Seismic and Gravity Surveys of Naval Petroleum Reserve No. 4 and Adjoining Areas, Alaska

EXPLORATION OF NAVAL PETROLEUM RESERVE NO. 4 AND ADJACENT AREAS, NORTHERN ALASKA, 1944–53

PART 4, GEOPHYSICS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 304–A

Prepared and published at the request of and in cooperation with the U.S. Department of the Navy, Office of Naval Petroleum and Oil Shale Reserves

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By JOHN R. WOOLSON *and others*

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

[All plates in pocket]

TABLES

EXPLORATION OF NAVAL PETROLEUM RESERVE NO. 4 AND ADJACENT AREAS, NORTHERN ALASKA, 1944–53

SEISMIC AND GRAVITY SURVEYS OF NAVAL PETROLEUM RESERVE NO. 4 AND ADJOINING AREAS, ALASKA

By John R. Woolson[1] and others

ABSTRACT

A program of petroleum exploration in and adjacent to Naval Petroleum Reserve No. 4, northern Alaska, was undertaken by the U.S. Navy in 1944. In 1945–46, the U.S. Geological Survey and U.S. Navy made an aeromagnetic survey. United Geophysical Co., Inc., under contract to Arctic Contractors, was responsible for the other geophysical phases of the exploration.

A reconnaissance gravity survey of the area north of lat. 68°30′ N. was completed in 1950. Seismic surveys, generally restricted to the Arctic coastal plain, were made from 1945 to 1953 to (1) map in detail areas of gravity or magnetic anomalies, (2) map areas of known oil seeps, or (3) serve as a means of reconnaissance to determine localities for future work. In the later part of the program some seismic work was done south and east of the Reserve.

The seismic work revealed the presence of several reflecting horizons by which structures in Cretaceous and older rocks could be contoured. A series of anticlinal folds in Cretaceous rocks was discovered and studied in sufficient detail to establish a number of drilling locations.

Except in the vicinity of Barrow and the western part of the Reserve, little relation was found between gravity and magnetic anomalies.

INTRODUCTION

Naval Petroleum Reserve No. 4, an area of about 37,000 square miles in Arctic Alaska, is entirely north of the Brooks Range, which with its related mountain systems, separates about 68,000 square miles of northern Alaska from the rest of the State. The United States Navy began a program of petroleum exploration of this large Reserve and adjacent public lands in 1944 (Reed, 1958). From 1945 to 1953, as part of this investigation geophysical studies were made primarily within the Reserve (fig. 1), but in the later years the work was extended east and south of the Reserve.

