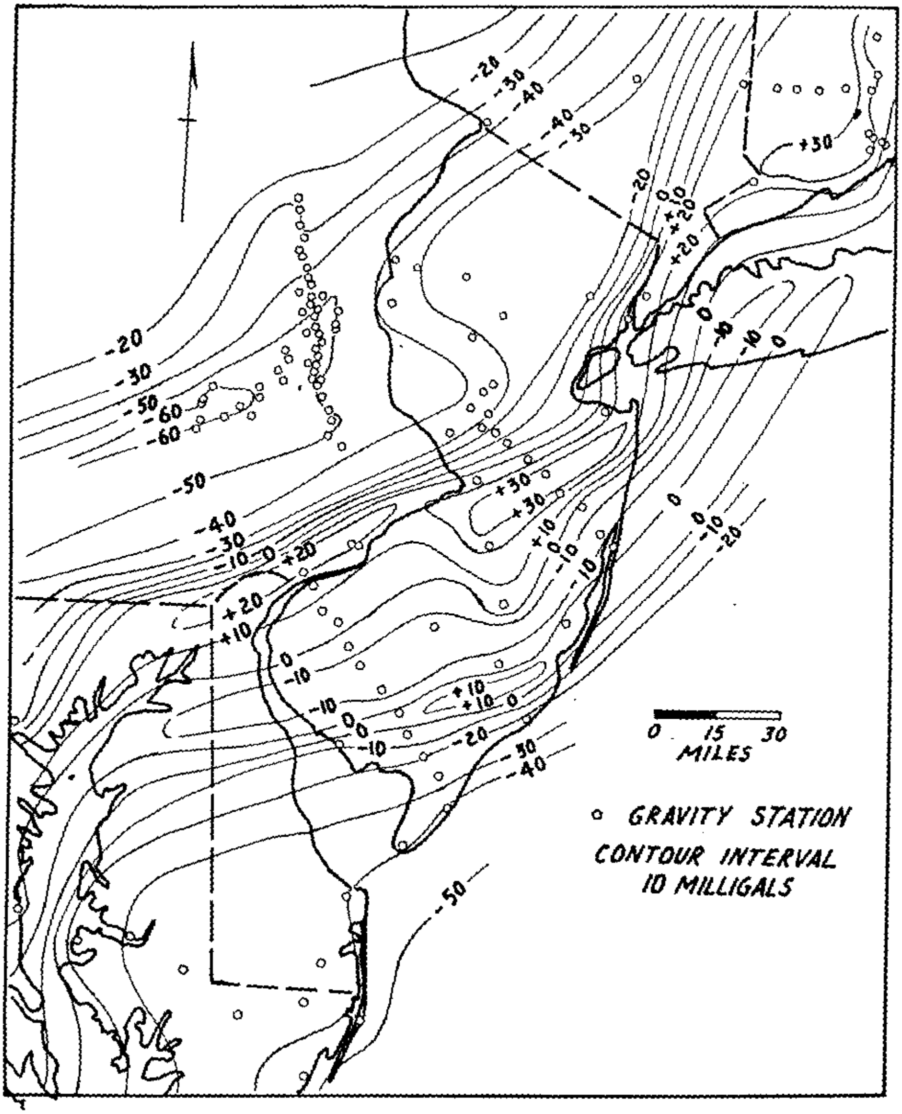

Fig. 17. Isostatic anomaly gravitational map of New Jersey based upon U. S. Coast and Geodetic Survey values.

the North Branch of Raritan River in the district southwest of Mendham; one was on the South Branch of Raritan River in the vicinity of Califon; and the fifth was on Musconetcong River southeast of the town of Washington.

The purpose of the surveys was to determine the topography of the rock floor which at each of the aforementioned sites is concealed by an overburden of unconsolidated materials. Because of the marked difference in porosity, density and other physical characteristics between the overburden and the underlying ancient, compact rock, it was believed that electrical methods of prospecting could be used with success.

The prospecting method adopted was the electric potential method in which two metallic stakes are driven into the ground, a current is forced through the ground between them, and the position of the equipotential curves is mapped.

Results of the work were apparently satisfactory in part and were summarized in a report from which the following statement relative to the Vernoy Site near Califon, Hunterdon County, is quoted:

"*Vernoy Site*

West of stations 98, 109 and 118 the overburden is conductive (400-800 ohms) and the bed rock resistive. The electrical diagrams are regular and easy to interpret. This area may be considered as having been studied quite in detail.

Further east, determinations 132 and 133 are also satisfactory, but measurements 108, 24, 25, 26, 27 and 28 are on much less regular ground, so that the values given for the depth to bed rock might be modified, somewhat, were additional work to be carried out in the valley on the prolongation of line 2+50 East, and to the south of this line. Such additional work would have been desirable, but was not performed due to lack of time, only."

The foregoing statement is quoted in full because the Vernoy Site was subsequently core-drilled and it was found that bed rock was very much deeper than had been anticipated from the electrical prospecting. This failure can probably be attributed to hurried work (see above), and the use of a technique not well adapted to the problem in hand whose results at best could only give a qualitative estimate on depth. If the work had been done a few years later it is certain that the electrical resistivity method would have been used rather than the equipotential one tried. If done now, it is probable that a seismic investigation would be made.

In addition to the electrical prospecting which has just been described, the American Telephone and Telegraph Company has made determinations of electrical resistivity in the Highlands area as part of their nationwide survey of ground resistances. These show marked variations with the physical nature of the geologic units examined and the values can be generalized into groups corresponding to whether the rock is crystalline, consolidated sediments, or unconsolidated sediments. The Highlands area falls into the first group and the resistivities noted for the crystallines are 2900 ohm-meters and 3300 ohm-meters. The latter value is on the crystalline rock at Trenton. Both these determinations are comparable to those noted elsewhere in the northeastern part of the country on similar rocks. On the other hand the values noted for the Triassic sediments in New Jersey are 100, 110 and 800 ohm-meters which are comparable to the values noted for other Triassic areas; and in the Coastal Plain the values are still lower, being 30, 17 and 24 ohm-meters. These variations in electrical resistivity appear to be a function of pore space and the amount of included ground water. In the Coastal Plain the sands and clays have a porosity of 25 to 40 percent and the ground water filling these pores has sufficient salts in solution to make a good electrolyte (i.e. liquid electrical conductor); as a result the resistivity per meter or foot is low. In the Triassic areas the sands and clays have become consolidated into sandstone and shale and the pore space is only about 10 percent; so that there is less included ground water and the rocks are poorer conductors and have higher resistivities. In the areas of crystalline rocks (schists, gneisses, crystalline limestone, and igneous rocks) the porosity is even less, being around 1 percent, and as a result these areas are characterized by the poorest conduction and highest resistivity.

Tests of the ground resistivity were made where a power line and telephone line paralleled each other for considerable distances. At such places one line was energized as a ground return circuit, that is, a current was passed through a grounded section of line, and the induced voltages in a grounded section of the other parallel line were recorded. The energized line was sometimes fifty miles long, but the test sections for the induced voltage in the other line were generally around a mile in length. Current was measured in the energized wire, and the voltage to ground in the parallel wire, and from these data the resistivity was computed.

These measurements gave what might be considered the normal resistivity values for the regions, and from them it is seen that certain limitations in the use of the resistivity method are indicated in the respective areas. For example, in the Coastal Plain it should be possible to locate a Triassic dike beneath the surface due to the marked change in resistivity between the diabase and the Triassic sediments, but the method would not be feasible if the diabase were in the basement crystalline rock since the diabase would have about the same resistivity as the surrounding rock.

In this connection it may be noted that the areas of high resistivity are characterized by marked communication disturbances during periods of sun spot activity. At such times high voltages are found to be induced in the telegraph and telephone lines to such an extent that the lines are put out of service and frequently equipment is damaged. The explanation of this phenomenon is that the marked changes in the earth's magnetic field which accompany these periods of extra-terrestrial activity induce large currents in the ground which serves as a surface conductor. In regions of high surface conductivity such as the Coastal Plain no damage results since little resistance is offered to the flow of current. In the Highlands, however, where the resistivity is high, the currents are forced through high-resistance material of poor conductivity with the result that high differences in potential are obtained (as much as 14 volts per mile) and telegraph and transmission lines have induced in them the accumulated voltage between the points where they are grounded. As these points may be twenty or more miles apart this potential may amount to several hundred volts in a section of line, and it is these voltages that cause the damage. As a result of the correlations made with surface geology, both the telephone and power companies know in which areas they are likely to have the most trouble and keep extra repair crews in those areas.

Another factor effecting transmission line service is frequency of lightning discharge. This, however, appears to be a topographic control on the whole, rather than a geologic one. This latter type of disturbance affects the magnetic field in the discharge area due to the secondary magnetic fields accompanying the lightning discharge. This complicates the geological interpretation of magnetic investigations in such areas since the polarization will not be that induced by the earth's field but rather that due to the lightning.

No other geophysical work is known to have been done in the Highlands area and it is doubtful if other methods would give more explicit information on the ore deposits there than the magnetic ones whose value has been demonstrated by the work of Edison and others. Depth determinations for the ore-bodies outlined by the magnetic method, however, could well be made with electrical resistivity methods due to the marked change in resistivity between the country rock and magnetite (i.e. the respective values are 10^{10} ohms/cm^3 and 10^{-1} ohms/cm^3).

Eve[1] and Keys in their book on geophysical prospecting cite depth measurements conducted with three different resistivity methods on an ore-body at Fisher Hill, N. Y., which is an area with the same geological setting as the New Jersey Highlands and apparently excellent results were obtained there.

Triassic Lowlands

This area is a much faulted structural basin filled with sandstone and shale which have been intruded by diabase (trap rock). The Triassic formations occur largely in the Piedmont area where the formations are exposed, but in part occur beneath the Coastal Plain where they extend for varying distances beneath the unconsolidated sands and clays.

Apparently the Triassic Lowlands were originally a fault-bounded trough roughly paralleling the Atlantic coast from Connecticut through Georgia. Subsequent earth movements arched this trough so that the sedimentary beds on the east side dipped to the east, and those on the west side dipped to the west. The center of the arch has since been removed by erosion and only the two flanking edges are now to be seen; those on the east flank being now covered in part by Coastal Plain sediments. In New Jersey the exposed portions of the Triassic beds have an average dip to the west of about 17 degrees, and the diabase intrusions, which are more or less conformable to the sedimentary strata, outcrop to form Rocky Hill and Sourland Mountain. In those areas where the intrusions reached the surface to form lava flows, we have the Watchung Mountains and other smaller ridges.

Magnetic investigations.—Magnetic work has been limited very largely to the study of the diabase sills. In 1930 Robert M. Parker, a student in Geology at Princeton University, ran a dip-needle and magnetic horizontal component survey along three traverses across Rocky Hill in the vicinity of Princeton. One of these was later checked by J. T. Wilson and the writer using an Askania variometer for measuring the vertical component of the earth's field. An effort was made to occupy exactly the same

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[1] Eve, A.S. and Keys, D.A., Applied geophysics p. 115, 1933.

station sites as those established by Parker, and the only real difference in results was in the amplitude of the observations. The Askania instrument with a sensitivity of 28 gammas to the scale division indicated a maximum change in magnetic amplitude of 60 scale divisions against ten degrees change in dip as noted with the dip needle. As would be expected in the light of the known petrology of the diabase sill the same pattern was revealed both in the results obtained with the dip needle and the horizontal component values on the three traverses made by Parker. Apparently the sill underwent a certain degree of differentiation after intrusion with the result that the rock occurs in zones of well defined mineral composition. The two faces which were top and bottom at the time of intrusion have about the same composition since these represent the chilled or quickly solidified portions of the molten rock where it came in contact with the country rock. Inside this chilled shell though, the rock remained liquid long enough for the crystals first formed to react with the rest of the liquid to form new minerals, and for the heavy minerals to settle toward the bottom. This process — called magmatic differentiation and crystal separation — if allowed to continue long enough would result in a definite series of stratified rocks of different composition grading from rocks rich in iron and magnesium at the bottom, to rocks rich in silica and the alkalies at the top. Since the diabase sill is in most places less than 1200 feet thick, this process did not progress to any great extent before the whole mass had cooled sufficiently to permit it to solidify. However, a certain amount of differentiation did take place and the liquid which did not crystallize until the last congregated near the top and its composition approaches that of the alkalic type of rock already mentioned. The rock in this part of the sill is referred to as the pegmatite facies of the diabase because of the large size of the mineral crystals as compared with those in the rest of the sill. Two of the minerals present throughout the sill are magnetite and ilmenite, both of which are magnetic, and their presence gives the rock a magnetic susceptibility sufficiently large to betray its location even when buried well beneath the surface of the ground. The concentration of ilmenite and magnetite, however, varies from place to place, depending upon the amount of magmatic differentation which took place. Near the bottom of the sill is an olivine-rich zone in which most of the iron present is in the form of that silicate rather than in magnetite, the magnetic iron oxide. As a result the magnetic attraction in this zone is lower than at the contact where there is a higher percentage of magnetite and lower percentage of olivine. Nearer the middle of the sill the olivine is replaced by pyroxene containing a lower percentage of iron and therefore more of the total iron occurs as the oxide, magnetite. The percentage of magnetite here is greater even than at the contact, and as would be expected, higher magnetic values are obtained. Up near the top, the pegmatitic facies is practically free from both magnetite and ilmenite, and at the upper contact the percentage of the magnetic minerals is large again. These variations appear to be reflected in Parker's dip-needle survey, and also in a later investigation by the writer.

On the profile (A-A, Fig. 31) showing the results of this later investigation, it will also be noted that a magnetic high is indicated beyond the limits of the diabase. This is due to contact metamorphic effects — particularly on the upper contact. That is, the heat from the diabase intrusion was so great that it altered the shale into a rock called hornfels in which new minerals such as epidote and magnetite were formed, and it is the presence of this magnetite in the baked shale that gives the high magnetic values noted. The magnetic method, therefore, appears to be feasible for studying magmatic differentiation in igneous rocks.

This survey also showed a marked polarization effect on the feather edge of the diabase at the lower contact as it was approached from the country rock. This was indicated by a sharp change in magnetic sign at the contact. An attraction on the south pole of the needle was first experienced and this was followed by a strong attraction on the north pole. This indicated that the polarization was that of the earth's field with a south magnetic pole induced on the upper side (here the truncated surface formed by erosion) and a north pole on the lower contact.

Although this effect is discernable to a small extent where the diabase is buried at shallow depths, it disappears entirely when the body is buried as much as fifty feet as will be shown in the discussion of magnetic investigations of the buried diabase in the Coastal Plain.

Similar reconnaissance type magnetic profiles carried out by the writer over the Watchung flows near Bound Brook show polarization effects as the edge of the flow is crossed similar to those observed on the diabase at Rocky Hill.

Electrical measurements.—Although no extensive electrical measurements have been made to the writer's knowledge in this part of New Jersey, electrical resistivity measurements were conducted by Dr. King Hubbert, of Columbus University, to determine whether the basalt flows of Hook Mountain extended beneath a sediment-filled valley northeast of Chatham, Morris County. The results of the investigation were described as successful although they have never been published.

Mr. Robert Robie, a student in Geology at Princeton University, also carried out some electrical resistivity measurements in the vicinity of Rocky Hill and Princeton. These measurements were made with a resistivity apparatus similar to that employed by the Bureau of Public Roads and the War Department. Direct current was used with porous pot potential electrodes and the Lee configuration. In the Rock Hill area a resistivity profile was run over the baked shale at the lower contact. An electrode spacing of fifty feet was used and the entire "spread" moved fifty feet at a time so that a three-fourths overlap was carried. The results of this work showed a marked agreement with the amount of surface water present (it was a rainy period), and this masked the effect attributable to the baked shale; but it was believed that a small stringer of diabase extending out from the main sill was found.

In a depth profile carried out on filled ground in Princeton to determine the depth to bed rock, more satisfactory results were obtained. An electrode spacing starting with three feet was carried in increments of three feet to fifty feet. On the assumption that the electrode spacing is equal to the depth of electrical penetration, and that the "break" in the depth-resistivity curve occurs at the point where there is a change in the rock, these measurements indicate that the bed rock is 13 feet below the surface, which value agrees with what is known about the amount of fill present.

The only other electrical measurements in this area have been those made by the American Telephone and Telegraph Company to which reference has already been made in connection with the work done in the New Jersey Highlands.

Gravitational measurements.—These consist of the random pendulum stations established by the U. S. Coast and Geodetic Survey and a line of gravimeter and magnetometer observations made by the writer as part of a transcontinental survey. The part in New Jersey runs from Phillipsburg, on the edge of the crystalline complex, through Clinton, Bound Brook, New Brunswick and Red Bank to Sea Bright on the shore. The results of this work will be discussed in connection with the other gravitational and magnetic profiles in the Coastal Plain.

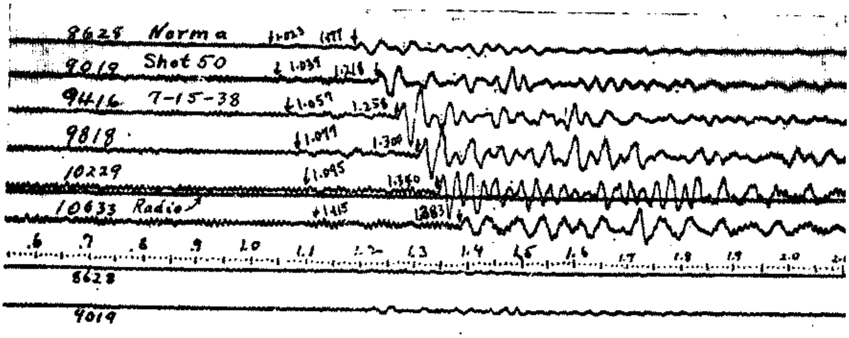
Coastal Plain

The Coastal plain sediments consist predominately of sands and clays ranging in age from Upper Cretaceous through the Pleistocene and Recent. Beneath the sediments occur crystalline rocks similar to those noted in the Highlands area, and also Triassic sediments with intrusive diabase (trap). The subsurface boundaries between the Triassic areas and the crystalline rocks are not known except in a few localities along the edge of the Coastal Plain. At Trenton where the crystalline rocks outcrop just to the southeast of the Triassic sediments, they are composed of gneiss, schist and gabbro. In the vicinity of Princeton Junction there is also a very narrow outcrop of crystalline rocks lying between the Triassic beds (dipping westward at about 17 degrees) and the coastal plain sediments dipping gently to the southeast. Northeast from this point the Coastal Plain overlaps directly on Triassic rocks as far as Staten Island, where the crystalline rocks are again visible at the surface.

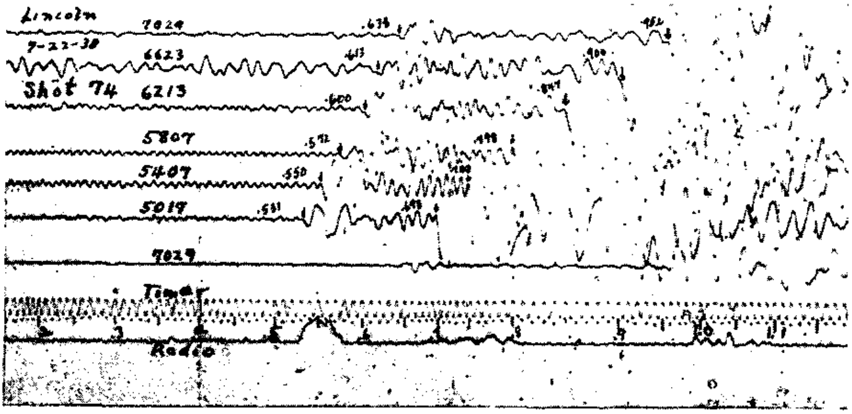
From random well data it has been known that the crystalline rock floor beneath the sediments dips to the southeast at average rates ranging from as little as 60 to more than 100 feet to the mile, but the depth to rock along the shore and the structure of the overlying sediments has been largely a matter of surmise. Since such knowledge is of economic value in aiding the search for ground-water supplies, as well as of scientific value, a cooperative project was undertaken by the Division of Geology and Topography of the New Jersey Department of Conservation and Development, and Dr. Maurice Ewing of Lehigh University, for making a seismic survey along a line running from Plainsboro in southwestern Middlesex County to Silverton on the west shore of Barnegat Bay near its northern end. This line was chosen because it was at right angles to the known geologic structure and therefore would give a maximum amount of information concerning the subsurface crystalline rocks; because it would give the maximum slope of the buried rock floor towards the southeast; and because several deep wells had been drilled on or near the line of the profile which gave information that could be used as a check on results obtained from the seismic work. Mr. A. C. Vine and the writer were associated with Ewing in the actual investigation and computation of results.

Seismic exploration.—The field technique employed in making the Plainsboro-Silverton (also called Barnegat Bay) profile was the same as that outlined in Part II of this report for seismic refraction measurements. Six geophones were used with spacing of 400 feet between them. The first shot, consisting of a few pounds of dynamite, was generally fired about four hundred feet beyond the end geophone and the shot distances were then progressively extended until arrivals on the photographic tape indicated that waves were coming in from the crystalline surface. The distance from the shot to the geophones necessary to obtain this was generally about three to four times the thickness of sediments present. Typical records showing the wave arrivals from the different horizons are reproduced in Fig 18. These are the actual records for two of the stations on another seismic profile across southern New Jersey. The first arrival of very low amplitude is from the basement crystalline rocks, the second more pronounced arrival from a horizon in the sediments, in this case the Vincentown formation. On the record for Norma the fine lines across the paper at right angles to the heavy traces are the time lines put on by the tuning fork at intervals of 1/200 second. The numbers beginning with 8,628 and going to 10,633 indicate the distance from each geophone to the shot in feet and label the respective traces on the record. The value written by each arrow marking the arrival of a wave is the time in seconds for the wave to reach the geophone from the shot point. The first arrivals have come over the longest path since they had to travel down to the crystalline basement, here 3,400 feet, and then up to the surface; and the second arrivals are from the Vincentown horizon which is only 940 feet down. The reason why the wave travelling over the longest path comes in first is because the velocity of the wave front in the basement crystallines is 18,044 ft./sec. here as compared to that of 5,830 ft./sec. in the Vincentown formation. This difference in velocity is illustrated graphically in Fig. 9 in the short period of time required for the first arrival to travel the length of the geophone spread, 2,000 feet, as compared to that of the second arrivals covering the same ground.

In the table of velocity values noted at the stations from Plainsboro to Barnegat Bay it will be seen that there are four distinct velocity groupings. The first is due to the surface material which includes the ground-water table and has a value much the same as that of water, around 5,500 ft./sec. The second horizon, associated with the Magothy-Raritan unconformity (an old erosion surface separating these two formations), has a value close to 7,000 ft./sec.; the third, associated with the Vincentown formation, has a value of about 6,200 ft./sec.; and that associated with the basement crystalline rocks ranges from 13,000 ft./sec.



NORMA



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LINCOLN

Fig. 18. Typical seisomgrams from Norma and Lincoln on Cape May seismic traverse. Six detectors were used, the distance of each from the shot being indicated on the appropriate trace. The units of time indicated along the bottom of each seismogram are somewhat larger than seconds. The first arrival on each seismogram travelled through the basement, the second though the "V" horizon.

to 21,000 ft./sec. It should be noted that although the upper and lower velocity values were observed at all stations, the intermediate ones do not both appear at all the stations, although one or the other does. This is due to the waves from one masking the arrival of waves from the other on account of their velocities being nearly the same and the horizons being relatively close together. There is also the possibility that locally one horizon may vary sufficiently in physical makeup so that a refraction is not obtained.

TABLE 4.—SEISMIC HORIZON VELOCITIES

(Feet per second)

Station	V_1 Surface layer	V_2 M horizon Magothy-Raritan	V_3 V horizon Vincentown	V_4 B horizon Basement
Plainsboro	4,000	....	....	18,800
Hightstown	5,300	7,140	....	18,500
DisBrow's Hill	5,480	6,400	....	18,100
Charleston Springs .	5,610	6,970	....	21,060
Jacksons Mills	5,150	....	6,000	16,000
Lakewood	5,575	7,900	....	13,000
Cedar Bridge	5,400	....	6,200	14,200
Silverton	5,350	....	6,350	18,800

V_1, V_2, V_3, and V_4 refer to the various velocity values

These velocity values were determined from the time-distance graphs; Fig. 19 illustrating the stations where straight profiles were run, and Fig. 20 a station (Charleston Springs) where a reverse profile was established in order to determine the amount of dip present. In the straight profiles only one station, Plainsboro, indicates abnormal sursurface conditions. The significance of these will be taken up later in connection with a magnetic survey of that area.

The depth values computed, using the velocity data and time intercrepts from the time-distance graphs, are reproduced in Table 5; and the position of the seismic horizons relative to their geologic counterparts as determined from well data is shown in Fig. 21.

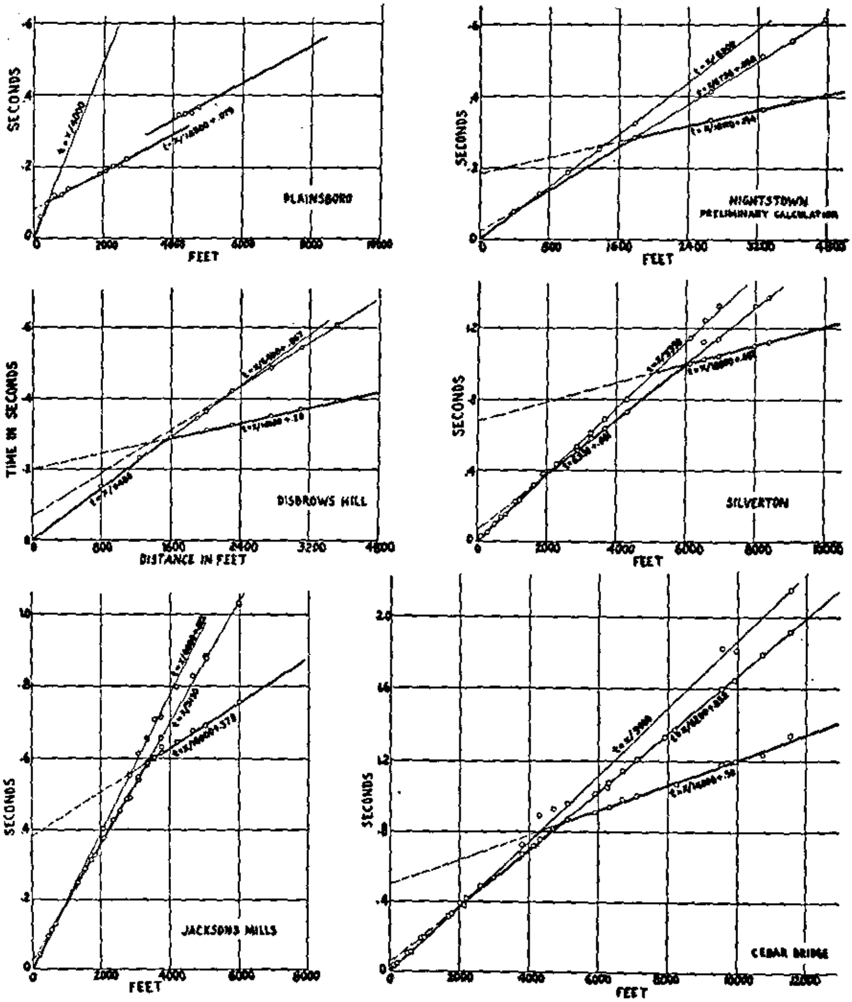

Fig. 19. Time-distance graphs for Barnegat Bay seismic traverse.

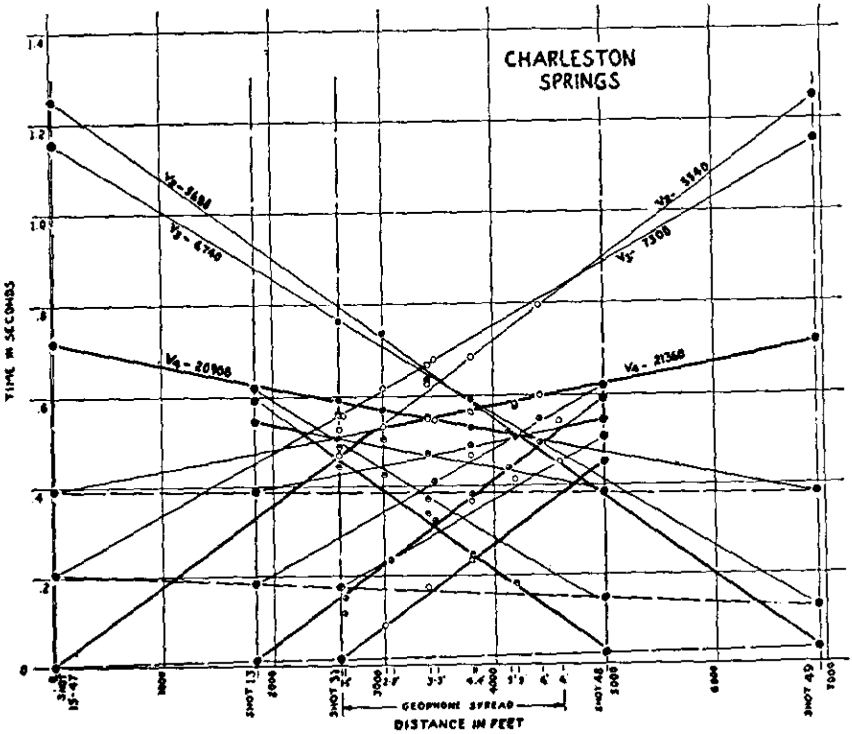

Fig. 20. Reverse profile time-distance graph for Charleston Springs Station, Barnegat Bay profile.