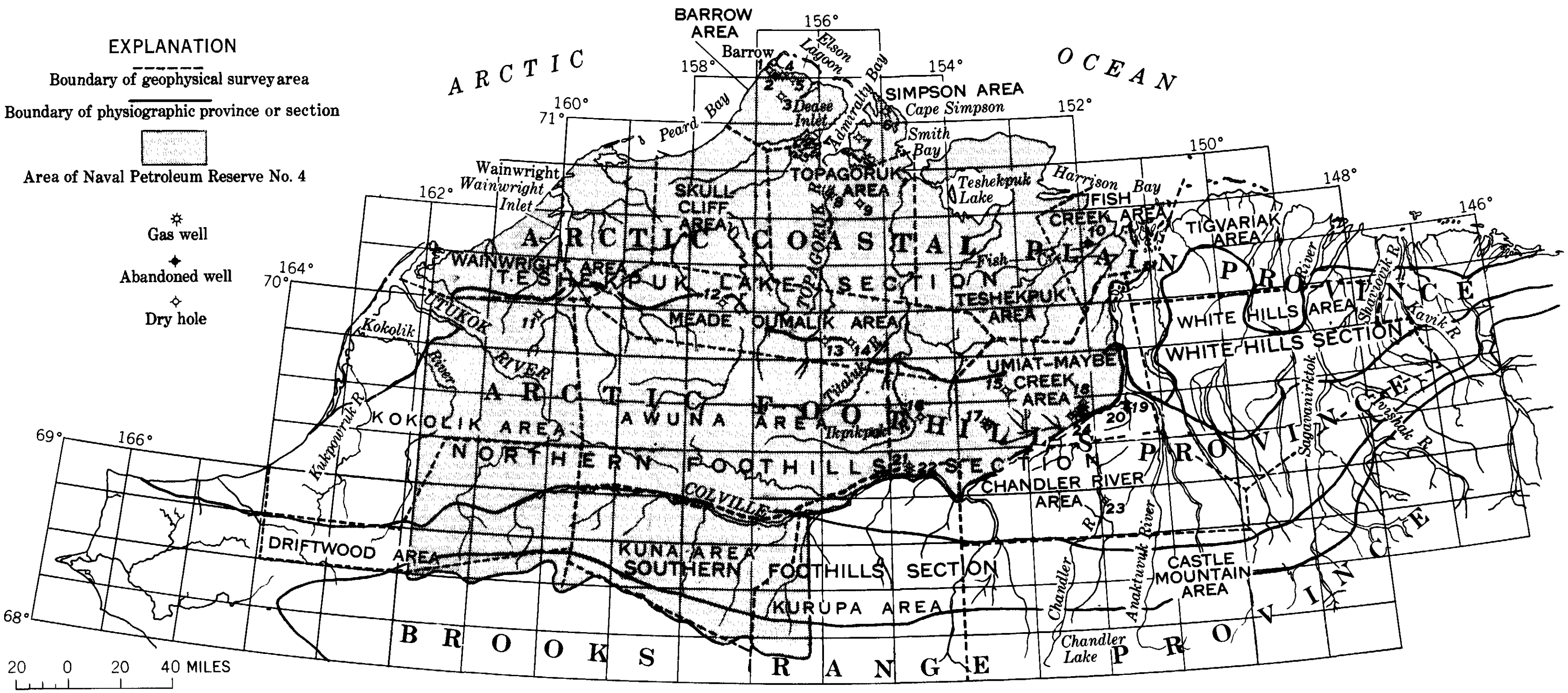
Before the geophysical exploration began, geologic knowledge of the area was necessarily based on a limited amount of surface work. The earliest hypothesis concerning the sedimentary basin north of the Brooks Range was that the deepest part of the basin was to the north, probably beneath the Arctic Ocean. It is largely due to results of seismic surveys and test drilling that the area is now interpreted as a single large asymmetric basin, whose long axis is parallel to the Brooks Range. The deepest part of the basin is within the Arctic Foothills province (pl. 1).

Naval Construction Battalion 1058 (Seabees) began the geophysical exploration with gravity work in 1945. In that year United Geophysical Co., Inc., worked under direct contract to the Navy Department, Bureau of Yards and Docks, and as a subcontractor to Arctic Contractors from 1946 to 1953. In addition, an airborne-magnetometer survey was made jointly by the U.S. Geological Survey and the U.S. Navy in the summers of 1945 and 1946. The geophysical exploration was then a cooperative effort to which the Navy Department, Arctic Contractors, the U.S. Geological Survey, various airlift contractors, and others contributed materially. The support of isolated field camps and maintenance of personnel under arctic conditions required the maximum effort from each organization and all persons concerned.

All the geophysical work, except as noted above, was done by United Geophysical Co., Inc. It supplied the technical personnel and supervision for the seismic and gravity surveys, with the exception of the first season's gravity work. It also supplied the seismic and gravity instruments, except the gravimeters used in 1945. Arctic Contractors supplied the necessary support in technical and other personnel, as well as the direction under which the geophysical exploration was done. As prime contractors, after the first season, Arctic Contractors supplied all other equipment and supplies used in the geophysical exploration.

At the conclusion of exploration in 1953 the broad aspects of one of the world's larger sedimentary basins had been defined. A series of anticlinal folds was discovered and examined in sufficient detail by seismic methods to establish drilling sites. A belt of folded rocks, extending east-west across the central part of the

[1] United Geophysical Co., Inc.



1. South Barrow test well 1
2. South Barrow test well 2
3. South Barrow test well 3
4. South Barrow test well 4
5. Avak test well 1
6. North Simpson test well 1
7. Simpson test well 1
8. Topagoruk test well 1
9. East Topagoruk test well 1
10. Fish Creek test well 1
11. Kaolak test well 1
12. Meade test well 1
13. Oumalik test well 1
14. East Oumalik test well 1
15. Square Lake test well 1
16. Titaluk test well 1
17. Wolf Creek test wells
18. Minga velocity test
19. Gubik test well 1
20. Gubik test well 2
21. Knifeblade test well 1
22. Knifeblade test wells 2 and 2A
23. Grandstand test well 1
24. Umiat test wells

FIGURE 1.—Index map of northern Alaska showing designation of areas of geophysical surveys. Numbers indicate location of wells listed.