The agreement in dip between the geologic horizons and their seismic counterparts further confirms the geologic identification of the seismic horizons.

TABLE 5.—SUMMARY OF SEISMIC RESULTS

Location	Elevation ft.	V_1 ft./sec.	V_2 ft./sec.	V_3 ft./sec.	V_4 ft./sec.	T_1 sec.	T_2 sec.	T_3 sec.	H_1 ft.	H_2 ft.	H_3 ft.	H ft.
Plainsboro............	100	4000	18800			.079			164			164
Hightstown...........	110	5300	7640+ 6750− 7140	19080+ 18120− 18500		.058	.194		+3°56′ 229	−1°0′ 430		660
Dis Brow's Hill.......	140	5480	6400	18100		.067	.200		360	254		614
Charleston Springs....	175	1600	5540+ 5680− 5610	7300+ 6740− 6970	21360+ 20900− 21060	.010	.184	.388	−12′ 8	+4°16′ 823	−16′ 355	1190
Jackson's Mills.......	115	5150	6000	16000		.022	.378		110	1090		1200
Lakewood............	130	1600	5575+ 5575− 5575	8050+ 7770− 7900	12500+ 13600− 13000	.050	.312	.480	0°0′ 42	+55′ 1030	−2°23′ 465	1540
Cedar Bridge.........	60	5400	6200	14200		.052	.500		262	1410		1670
Silverton.............	10	5350	6350	18800		.061	.697		308	1910		2220

(1) Depths in last column have been rounded off *to nearest 10 feet.*

(2) Angles indicated in columns H_1, H_2, and H_3 represent slopes in the corresponding interfaces, measured with *respect to the mean surface of the ground,* taken over the line of the station.

TABLE 6.—VARIATIONS OF DIP, BARNEGAT BAY SECTION

(Feet per mile)

Part 1. Based on well logs

Formation	Sections of Figure 12			
	A	B	C	D
Kirkwood	....	21	21	18
Unconformity				
Shark River	....	....	23	24
Unconformity				
Manasquan	....	32	25	15
Vincentown	....	32	26	27
Hornerstown	....	33	26	28
Unconformity				
Red Bank	....	48	6	46
Navesink	....	48	6	44
Mt. Laurel-Wenonah ..	35	46	6	44
Marshalltown	....	46	6	44
Englishtown	38	50	6	53
Woodbury	40	50	....	....
Merchantville	48	50	....	....
Unconformity				
Magothy	No data			
Unconformity				
Raritan	65	65	66	....
Unconformity				
Basement surface	65	65	66	....

Part 2. Based on seismic data

V Horizon (Vincentown)	....	32	28	28
M Horizon (Magothy?)	....	65	68	....
B Horizon (Basement surface) ..	65		68	160

The subsurface geologic structural conditions indicated by these data on the profile (identified as the Barnegat Bay Profile) show that there is a minor anticlinal fold (upward arch) whose crest is in the vicinity of Lakewood and it involves the formations between the basement crystalline rock and the Vincentown formation.

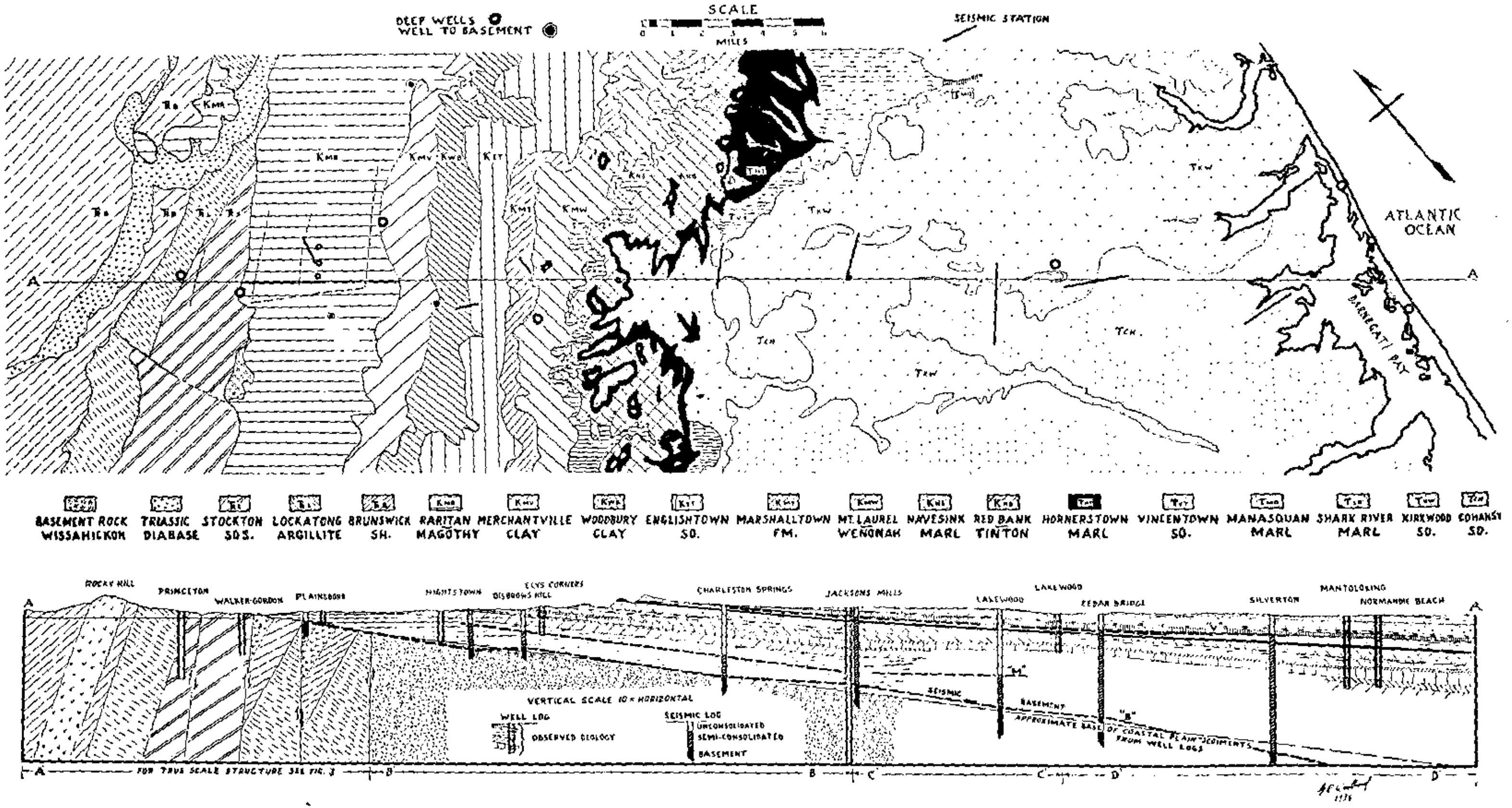

Fig. 21. Seismic-geologic profile across Atlantic Coastal Plain along Barnegat Bay traverse.

This is borne out by the deep water wells at Lakewood which penetrate this structure and draw their supplies from the Englishtown sand.

In other parts of the world crude oil has been found in similar structures in sand of the same age; but either biological conditions were not right for the growth of the tiny organisms which furnished the oil elsewhere, or else the oil which once was present has been driven seaward by the flushing action of the fresh water which now fills the sand beds.

While discussing oil possibilities, we might mention here that some years ago a very deep well was drilled at Jacksons Mills in western Ocean County, at a point where the subsurface sediments form a syncline, or trough, as shown in the geologic section, Fig 21. The choice of location was unfortunate, to say the least, since oil would normally be driven from such an area by ground-water movements. The section also shows that much money was wasted in sinking the well far into the underlying crystalline basement rock where the possibility of finding oil is practically nil.

Another condition shown by the seismic data is an abnormal increase in thickness of material between the postulated Magothy-Raritan unconformity and the basement rocks at the Lakewood seismic station, the most southeasterly point at which this horizon was identified from the seismic records. This condition may well indicate the presence of Lower Cretaceous beds beneath the Raritan formation, and that this point therefore is southeast of the former shoreline of the Lower Cretaceous seas. In this connection it should be noted that although Lower Cretaceous sediments do not outcrop anywhere in New Jersey, they occur across Delaware River in Delaware and have recently been found in a deep well at Salem, N. J.

In order to check the magnitude of the relief (difference in elevation of high and low points) indicated seismically for the rock floor, and also to obtain an idea of the lateral variations in relief, profiles were drawn across the map published by the Maryland Geological Survey to show the basement relief in the vicinity of Baltimore, and these are compared in Fig. 22. It was found that the maximum relief indicated for New Jersey, about 280 feet, is only a few feet less than the maximum relief (285 feet) proven to exist at Baltimore, and this agreement was considered a very satisfactory check of the seismic determinations.

Cape May Profile.—A similar seismic refraction profile was established by Ewing, Vine and the writer across southern New

Jersey from Bridgeport on Delaware River to Avalon at the shore. It is considered significant that the same seismic velocity variations were noted in the southern part of the State as in the Barnegat Bay area, with the addition of a 3,000 ft./sec. zone associated with the surface gravels. Also, that the seismic horizons appear to have the same geologic equivalents: the Vincentown formation, the Magothy-Raritan unconformity, and the basement crystalline rock.

From the seismic-geologic section, Fig. 23, it is seen that the same structural conditions are indicated on this profile as were observed on the Barnegat Bay profile. That is, a marked thickening in the sediments is noted below the Magothy-Raritan horizon at the Millville station and also an anticlinal structure is present just east of this station. As on the Barnegat Bay profile this sudden thickening in the geologic column below the Magothy-Raritan seismic horizon is believed to reflect the presence of Lower Cretaceous sediments.

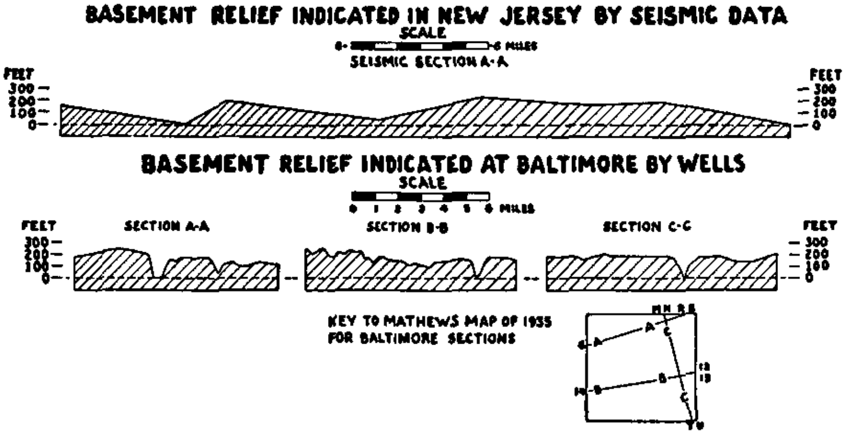

Fig. 22. Comparison of basement surface relief in New Jersey with that in the vicinity of Baltimore, Maryland.

The basement configuration at the axis of the anticlinal structure in the sediments on this profile does not agree with it as much as would be expected, however, and this may be due to false seismic depth measurements at this point occasioned by the assumption that the seismic velocity of all the material from the Magothy-Raritan horizon down to the basement is the same. Since it is impossible to detect changes to lower velocity material below higher velocity zones, the presence of the postulated Lower Cretaceous sands in this area which would have a lower velocity than the overlying Upper Cretaceous clays would result in the

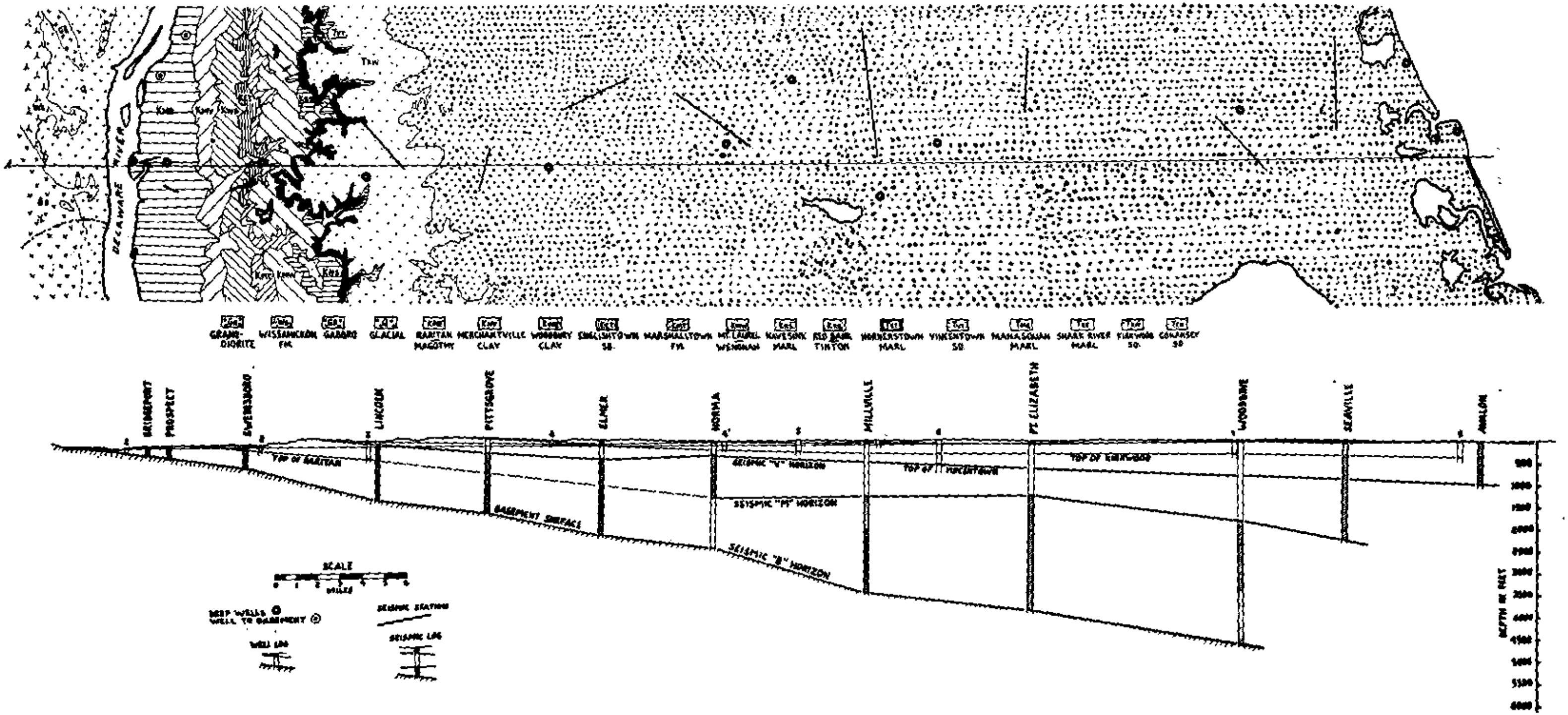

Fig 23. Seismic-geologic profile across the Atlantic Coastal Plain along Cape May traverse

calculated depth to basement being too great. This would also apply to the measurements on the Barnegat Bay profile. Though Lower Cretaceous strata were found in the deep well at Salem, there are no wells in the vicinity of this profile which penetrate deep enough to verify their existence here.

Another structural indication given by these seismic profiles is that whereas at the peak of the anticline mentioned the elevation of the Magothy-Raritan horizon is -1370 feet on the Barnegat Bay profile, and -1234 feet on the Cape May profile, the elevation of the basement at these same two points is -1610 feet and -3807 feet respectively. It, therefore appears that although the Magothy-Raritan unconformity is found at about the same level along the coast, the depth to the basement has changed over 2,000 feet. This would indicate that the Raritan and the postulated Lower Cretaceous sediments thicken considerably towards the southwest and that the area in the vicinity of Delaware Bay must have been progressively sinking as the sediments were deposited. This is in agreement with physiographic data indicating that the coastline southward from Cape May is a drowned one (i.e one that has been submerged) so that the sea now extends up the former river valleys. Because of this downwarping, the sediments become thinner the further northeast one goes in New Jersey and the various horizons in the Cretaceous also occur nearer and nearer to the surface.

The time-distance graphs for the stations along the Cape May profile are presented in Figs 24-26, which also show the areal distribution of the geophones and the shots fired at the various stations. The computed data for each station are summarized in Tables 7 and 8.

It will be noted in connection with this profile that practically all depths were determined with reverse station profiles (that is, by placing shots off both ends of the geophone spread), and from these data the degree of slope of each seismic horizon in the azimuth of the station was determined. These computations confirmed the dip to the southwest and also showed that this southwestward dip is even greater than that toward the shore.

The observed velocities fall into the same numerical groups as noted on the Barnegat Bay profile and have the same geological equivalents. Although the velocity values for the sedimentary horizons are fairly consistent, those noted for the basement rocks vary between wide limits. These variations are thought to be due to changes in the lithology of the basement, and on the basis of similar observations in Virginia where somewhat better control

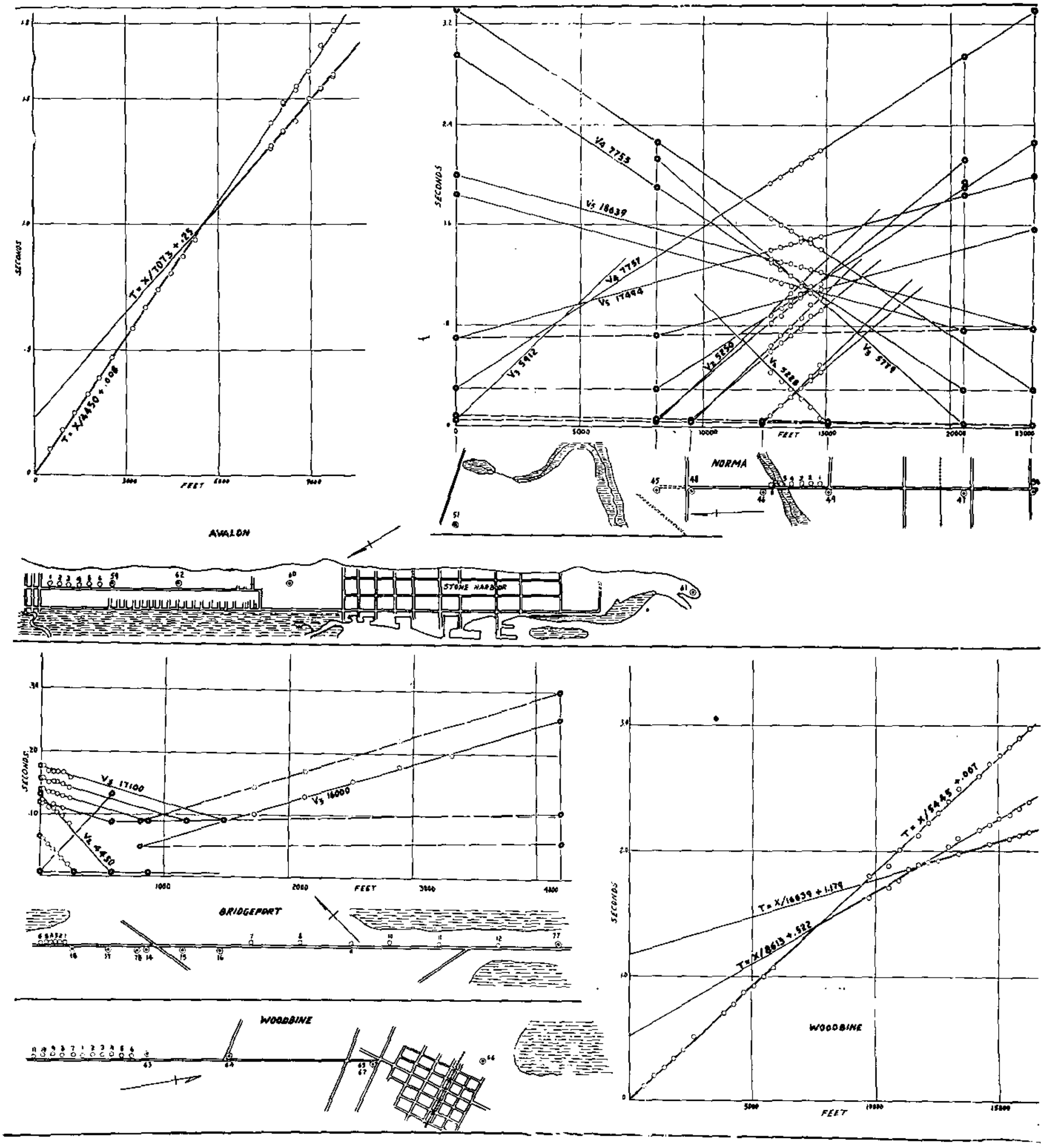

Fig. 24. Time-distance graphs and station maps for Cape May seismic traverse.

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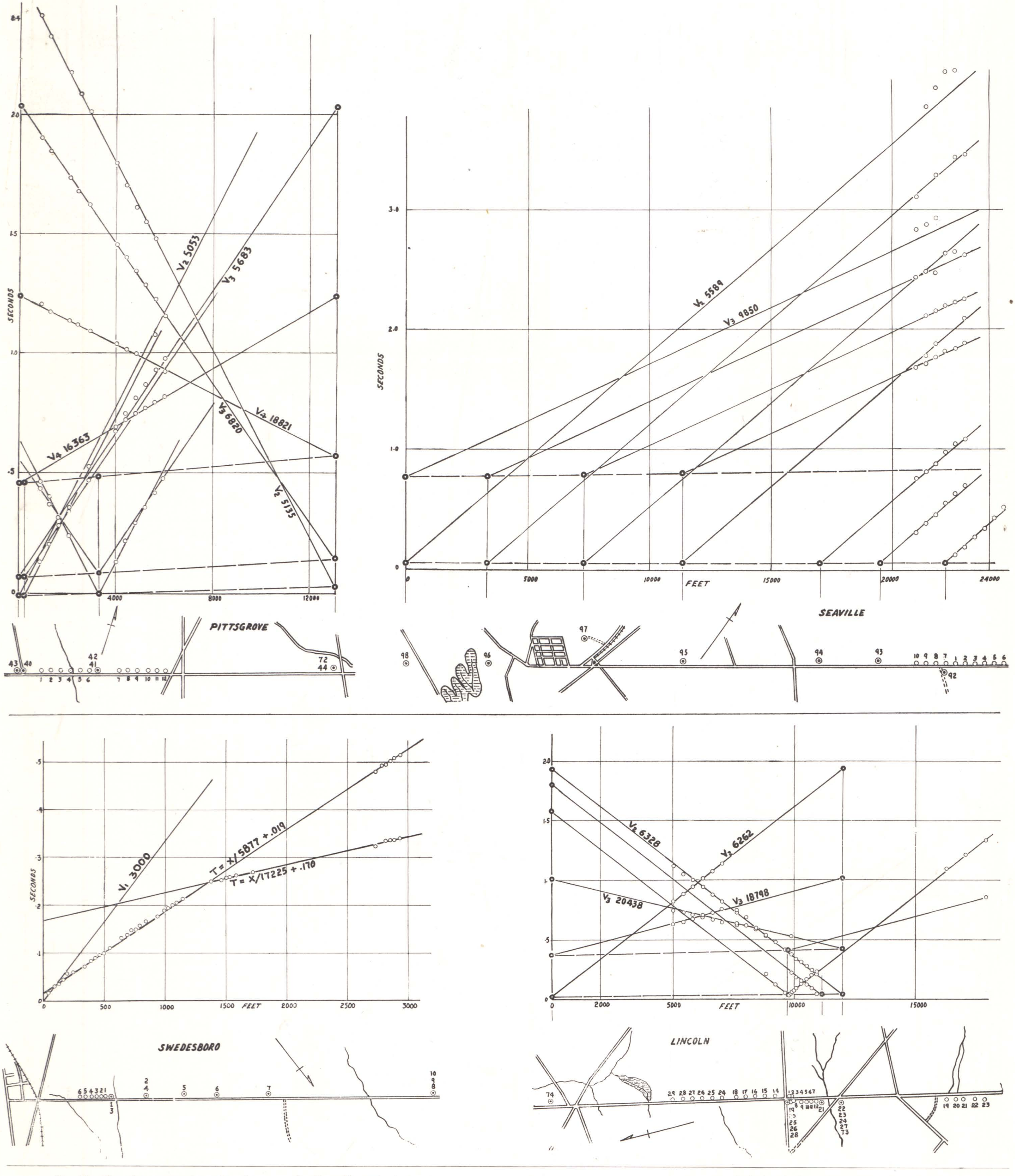

Fig. 25. Time-distance graphs and station maps for Cape May seismic traverse.

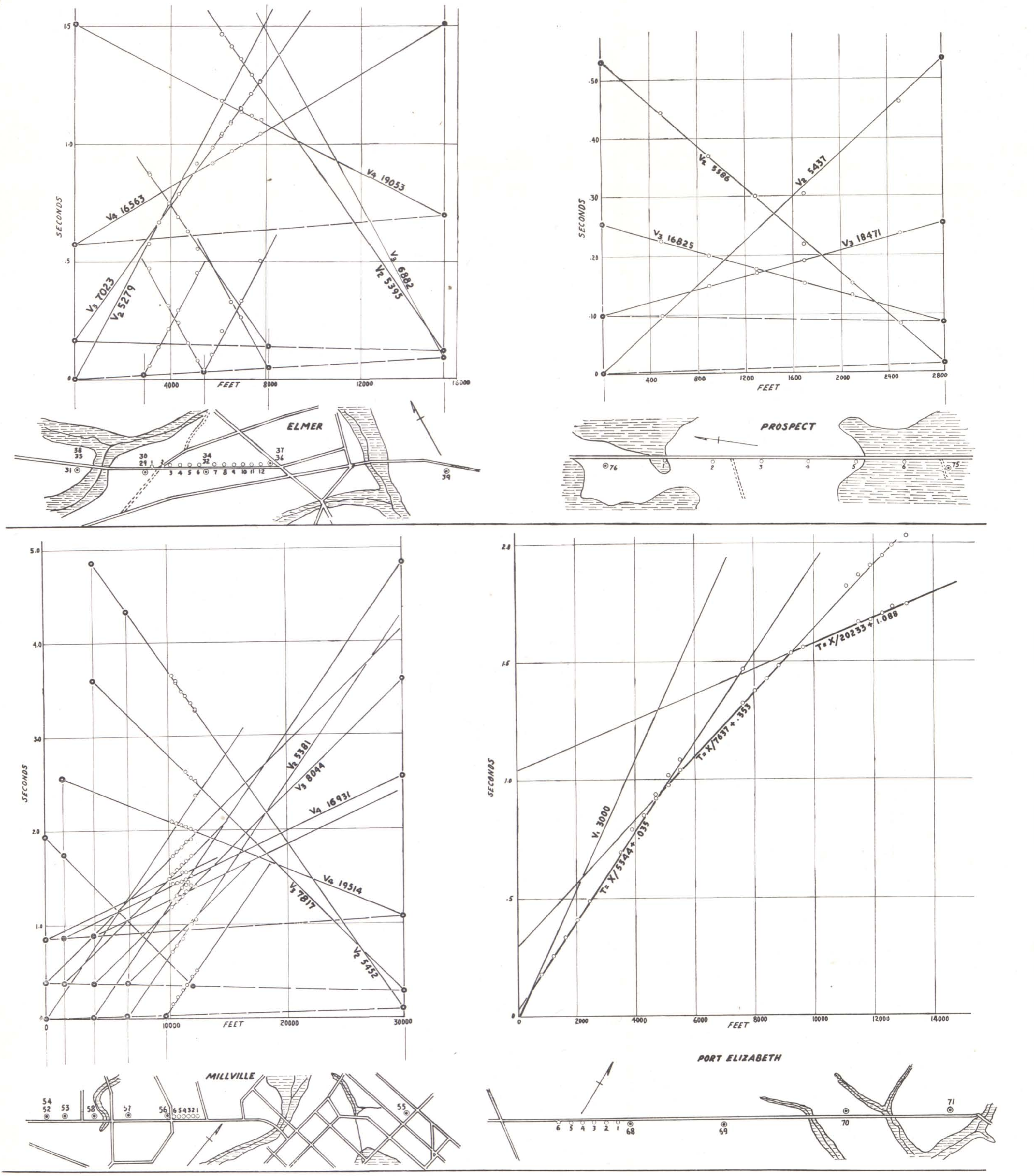

Fig. 26. Time-distance graphs and station maps for Cape May seismic traverse.