Reserve for at least 250 miles and having a minimum width of 30 to 50 miles was outlined (pl. 1). The northern part of this belt was examined more closely by seismic methods than the southern part. Surface geologic methods, particularly photogeologic and field mapping by the Geological Survey, have shown that this folded belt extends into the foothills of the Brooks Range.

During the geophysical exploration, seismic, gravimetric, and magnetic methods were used. Of these, the seismic surveys yielded results allowing a direct and detailed interpretation of the subsurface geologic aspects of the region. The gravity and magnetic surveys were used primarily as regional reconnaissance methods of exploration. The interpretation of complex thrust faults in the southwest part of the Reserve (section *C–C′*, pl. 1) resulted from combining geologic field and seismic data.

After each operating season the geophysical supervisor incorporated the results obtained with results of earlier seasons. The interpretations presented here are based mostly on seismic data and are a synthesis of the work and ideas of the men who were associated with the geophysical exploration from 1945 through 1953. The results of the airborne magnetometer survey, by M. S. Walton, Jr., J. R. Balsley, Jr., and J. R. Henderson, Jr., of the U.S. Geological Survey, were used in this geophysical study. In addition, results of geologic and photogeologic mapping and paleontologic studies were made available by the U.S. Geological Survey during the exploration program. This report was prepared largely by J. R. Woolson, United Geophysical Co., Inc., from the large amount of data accumulated during the exploration program. Results of paleontologic and stratigraphic studies by the U.S. Geological Survey were incorporated. The following men of United Geophysical Co., Inc., contributed materially to this report: B. N. Grant, M. W. Harding, S. Allen, E. J. Munns, J. A. Legge, F. E. Wianko, E. W. Gilbert, R. L. Benedicktus, S. W. Spannare, L. B. Luhrs, W. H. Myers, J. H. Boring, A. B. Sanders, H. B. Chalmers, A. Palenske, C. Post, R. J. Spittel, W. R. Fillipone, W. B. Howard, S. O. Patterson, G. C. Donohue, and W. L. Romine.

OPERATIONS

In 1945 the gravity survey was conducted by a unit of the Seabees, and the work done by this group has been incorporated with the later gravity surveys made by United Geophysical Co., Inc.

The magnetometer work was done in 1945–46 as a cooperative effort between the Navy and the U.S. Geological Survey.

From 1946 through the completion of the work in 1953, all the seismic and gravity geophysical operations were under the direction of a geophysical supervisor or geophysical project manager of the United Geophysical Co., Inc., who was responsible to Arctic Contractors for the entire operation and particularly for the presentation and interpretation of geophysical results.

From 1948 through 1952, United Geophysical Co., Inc., maintained a geophysical-operations superintendent in the Reserve to handle and store supplies and to supervise general operations.

From 1945 through 1947, in the early part of the 1948 season, and in 1953, preliminary interpretation was done at the field camps of the crews. From 1948 through 1952, final interpretations of the season's results were made by a group of seismologists and computers who worked in the Fairbanks office on a year-around basis. The purpose of the Fairbanks interpretational group was to coordinate the interpretation for adjoining areas of work and unify surveys for different seasons in the same area. This system was abandoned for the 1953 season because the area surveyed was isolated from areas of any previous seismic work.

Direct contact was maintained between the geophysical operations superintendent and general superintendent at Point Barrow in regard to support and logistics.

Because of the large area of responsibilty for operation of the seismic field crews, the duties of party chief were divided into those of a party manager, whose primary responsibility was crew operation, and those of a seismologist, whose primary responsibility was interpretation of the results. Although each was separately responsible for his part of the work, it was necessary that they work closely together, because the observer and the surveyor were responsible to both men.

All geophysical operations were conducted from mobile camp units, which were sled-mounted and were towed from one centrally located camp site to the next by crawler tractors. It was found best to plan the work and camp moves in the winter and spring so that the camp site would be within 8 to 10 miles of the field operations. After the thaw, the distance was reduced to approximately 5 miles.