TABLE 7.—OBSERVED VELOCITIES AND BASEMENT SLOPE

Prospect:	$V_1 = 3000$ $V_{2a} = 5437$ $V_{3a} = 18471$	$V_{2b} = 5586$ $V_{3b} = 16824$	$V_1 = 3000$ $V_2 = 5510$ $V_3 = 17598$	$T_{2a} = .0018$ $T_{3a} = .0995$ $w = 1° 50.43'$
Swedesboro:	$V_1 = 3000$ $V_{2a} = 5877$ $V_{3a} = 17225$		$V_1 = 3000$ $V_2 = 5877$ $V_3 = 17225$	$T_2 = .019$ $T_3 = .170$
Pittsgrove:	$V_{2a} = 5053$ $V_{3a} = 5683$ $V_{4a} = 16363$	$V_{2b} = 5135$ $V_{3b} = 6820$ $V_{4b} = 18821$	$V_1 = 3000$ $V_2 = 5100$ $V_3 = 6710$ $V_4 = 17560$	$T_2 = .001$ $T_3 = .089$ $T_4 = .495$ $w = -25.8'$
Elmer:	$V_1 = 3000$ $V_{2a} = 5279$ $V_{3a} = 7023$ $V_{4a} = 16563$	$V_{2b} = 5395$ $V_{3b} = 6882$ $V_{4b} = 19053$	$V_1 = 3000$ $V_2 = 5336$ $V_3 = 6948$ $V_4 = 17697$	$T_2 = .650$ $T_3 = .140$ $T_4 = .636$ $w = 3° 00.2'$
Lincoln:	$V_1 = 3000$ $V_{2a} = 6262$ $V_{3a} = 18798$	$V_{2b} = 6328$ $V_{3b} = 20438$	$V_1 = 3000$ $V_2 = 6245$ $V_3 = 19582$	$T_{2a} = .039$ $T_{3a} = .419$ $w = +2.26'$
Norma:	$V_{2a} = 5250$ $V_{3a} = 5912$ $V_{4a} = 7757$ $V_{5a} = 17494$	$V_{2b} = 5228$ $V_{3b} = 5779$ $V_{4b} = 7755$ $V_{5b} = 18639$	$V_1 = 3000$ $V_2 = 5240$ $V_3 = 5830$ $V_4 = 7756$ $V_5 = 18040$	$T_2 = .029$ $T_3 = .049$ $T_4 = .293$ $T_5 = .704$ $w = -43.8'$
Millville:	$V_1 = 3000$ $V_{2a} = 5381$ $V_{3a} = 8044$ $V_{4a} = 16931$	$V_{2b} = 5452$ $V_{3b} = 7817$ $V_{4b} = 19514$	$V_1 = 3000$ $V_2 = 5440$ $V_3 = 7926$ $V_4 = 18086$	$T_2 = .026$ $T_3 = .353$ $T_4 = .946$ $w = 3° 21.02'$
Port Elizabeth:			$V_1 = 3000$ $V_2 = 5344$ $V_3 = 7637$ $V_4 = 20233$	$T_1 = .035$ $T_2 = .353$ $T_3 = 1.088$
Woodbine:	$V_1 = 3000$ $V_{2a} = 5445$ $V_{3a} = 8613$ $V_{4a} = 16639$		$V_1 = 3000$ $V_2 = 5445$ $V_3 = 8613$ $V_4 = 16639$	$T_1 = .007$ $T_2 = .522$ $T_3 = 1.179$
Seaville:	$V_1 = 3000$ $V_{2a} = 5589$ $V_{3a} = 9850$		$V_1 = 3000$ $V_2 = 5589$ $V_3 = 9850$	$T_1 = .037$ $T_2 = .688$
Avalon:	$V_1 = 3000$ $V_{2a} = 5495$ $V_{3a} = 7073$		$V_1 = 3000$ $V_2 = 5495$ $V_3 = 7073$	$T_1 = .002$ $T_2 = .227$
Bridgeport:	$V_1 = 3000$ $V_{2a} = 4450$ $V_{3a} = 17100$	$V_1 = 3000$ $V_{2b} = 4450$ $V_{3b} = 16000$	$V_1 = 3000$ $V_2 = 4450$ $V_3 = 17100$	$T_2 = .008$ $T_3 = .082$

V = True velocities, ft./sec.

V_a and V_b = Reversed apparent velocities, ft./sec.

T values = Time intercepts, sec.

w values = Basement slope (horizontal angle)

TABLE 8.—TRUE VELOCITIES AND DEPTHS

Station	"V_1"	"C"	"V"	"M"	"B"	H_1	H_2	H_3	H_4	H Total
Bridgeport	3,000	4,450			17,150	16	187			193
Prospect	3,000	5,510			17,598	3	283			286
Swedesboro	3,000	5,881			17,225	21	488			508
Lincoln	3,000		6,295		19,582	67	1,246			1,313
Pittsgrove	3,000	5,100	6,710		17,560	2	346	1,323		1,671
Elmer	3,000	5,336	6,948		17,697	91	354	1,698		2,143
Norma	3,000	5,240	5,830	7,756	18,040	53	275	939	1136	2,403
Millville	3,000	5,480		7,926	18,086	47	1,212	2,160		3,419
Port Elizabeth	3,000	5,344		7,637	20,233	63	1,171	2,573		3,807
Woodbine	3,000	5,445		8,613	16,639	13	1,806	2,773		4,592
Seaville	3,000	5,589		9,850		66	2,192			2,258
Avalon	3,000	5,495	7,073			4	973			977

V_1 = Surface gravel velocity, ft./sec.
"C" ....V_2 = Cohansey formation velocity, ft./sec.
"V" ....V_3 = Vincentown horizon velocity, ft./sec.
"M"............V_4 = Raritan-Magothy horizon velocity, ft./sec.
"B" ....V_5 = Basement velocity, ft./sec.
H = thickness of respective velocity horizons, ft.
H total = depth to basement, ft.

is had from well and outcrop data, appear to represent rocks ranging in type from granite to dense gabbro. That such variations of rock types are probably present in New Jersey is also indicated by other geophysical data obtained over the same traverses.

Gravity measurements.—Through cooperation of the U. S. Coast and Geodetic Survey with the State Department of Conservation and Development a series of pendulum gravitational measurements were established at intervals of about five miles along the lines followed by the seismic traverses. As outlined in Part II these values were obtained by swinging a pendulum in a vacuum and timing its period of swing very accurately for several hours. The gravitational values computed from these data were then compared with the theoretical values that should have been obtained for the station based upon changes due to the shape of the earth, the position above sea level and the effects derived from elevation and the surrounding terrane. If the observed

TABLE 9.—VELOCITY TABLE

(In feet per second)

Station	Surface gravels	Surface formation	*"V"* horizon	*"M"* horizon	*"B"* Basement
Bridgeport	3,000	4,450			17,150
Prospect		5,510			17,598
Swedesboro	3,000	5,887	(5,887)*		17,225
Lincoln	3,000		6,295		19,582
Pittsgrove	3,000	5,100	6,710		17,560
Elmer	3,000	5,336	6,948		17,697
Norma	3,000	5,240	5,830	7,756	18,040
Millville	3,000	5,480		7,926	18,086
Port Elizabeth	3,000	5,344		7,637	20,233
Woodbine	3,000	5,445		8,613	16,639
Seaville	3,000	5,589		9,850	
Avalon	3,000	5,495	7,073		

* Surface *formation* here.

values were greater than the computed ones a positive anomaly was said to exist, and if the observed values were less than the computed ones a negative anomaly was indicated.

Marked variations were found on both profiles, and areas of marked positive gravity anomalies were noted at approximately the same places that high seismic velcocities had been observed for the basement crystalline rocks. Since the respective station sites for the two sets of data do not agree exactly in position the data unfortunately cannot be compared as directly as might be desired; but the values obtained are regarded as highly suggestive of a direct correlation between the two, particularly in the high velocity areas: Charleston Springs on the Barnegat Bay profile, and the Millville-Port Elizabeth area on the Cape May profile. It must be remembered though that exact correlation is not possible since the two measurements are not only of different properties but also involve different sized samples of material.

The seismic value is a measurement of the average seismic velocity of the various kinds of rock embraced by the station with a depth of penetration dependent upon the surface spread and including a lenticular sample of the formations. The gravity measurement is that of the mass of a hemisphere of material extending out in all directions around the station and involving mass distributions down in the basement crystalline rocks which may differ markedly in physical properties from the rock actually forming the crystalline floor beneath the sediments. A mass of igneous rock deep in the basement, therefore, would be detectable in the gravity values but not necessarily so in the seismic measurements unless the surface spread were sufficiently large to permit the seismic waves to penetrate to that depth. A subsidiary limiting control on the seismic measurement is that sufficient dynamite has to be fired to permit the explosion waves to penetrate not only to the depth of the refracting horizon but also to return to the surface.

An analogous problem was raised at the two most easterly stations on the Cape May seismic profile for which no depth determinations or seismic velocities are given for the basement crystalline rocks. The situation there was that the area overlies lagoonal deposits with a considerable thickness of peat which absorbed so much energy that the wave arrivals from the basement could not be detected even when explosive charges of 200 pounds of dynamite were used. The only horizons detected were those occurring in the overlying sediments at relatively shallow depths. Although gravity measurements here embrace the basement rocks which have a velocity of about 18,000 feet per second, the seismic records showed no material with a velocity in excess of 8,000 feet per second because of the shallow penetration of the explosion waves.

That the gravity anomalies are not related except in a regional way to the thickness of light coastal plain sediments, or the configuration of the dense basement rock, is shown in Fig. 27 where the respective seismic depth data, basement velocities and gravity anomaly values are plotted for the two profiles. The marked gravity low indicated on the east flank of the Barnegat Bay profile is part of the regional gravity trough already referred to in connection with the New Jersey Highlands and it will be discussed later in its relation to the State as a whole. Since the distribution of the velocity variations on the two profiles are similar (18,000 ft./sec. to 20,000 ft./sec. to 16,000 ft./sec.), it would appear that banded Appalachian-type rock variations are present in the basement crystalline rocks similar to those observed in the exposed crystalline rock of the Piedmont and other parts of the eastern seaboard. (See sketch map of State in Fig. 27). On this assumption a quantitative calculation was made assigning different rocks to the respective velocity areas to see which had a density value, which if corrected, would remove the high anomaly observed at Charleston Springs on the Barne-

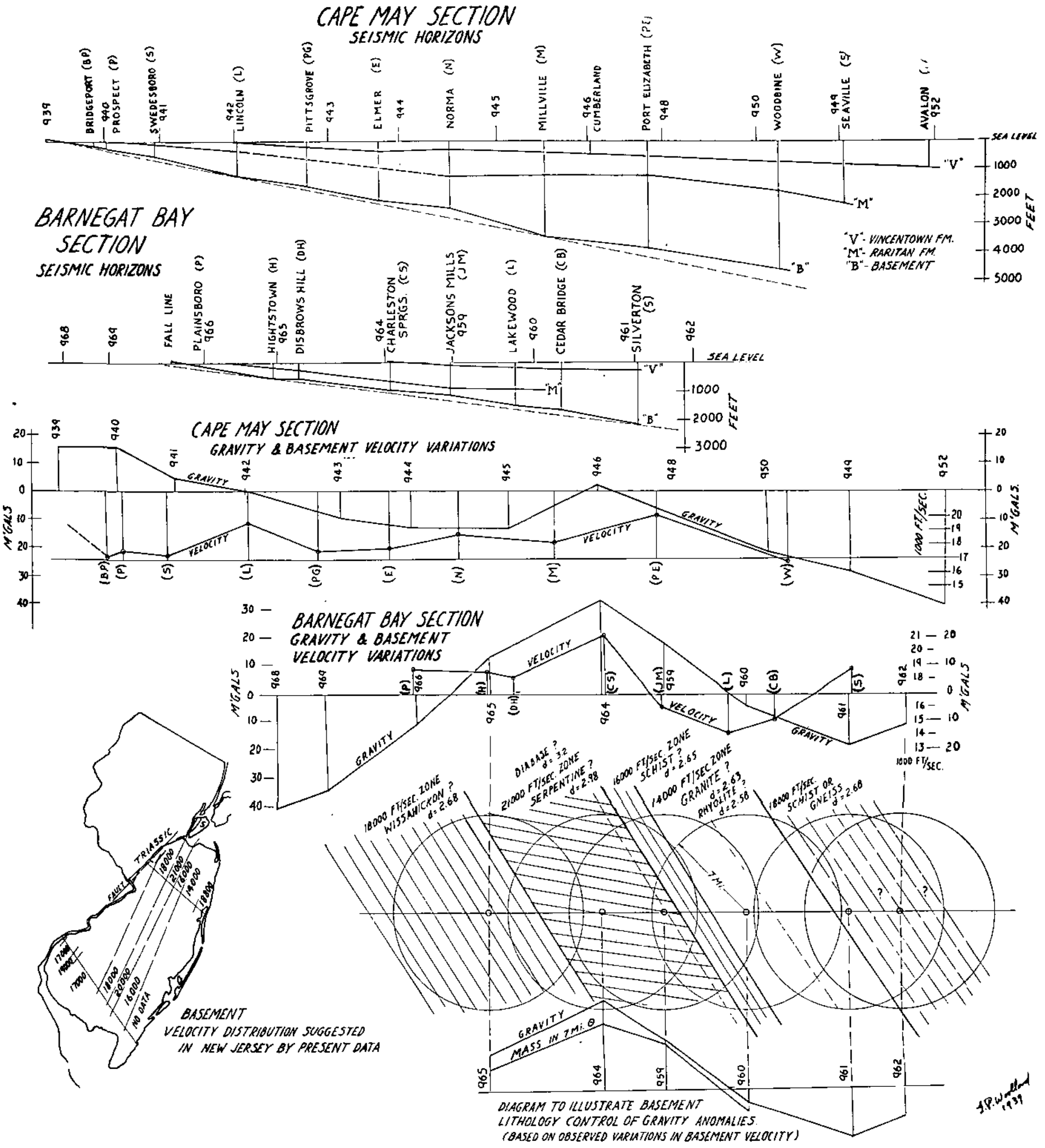

Fig. 27. Comparative seismic velocity, gravitational and geologic structural profiles along the Barnegat Bay and Cape May traverses.

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gat Bay profile. The values for the six gravity stations in this area were thus corrected for a series of assumptions. These were that the 18,000 feet per second material was Wissahickon gneiss with a density of 2.68; the 21,000 feet per second material was serpentine with a density of 2.98, or diabase, or similar rock with density of 3.2; the 16,000 feet per second material was Wissahickon schist with a density of 2.65; and the 14,000 feet per second material was granite with a density of 2.63, or rhyolite with a density of 2.58. These rocks are all known to occur in intimate relation in the Piedmont of Virginia at the edge of the Coastal Plain, and the densities are those of samples obtained there by the writer. Their postulated distribution is indicated in their projection on the Barnegat Bay profile of Fig. 21 in which the rock distribution was governed by the seismic station distribution and the observed velocities. In making the gravitational observations the mass effect within a circle of seven miles radius around each station was considered and on the assumptions of mass changes alone it is seen that these mass variations would give a change comparable to the anomaly curve. The actual gravitational change to be expected for each set of conditions postulated was then computed for a column of rock extending down 3.2 kms. and resultant gravity curves obtained as shown in Fig. 28. From these it is noted that Case II, the assumption of Wissahickon gneiss, schist, granite and diabase give the smoothest residual curve, and since the slope of this residual curve is essentially that of the regional seaward slope for gravity, in this area, the above rocks are regarded as being representative of those actually present.

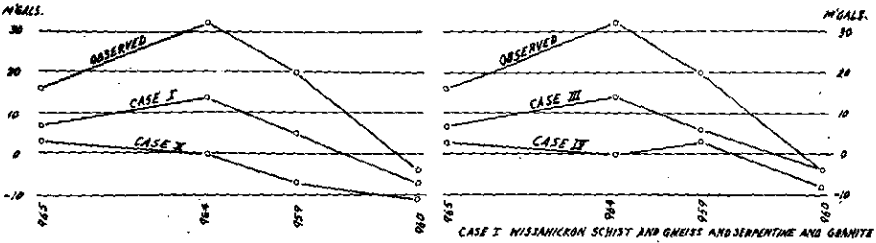

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FIGURE 28.—*Residual gravity anomaly curves on Barnegat Bay traverse*

Corrected for basement lithology variations as determined from seismic variations. Case I Wissahickon schist and gneiss and serpentine and granite; Case II Wissahickon schist and gneiss and diabase and granite; Case III Wissahickon schist and gneiss and serpentine and rhyolite; Case IV Wissahickon schist andgneiss and diabase and rhyolite.

Magnetic observations.—As a further check on the seismic and gravity findings the writer and Meredith E. Johnson, State Geologist, established a series of magnetic measurements of the vertical component along these same profiles with a spacing of about seven-tenths of a mile between stations. The results of this work are shown in Fig. 29 along with the gravity anomaly values and basement seismic velocity variations. One of the most noticeable features of the magnetic results is the marked change in amplitude from the western end of the profiles to the eastern end. This change is a reflection of the depth of sediments overlying the basement and it also indicates that the control is probably associated with the basement rocks rather than some horizon in the sediments. For comparative purposes datum lines have been passed through all the profiles in order to separate what might be termed regional effects from the local ones.

On the western end of the magnetic profile the first magnetic high does not have an alignment correlation with either the gravity or seismic data, but there is an agreement between the three sets of data at the second magnetic high. The pattern on all three sets of data, however, is the same (i.e. two highs separated by a low). Since the three sets of data are frequently found offset from each other, particularly the magnetic data, this repetition in pattern is regarded as more significant than the actual vertical alignment.

Continuing southeast, the next magnetic high shown in Fig. 29 definitely has no correlation with either the gravitational or seismic data. The physical properties indicated by the three sets of data are that the material has a marked magnetic susceptibility, a low density and low elastic properties. The only rock known in the Piedmont crystalline complex which might have these properties is possibly aporhyolite.

The broad magnetic high following this feature has a correlation in the seismic and gravitational data and apparently reflects a gabbroic type of rock of high density, elastic properties and magnetic susceptibility. The intervening low magnetic values correlate with lows in the seismic and gravitational data and these are believed to reflect the presence of rocks of granitic type which have the general properties indicated.

On the Barnegat Bay profile the most westerly magnetic high is due to the outcrop of the Rocky Hill diabase. The second magnetic high is probably related to the gabbro which is exposed at the surface just a few miles south of the profile; the third is known from well data to be due to a step-faulted block of the Rocky Hill diabase buried beneath the deposits of the Coastal Plain; and the fourth is possibly due to a local occurrence of gab-

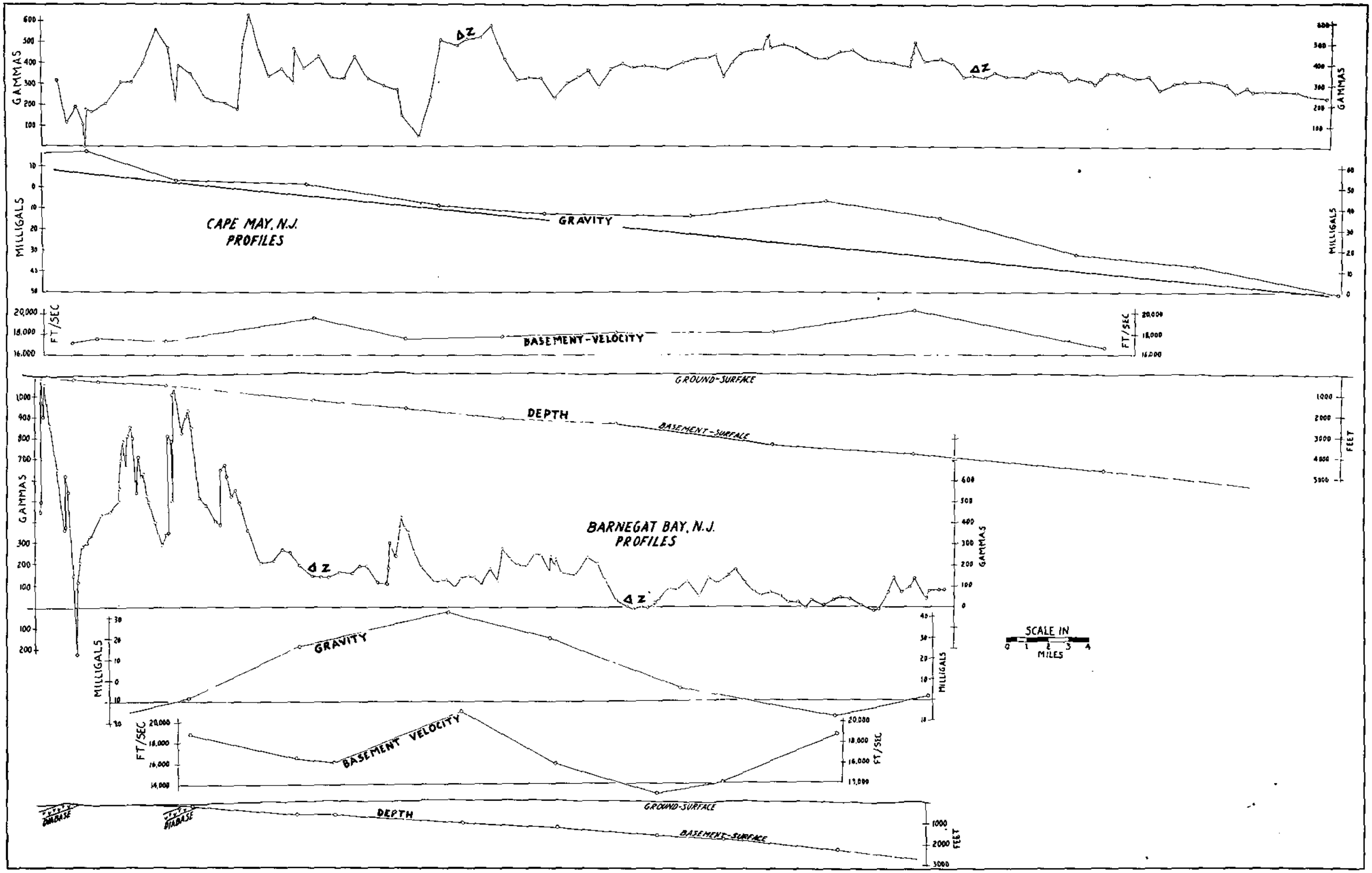

Fig. 29. A Comparison of magnetic, gravitational and seismic data with the geologic structure on the Cape May and Barnegat Bay traverses.

bro in the crystalline rock basement. (This last interpretation is based on the areal map shown in Fig. 34). However, considering the other two sets of data over this same traverse, it is noted that the marked regional gravity trough to which previous reference has been made, blankets completely the effect of the Rocky Hill diabase and the gabbro. The seismic velocities, however, indicate the presence of the high-speed diabase (the seismic station here was known from well data to be over diabase) and there is an agreement between the magnetic low and seismic velocity low where the basement rock is known from well data to be Wissahickon schist. The sharp, isolated, magnetic high which occurs near Perrineville is seen to be offset from the high point of the seismic and gravitational data, and there is another broad magnetic high which falls on the other flank of the high area in the seismic and gravitational data. Whether the gravitational high is a regional feature with a deep-seated cause, or related to a near basement surface mass of rock responsible for the highs in the other two sets of data is unknown. The fact that such marked highs do occur in the other data would suggest that the gravity does reflect such a mass of rock, stringers from which would be responsible for the values noted in the seismic and magnetic measurements.

A possible explanation of the sharp, magnetic high is that it represents a diabase sill similar to those observed at the western end of the profile, but here possibly lying on the other side of the Triassic arch and dipping to the east as do the Triassic formations in the Connecticut Valley. This explanation is, of course, purely hypothetical.

Although all the data show a trough with a marked upswing in values at the coast, the magnetic data indicate another magnetic high which has no counterpart in the seismic and gravitational values. The significance of this feature is possibly the same as that attributed to the similar condition on the Cape May profile.

Although there are no other locations where all three types of data can again be compared, there is a third magnetic and gravitational profile from Sea Bright passing through New Brunswick to Phillipsburg which the writer established as part of a transcontinental survey under a grant from the Geological Society of America. The results in New Jersey are shown in Fig. 30. In the Phillipsburg area two marked magnetic highs occur which are believed to be associated with the serpentines in that area; and in the vicinity of South River a marked, asymmetric magnetic high occurs on the west flank of a gravitational high similar in mag-

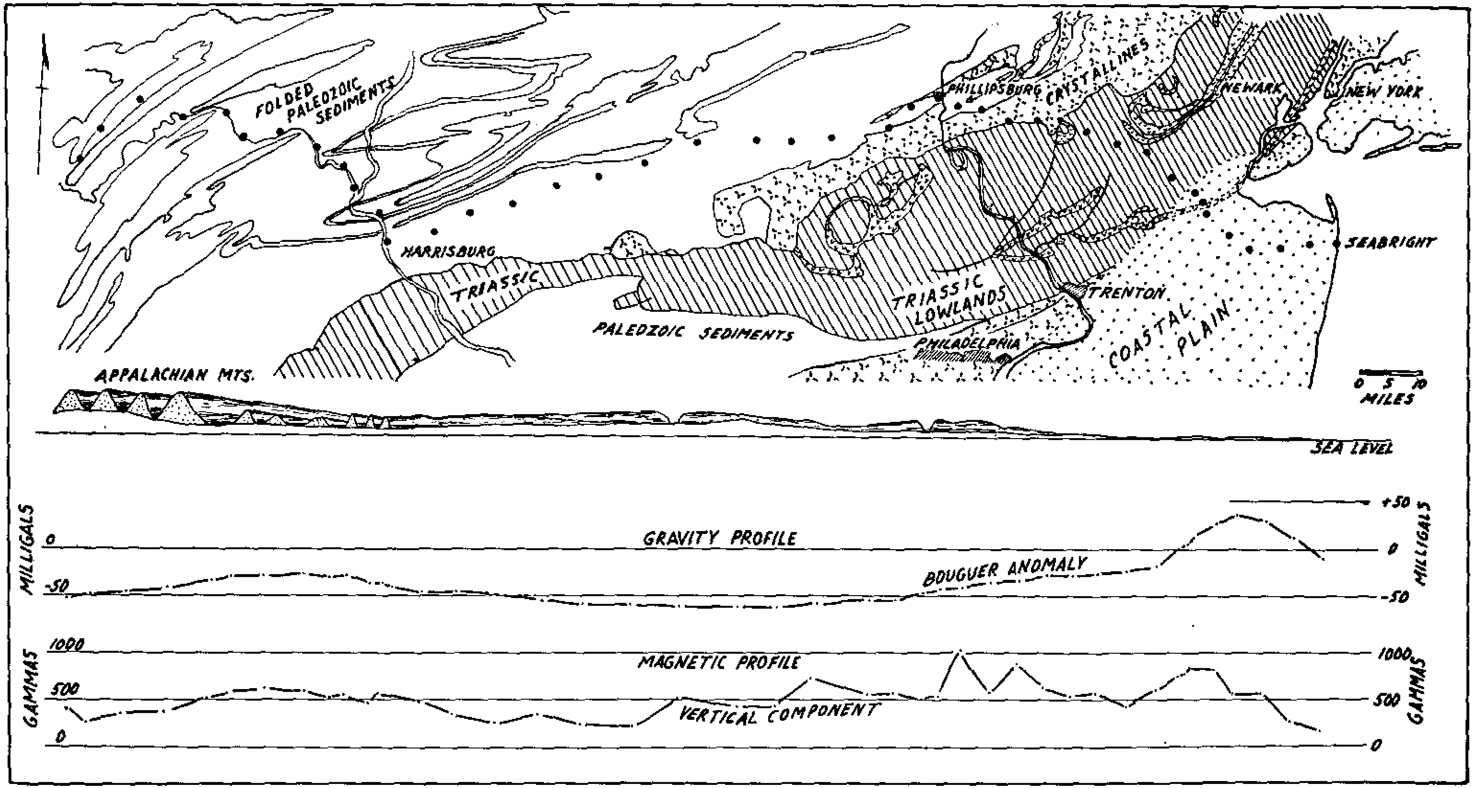

Fig. 30. A comparison of gravitational and magnetic data with the regional geology on a traverse passing through Phillipsburg and Sea Bright, New Jersey.

nitude to the one noted on the Barnegat Bay profile. In this case, the magnetic high is known from well data to be due to the subsurface connection between the Rocky Hill diabase and the Palisades diabase which parallels the western shore of Hudson River.

Rocky Hill extensions.—It is known from well data that the Rocky Hill diabase which disappears beneath the Coastal Plain near Deans carries on through South River, Sayreville and Perth Amboy to Staten Island; and the effect of this rock on the artesian water supply of the region has been discussed by H. C. Barksdale[1] of the New Jersey State Water Policy Commission.