It was found best to limit the geophysical program to the period February through July. During the fall, thickness of snow on the tundra or ice on the lakes is insufficient for landing of light planes, and it is thus difficult to give the crews adequate support. The extreme cold and darkness during December and January make progress so slow as to be economically impractical. During August and September the depth of thawed ground is such that progress is slow and the wear on equipment is extreme. In some years, however, operations were conducted during the months of August through January. During these months the work was either on an experimental basis or the additional information obtained justified the higher unit cost.

The transporting of supplies of gasoline, diesel fuel, and dynamite from the Point Barrow base camp to the field locations of the geophysical operations necessitated careful planning. Because the large rivers could not be crossed on the ice after approximately May 15 of each season, it was imperative to cache these supplies in the areas where the crew would be working after that date. Actually, it was found expedient to cache the entire season's supplies for the crews during the period January through April. It was possible in some places to construct air strips for the bigger planes (C–46 and C–47) and supply the crews by this means or, in an emergency, to parachute supplies to the crews.

The general outlines of the year's program were established each fall and the details were worked out during the following months. This necessity for long-range planning destroyed some of the flexibility that would ordinarily be desirable. It was generally possible, however, by judicious control of the caches, to allow the crews to investigate most leads that developed as their work progressed. One of the methods of increasing flexibility of program development was to cache 25 percent more than the anticipated requirements in areas where favorable structures might be indicated.

INSTRUMENTS

GRAVITY INSTRUMENTS

LaCoste-Romberg vertical seismo-gravimeters (Dobrin, p. 55–56) were used from 1946 through 1950. Electronic altimeters, which depend on air-pressure differences, were found to be the most satisfactory method of obtaining vertical control. These instruments are corrected against a standard mercury tube barometer in the field office. Standard land-surveying techniques were used by the crews transported by weasel vehicles.

SEISMIC INSTRUMENTS

Two different types of seismic instruments were used in the Reserve and adjoining areas. Because of the sharp decrease in the amplitude of reflected energy with elapsed time on the records, it is necessary to increase the amplification of the instruments with elapsed time. The difference in instrumentation was the manner by which this increase in amplification was accomplished. From 1945 through 1949 the rate of increase of amplification was preset by the operator in devices known as expander instruments. From 1950 to the suspension of operations in 1953, the rate of increase of amplification was automatically controlled as a function of the amplitude of the input energy. Both types of amplifiers are adaptable to refraction shooting by making changes in the components, which can be made in the field.

Various patterns of geophone placement on the ground were used. Through much of the northern part of the area, one geophone per recording trace was sufficient. In the extreme southern parts of the area, as many as twelve geophones, arranged in "star" patterns, were used. It was necessary to dig holes through the loose snow or thawed tundra to plant the geophones on hard ground. Geophones with a lower frequency peak response were used for refraction shooting. Shot depth, charge size, geophone pattern, and amplifier-frequency response were varied and subject to continuous check by the instrument operator and the seismologists to obtain as good quality records as possible.

The seismic reflections were plotted on cross sections (profiles) showing depth. To do this, time is converted to depth using velocity data. The cross sections were constructed by using a circular ray-path method of plotting in the areas of increasing velocity with depth, and a straight-ray-path method in areas of constant velocity. The cross sections were used to construct subsurface maps of the various areas surveyed. The cross-section method of representation was used, because it is particularly useful for solving stratigraphic problems and because reflection records shot along lines of profile are readily plotted on cross sections.

The refraction records were computed on the assumption that the energy traveled along straight-ray paths in the various velocity layers, and that Snell's Law is valid to determine the angle of refraction at velocity interfaces.

EQUIPMENT

GRAVITY SURVEYS

Light planes, weasels, and helicopters were used to transport the gravimeter from station to station. Of these, the helicopter proved to be the most satisfactory; it was used in 1950 only, to complete the survey in the western part of the Reserve north of lat 69°30′ N. This survey was made with station locations on an approximate 2-mile grid. The camp equipment (jamesway huts) was mounted on sleds, with a layer of empty fuel drums between the top of the sled and the base of the hut to serve as floats for river crossings. The camp equipment was moved to the various camp locations by LVT (landing vehicle, tracked).

The 1949 gravity surveys were made with the aid of a light plane for transporting crew and instruments, except that during the spring breakup a weasel-transported party made a survey of an area south of Barrow camp. They used the Barrow camp and Wainwright Village as base camps and thus had no camp-moving problem.