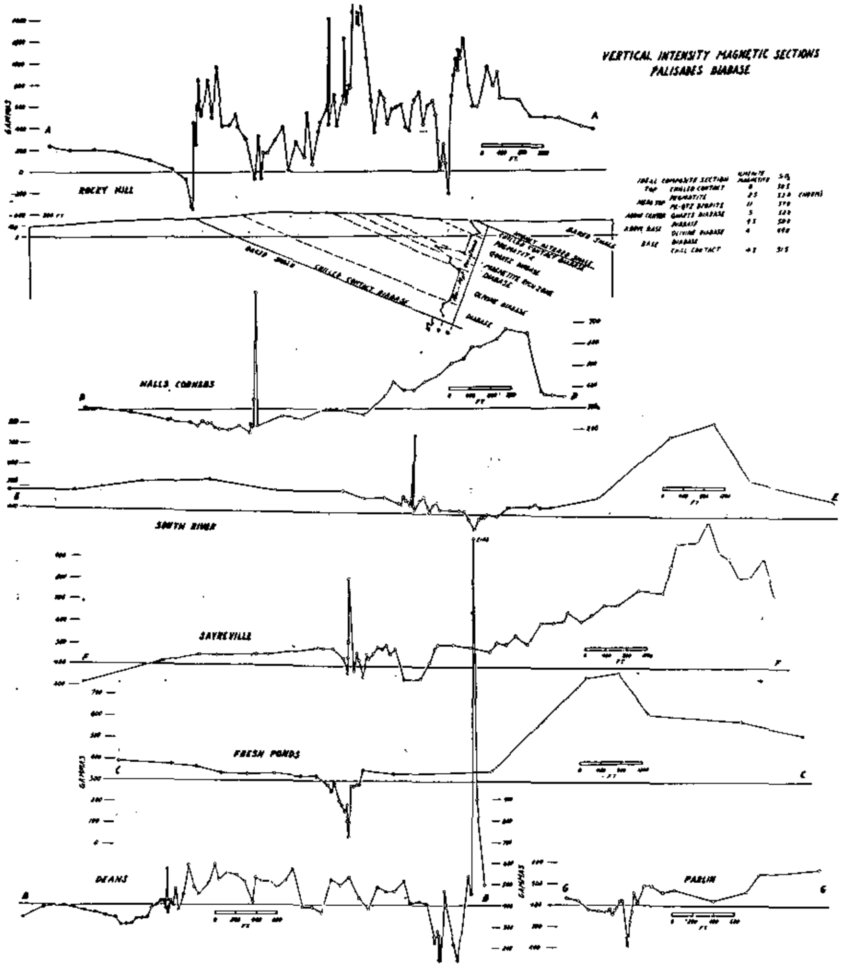

Fig. 31. Magnetic profiles over the Rocky Hill diabase and its buried extension lying beneath the Atlantic Coastal Plain.

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[1] Barksdale, Henry C., Water supplies from the No. 1 Sand in the vicinity of Parlin, New Jersey, State Water Policy Comm. Spec. Rept. 7, 1937.

However, the exact position of the diabase was not known until the writer, in cooperation with Meredith E. Johnson, State Geologist, established a series of magnetic profiles at right angles to the supposed strike of the diabase to locate its position.

A knowledge of the position of the diabase in this area is important since it existed as a topographic high, or island, when the coastal plain sediments were being laid down. Hence, some of the sandy horizons now carrying artesion water are separated by it and water cannot circulate freely from the northwest to the southeast side of the buried sill. This is borne out by bore-hole data which show that the mass acts locally much like a dam on the underground water supply, so that the water available for towns southeast of it has to be derived largely from the rainfall which falls on that side rather than from the large gathering area which lies northwest of the sill.

In this investigation the various magnetic profiles were established with a spacing of about 400 feet between stations and these are shown in Fig. 31. The Rocky Hill section was a calibration profile conducted over the outcrop of the diabase and the relation of the magnetic values to the mineralization of the diabase sill has already been commented upon in connection with the discussions of geophysical investigations in the Triassic areas. The other sections show that an asymmetric curve was obtained in each case except for the outcrop sections, A-A and B-B, and the short profiles where work was stopped by natural obstacles as on section G-G.

The southern contact on the profiles exhibits no marked characteristics and it was picked as being that point at which irregular values were first noted. Some of the anomaly forms have shapes similar to church steeples and these are for the most part regarded as having no geological significance, since the width of the anomaly in most cases indicates that the depth of the disturbance is too shallow to be associated with the diabase. As much of the survey was across filled ground these erratics are believed to be the effect of old automobile parts or other scrap iron.

Back from the contact the magnetic curves show an asymmetric shape with a pronounced change in values and this characteristic shape was used to verify the contact indications. This shape, incidentally, is that which should in theory be noted over a magnetic sill of infinite extent dipping concordantly with the actual diabase sill. The northern contact of the sill cannot be accurately determined due to its gradual dip and contact metamorphic effects, so a point was picked which seemed to satisfy the well

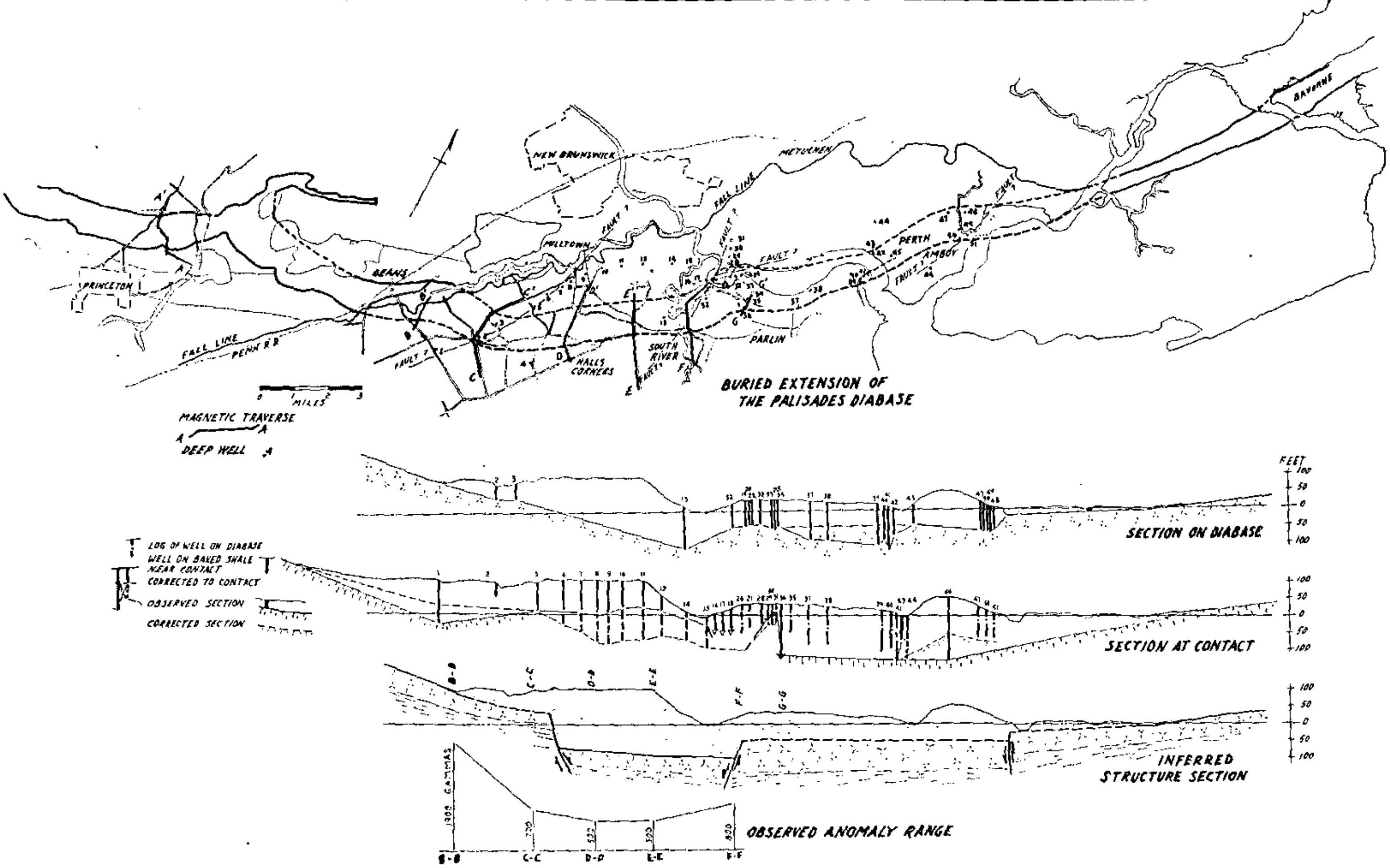

Fig. 32. The position of the buried connection between the Palisades diabase and Rocky Hill as outlined by magnetic measurements and well data.

data. These points were then connected and used with the well data to give the position of the subsurface outcrop of the diabase as shown in Fig. 32. In order to see if structural relations were indicated that would account for the burial of the diabase, a geologic section based on wells actually reaching the diabase was then drawn, and another at the contact which was based on wells entering baked shale. Since there is a relief on the surface of the diabase of over a hundred feet, wells near the contact would give different results from those occurring on the crest, and thus the position of the well was borne in mind in drawing the section which is taken as along the crest. Similarly, wells entering baked shale had to be projected to the southeastern contact using a regional dip of 17 degrees to the northwest.

In both profiles similar structural conditions were found: namely, normal faulting with the buried mass dropped down. The diabase apparently is broken at three points, giving a series of steps with the highest block occurring in the highly industrialized area adjacent to South River and Parlin where the need for water is the greatest. A qualitative check on this discovery is indicated in the amplitude of the magnetic values (note: the deeper the burial, the smaller the amplitude), and from Fig. 31 it will be noted that these check the above interpretation.

Plainsboro.—As mentioned in connection with the seismic work in the Coastal Plain, an abnormal time-distance graph was obtained at the Plainsboro seismic station. There was a definite offset in the high velocity line which indicated a marked change in slope. Since there was also a marked change in the character of the wave forms for the shot which gave this offset, the record was also used in determining the probable cause. The high velocity wave arrivals had been of high frequency up to this point and this was characteristic of the high velocity wave at the other stations. However, on the shot in question this wave came through as a low frequency form indicating a filtering action. The most likely natural filter would be the broken rock and gouge of a fault zone, as there was no change in velocity despite the change in wave form. A fault was thus postulated that would introduce sufficient low velocity material in the wave path to give the time lag observed and yet not affect the average velocity for the wave path as a whole. Although nothing was known at the time concerning the nature of the basement rocks here, it was subsequently found from well data that the area was underlain by diabase and baked shale and since another well at Plainsboro showed Stockton sandstone, the lowest member of the Triassic series, to be present

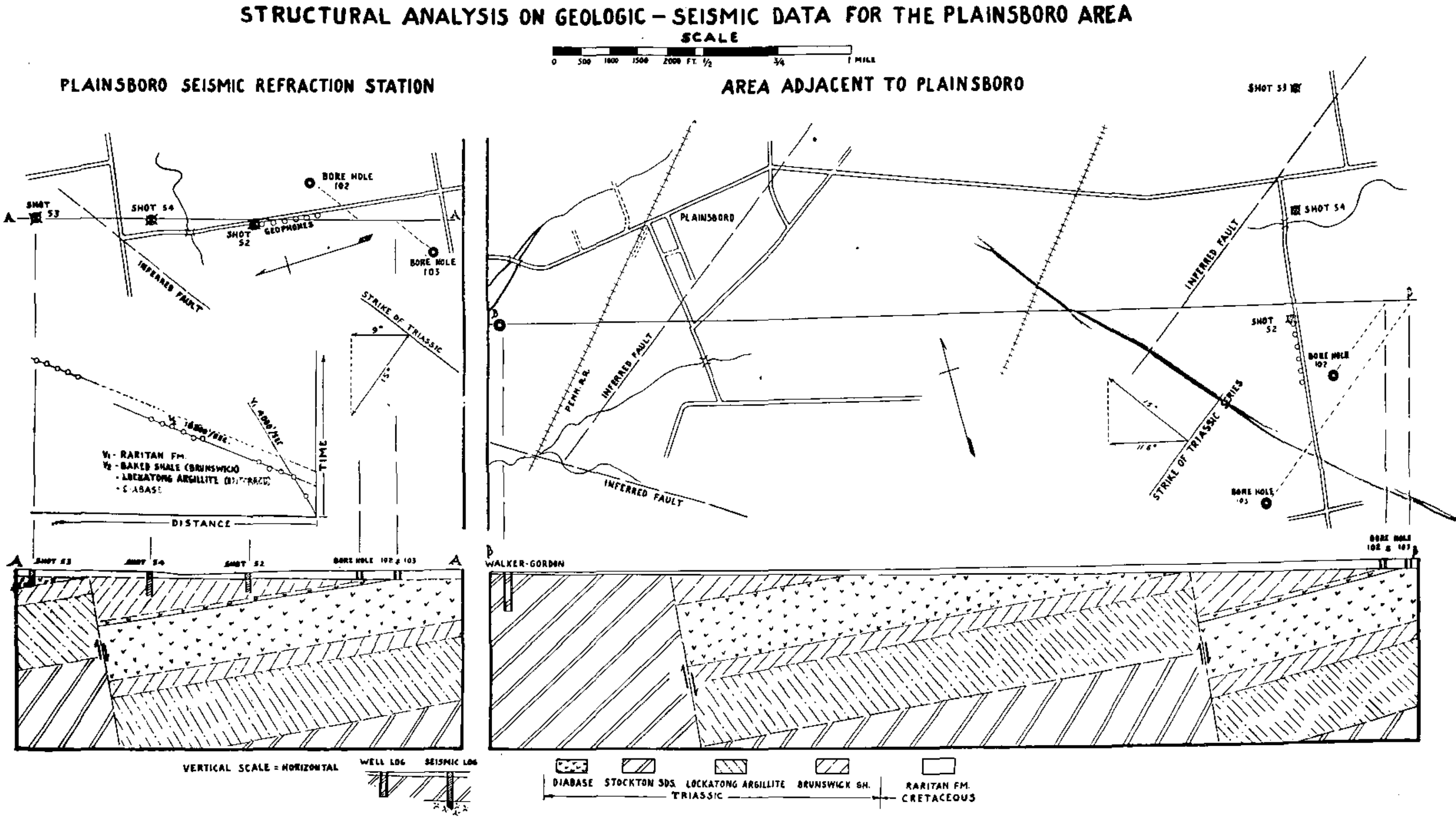

Fig. 33. Seismic investigations in the vicinity of Plainsboro and their geological interpretation.

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there, a fault would be necessary to explain the presence of these different rocks between the seismic station and Plainsboro.

The diabase occurs in shale forming the upper member of the Triassic series and since the strata dip westward it would be impossible for a lower member of the series to outcrop to the west unless faulting raised it so that the upper members could be removed by erosion. However, as a well at the Walker-Gordon Dairy Farms near Plainsboro showed a thickness of more than 660 feet of Stockton sandstone at that point, a second fault had to be postulated since an assumption of only one located at the seismic station would have given an excessive thickness for that formation. Accordingly another fault was postulated running nearly parallel to the Pennsylvania Railroad in the vicinity of Plainsboro. This location was decided upon since a well near Deans lying on the above line, showed Triassic sediments standing on end which would be indicative of faulting. Further, a cross-fault had to be postulated since the crystallines outcrop at Princeton Junction, and this was drawn as shown in Fig. 33 which shows the final geologic interpretation of all the data obtained. All known well data were satisfied by this interpretation, but it was wrong in that the seismically determined fault had a strike paralleling the majority of those noted in the exposed Triassic. This was not determined, however, until a magnetic survey was conducted over the same area. This survey, shown in Fig. 34, indicated the diabase as a magnetic, asymmetric high of the same shape and dimensions as obtained over the Rocky Hill-Palisades buried section. Also it is seen to have the general strike of the Triassic formations and to be parallel to the Pennsylvania Railroad and about 1½ miles southeast of it. This magnetic high terminates abruptly at the road running from Plainsboro to Cranbury and it is the same position as that determined as a probable fault by the previous seismic work. Further, it will be noted that the magnetic strike instead of being essentially NE-SW as on the south side of the road, is perpendicular to this trend on the north side, thus indicating a very marked structural change. The fault, therefore, appears to be verified, but its strike appears to be NW-SE.

To the south, the magnetic values indicate that the diabase ends in the vicinity of Dutch Neck, but the boundary is not as definite as on the northern end. However, there is well data which gives positive information on subsurface conditions in this area, and well No. 6 (Fig. 34), just north of Dutch Neck, penetrated crystalline basement rock which would indicate that the boundary be-

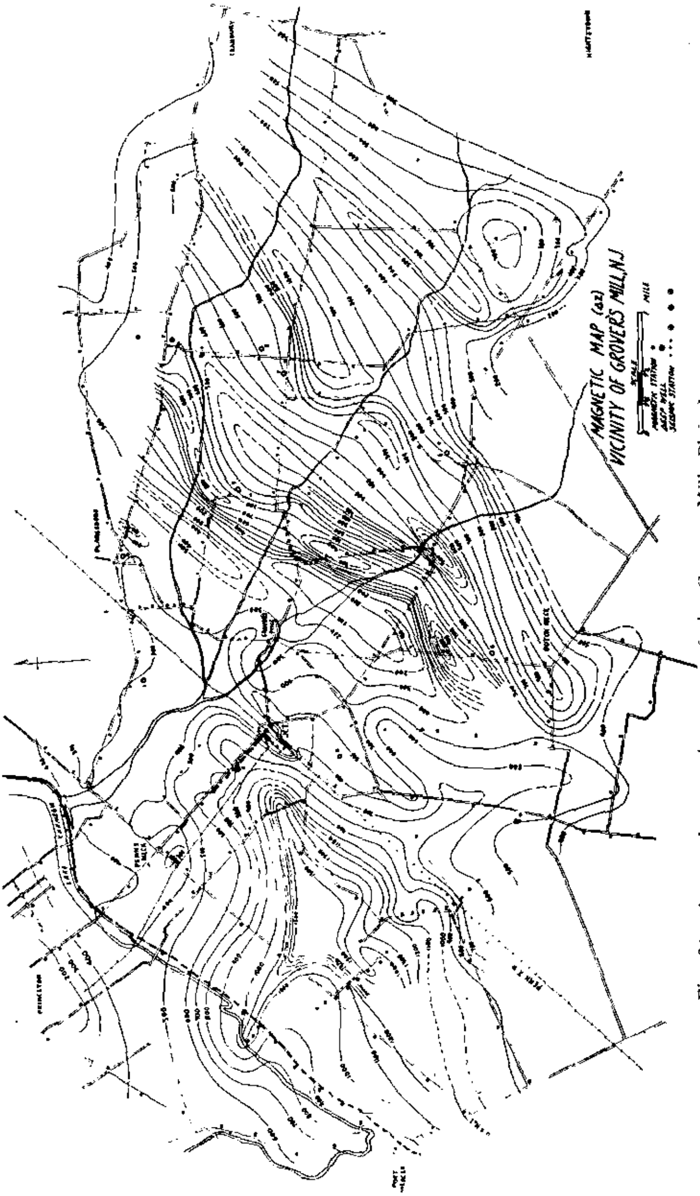

Fig. 34. An areal magnetic survey of the Grovers Mills-Plainsboro area.

tween the Triassic diabase and the crystallines is very close to this point. If it were not for the presence of baked shale in well No. 8, adjacent to well No. 7 where diabase is present, it would not be necessary to postulate that an entire block of Triassic material is present since diabase could occur in the crystallines; but the sediments indicate that such is the case and the problem narrows down to a determination of the boundaries of this block.

The northern boundary appears to be a fault as indicated in both the seismic and magnetic data; the eastern boundary is based entirely on well data, namely wells Nos. 6 and 7, both of which show crystalline rock. The southern boundary is fixed roughly by the magnetic contours, wells Nos. 6 and 3, both of which went into crystallines, and the crystalline outcrop near Princeton Junction. The western boundary has to be a fault to accommodate the well data already referred to at the Walker-Gordon Dairy Farm. These probable boundaries are outlined in Fig. 35, together with other faults that appear to be in the same general area whose presence is indicated by both outcrop and well data.

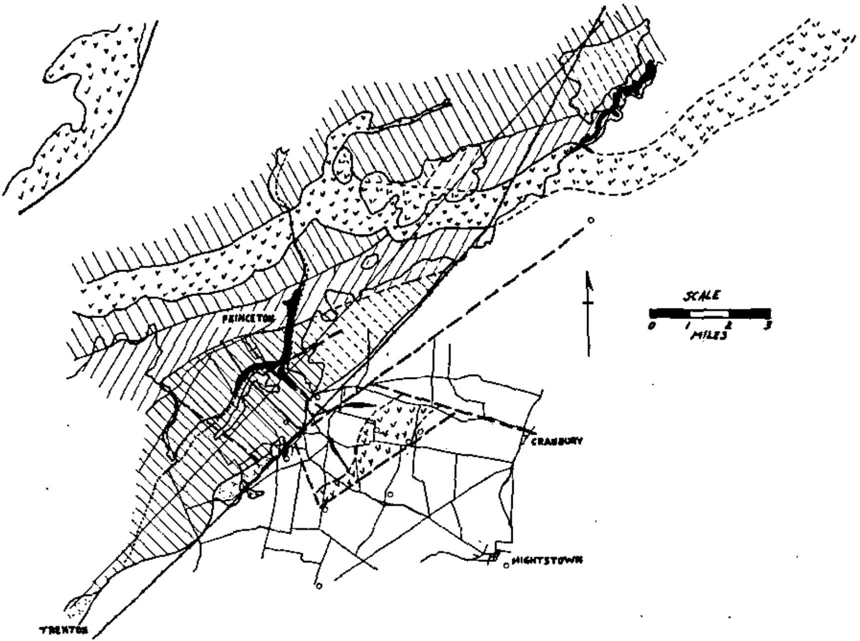

Fig. 35. Subsurface geologic structural conditions beneath the coastal plain in the Grovers Mills-Plainsboro area as outlined by magnetic measurements and well data.

Another feature appearing on the magnetic map (Fig. 34) is a marked, magnetic high lying just east of U. S. Route 1 and between Penns Neck and Port Mercer. This area has the largest magnetic anomaly values in the region (over 1500 gammas) and is believed to reflect the presence of gabbro similar to that which outcrops a few miles southwest. The nature of the magnetic high occurring on the Barnegat Bay profile just west of Hightstown is also shown and it appears to be a small isolated area that might be related to a local variation in the basement crystallines.

Electrical measurements.—Other than the resistivity measurements made by the American Telephone and Telegraph Company, the only electrical prospecting done in the Coastal Plain of which the writer has heard, was an investigation made by the State Water Policy Commission of the salt water intrusion of the 100-foot Sand in the Atlantic City well field between Absecon and Pleasantville. The rather unsatisfactory results obtained were attributed to instrumental difficulties and inexperience in eliminating them rather than to any failure of the method. Artificial ground currents may also have been partly responsible for the difficulties encountered in view of the close proximity of the water-works power plant to the well field.

Other investigations have been limited to trial radio attenuation measurements which suggest the possibility of porosity changes in the sediments and also possibly the location of faults. For example: marked fading in radio reception has been noted in crossing a fault in Brewers Hill in the vicinity of Princeton and also over an area about a mile wide just east of Lakewood.

STATE-WIDE GEOPHYSICAL INVESTIGATIONS

In Fig. 17 the general gravitational anomaly distribution for the state as a whole is shown. This clearly shows the marked gravitational trough to which reference has previously been made in connection with the Barnegat Bay profile. Because of its size, it is believed to have a deep-seated cause which may extend to the bottom of the granitic crust and be a reflection of its configuration. The smaller features in the Coastal Plain are believed to have a much shallower control as indicated by the agreement between the gravitational values and other measurements previously discussed.

Despite the regional effect of the gravity trough, satisfactory interpretations of gravity work in the effected area can be made if the trough effect is subtracted from the results obtained. These residual results will be small, though, and corrections for all subsidiary effects — particularly of the surrounding terrane —

would have to be carefully done in order to obtain satisfactory results.

The U. S. Coast and Geodetic Survey has established a series of magnetic stations for determining the variation in the earth's field magnetic strength, and in addition the secular variations due to the migration of the earth's magnetic poles with time. This migration causes the general field to change from year to year so that the same magnetic intensity will not hold at one point from one year to the next. By periodically reoccupying the same bases though, these changes can be determined and their trend established. Such changes concern not only magnetic surveys of the type outlined in the Coastal Plain where the values have to be corrected for them, but also mapping and other surveying where compass bearings are used. For example, a survey line made on a compass bearing ten years ago might end several yards distant from the previous terminal point if retraced today, and it is only by knowing these changes that old surveys can be rerun.

Aside from a few measurements of temperature in deep wells, the only other type of geophysical investigation that has been made in New Jersey is the determination of seismic epicenters; that is, focal areas of earthquakes. Earthquakes in this area can be attributed entirely to movement along faults extending down into the basement, and the movement is generally the result of a sudden release from long accumulated strain.

There have not been any great earthquakes in this region within historic time, although there have been a number of minor ones. The distribution of these suggest that perhaps two fault systems are present which are still active. One extends along a line passing through New York and Burlington, and the other parallels Appalachian structure through the Highlands. There is plenty of geologic evidence also to show the existence of these fault zones, one important fault having been mapped from Trenton southwest for a distance of more than 60 miles, and several overthrusts being known in the Highlands where the strata have been broken and pushed laterally over one another for distances of a mile or more. The forces producing these movements are probably due to different causes, but one may be due to the sinking of the area to the south as evidenced by the drowned river valleys; and another might be due to the isostatic rise of the area to the north due to retreat of the polar ice sheet which formerly covered all this region. These two conditions might be a reflection of one and the same action, but the differential movement is localized on the natural breaks in the crust, the faults. Therefore, *the probability of a major earthquake happening at any location* other than along the lines already indicated by minor quakes is remote, and if the movement of the crustal blocks is as postulated: namely, peripheral to the north (i.e. acting along a northeast-southwest line), the maximum differential movement would be on faults trending in that direction, such as the one extending along the St. Lawrence Valley where several major earthquakes have happened within historic time. Minor movements on the northeast-southwest and north-south fault systems extending through New Jersey are relatively frequent and hence the possibility of sufficient strain accumulating to cause a major earthquake is considered remote — particularly since the St. Lawrence Valley fault appears to accommodate the major crustal movements for this region as indicated by the intensity of past earthquakes there.

Conclusions

In summarizing the geophysical investigations that have been conducted in the State of New Jersey, the writer believes that sufficient evidence has been presented to show: (1) that geophysics has a real role in geologic investigations; (2) that certain methods have more value than others in obtaining pertinent data on different types of geologic problems; (3) that there are marked advantages in having more than one type of geophysical data for the same area; (4) that definite advantages are to be gained by combining geophysical knowledge with what is known of the geology in order to interpret the geophysical results, and (5) that a knowledge of geology is important in understanding many physical phenomena which usually are not thought of in connection with geology; as, for example, why telephone and power line service is not as good in some places as in others; why some areas cannot be surveyed with ordinary compass methods; why some areas are likely to have earthquakes and others not; why artesian water in one area is both good and plentiful, whereas in another it is salty and scarce; why radio reception is good in one area and bad in another, and so on. The answer to these questions lies for the most part in the geology that is beneath the surface of the ground and they can only be answered and this area economically explored by the application of geophysical methods of exploration.

BIBLIOGRAPHY

Ambronn, R. and Cobb, M. C., Elements of geophysics as applied to the exploration for minerals, oil and gas: McGraw-Hill, New York, 1928.

American Institute of Mining and Metallurgical Engineers, volumes on geophysical prospecting for the years 1929, 1932, 1934 and 1940.
Also, separate technical publications.

Card, R. H., Correlation of earth resistivity with geologic age and structure: Amer. Inst. Min. Met. Eng., Tech. Pub. 829; also, Geophysics, 1940; pp. 380-389.

Ewing, M., Woollard, G. P., Vine, A. C., Geophysical investigations of emerged and submerged Atlantic Coastal Plain; Part III, Barnegat Bay, N. J. section: Geol. Soc. Amer. Bul. 50, pp. 257-296, 1939. Part IV, Cape May, N. J., section: Geol. Soc. Amer. Bul. 51, pp. 1821-1840, 1940.

Eve, A. S. and Keys, D. A., Applied geophysics: Cambridge Univ. Press, London and Macmillan Co., New York, 1933.

''Geophysics'', the monthly journal of the Society of Exploration Geophysicists.

Heiland, C. A., Geophysical exploration: Prentice Hall, Inc., New York, 1940.

Jakosky, J. J., Exploration geophysics: Times-Mirror Press, Los Angeles, 1940.

Nettleton, L. L., Geophysical prospecting for oil: McGraw-Hill, New York, 1940.

Woollard, G. P., Ewing, Maurice and Johnson, Meredith E., Geophysical investigations of geologic structure of the coastal plain: Trans. Amer. Geophys. Union, pp. 98-107, 1938.

Woollard, G. P., A comparison of magnetic, seismic and gravitational profiles on three traverses across the Atlantic Coastal Plain: Trans. Amer. Geophys. Union, pp. 301-309, 1940.