The 1947 gravity surveys were similarly made out of established base camps. In 1945 and 1946, weasels were used for transportation and crawler tractors to move the camp equipment. The air-transported (light plane) crews made surveys using stations located on an approximate 5-mile grid, which gave only a broad regional gravity map. The weasel-transported survey used stations located at quarter-mile intervals. This resulted in a more detailed survey than was necessary when gravity surveys are used as a reconnaissance tool. For this reason the helicopter is considered the most satisfactory method of transporting the gravimeter.

SEISMIC SURVEYS

Because of the necessity of drilling shotholes and maintaining isolated field camps, the seismic operations used more equipment than the gravity crews. The drilling equipment consisted of sled-mounted portable rotary drills. Two kinds of drills were used: a Failing 314–C hydraulic pulldown and a Mayhew 1000-chain pulldown. For a few holes, spudders were used for shothole drilling. The drills were originally mounted in an enclosed wanigan in which the mast protruded through the roof. During the later stages of the operation, the drills were entirely enclosed in a wanigan specifically constructed for them; the mast remained up when the drill was moved (fig. 2). A D–8 "cat" (caterpillar tractor) was required to move the drill.

The drills used water to return cuttings to the surface, except in 1952 and 1953, when two of the drills were equipped to use compressed air to return the cuttings. Depending on the length of water haul, one or two D–8 tractors were required to haul water to the drill. For winter operations, water was obtained by blasting holes in lakes that had not frozen to the bottom.

The water wanigans were sled mounted and each had one or two 1000-gallon pontoons. Usually a two-pontoon wanigan was used to supply water for the drill and camp. A diesel-fuel heater was used in the wanigans to keep the water from freezing. A water-circulating-type heater was tried in the water wanigans and abandoned.

An air compressor was used to return the drill cuttings to the surface. This method is ideally suited to Arctic operations, where the ground, except for a

A. Seismograph map, looking north.

B. Seismograph drill and tractor party.

C. Blasting mud pit.

FIGURE 2.—Seismograph operations near east fork of Ikpikpuk River, July 1947.

superficial thaw layer, is frozen the year around. The compressed air at the bit was cooled to slightly below 0°C. by vulcan radiation and by orifices in the swivel and in the bit sub, thus preventing thawing. The compressor, which furnished 500 cubic feet per minute at 100 pounds per square inch, and the compressor power plant, a caterpillar D–13,000 diesel engine, were installed in a separate wanigan. A smaller compressor and a pill tank were also installed in the wanigan to supply a surge of compressed air in the event of bit block off. The drills were rigged so that water or compressed air could be used by merely opening and closing the appropriate valves.

In the foothills areas, where time-consuming 5- to 10-mile water hauls were common, the method of drilling with compressed air resulted in an estimated 2 to 3 times the footage per tour that would have been obtained with water return. In some areas, where unsuccessful attempts had been made to drill with water, it was possible to drill shotholes with compressed-air cutting return.

The surveyor used both a transit and level to obtain the necessary horizontal and vertical control. In areas of high relief the transit was used to obtain vertical control. From 1945 through 1948 a system of triangulation stations was established and the horizontal control was tied to the stations. After that time, sufficient accuracy of location was obtained by the use of better topographic maps and the erection of marked barrels at the turns and intersections of lines.

The shooter used a single-pontoon water wanigan to haul water to tamp the charges. This wanigan was hauled by a D–7 caterpillar tractor.

The seismic instruments were installed in a weasel-hull wanigan or in an LVT (landing vehicle, tracked). Because of the necessity of using water to develop and fix the seismic records and the better operation of electronic instruments at warmer temperatures, the LVT installation was most desirable. The conversion from a weasel-hull wanigan to the LVT was made in 1949 and 1950. It then became standard practice to use the LVT for the seismic-instrument installations.

One D–8 tractor was used in camp to haul fuel and camp water, and for other miscellaneous operations.

The basic moving equipment for each seismic crew was: two D–8 tractors for each drill if water was used and one tractor if compressed air was used; one D–7 tractor to haul the shooter's wanigan; one D–8 tractor for camp use, and one LVT to haul the recording instruments.

In addition to the previously mentioned vehicles, approximately 11 weasels or similar carriers were necessary for crew use. These weasels were used as follows: Three by the survey crew; three by the recording crew; one by the shooting crew; two by the drill crew; one by the mechanics, and one by the party manager.

When more than one drill crew was used, it was helpful to add the crew as an independent unit together with all the water wanigans, tractors, and weasels necessary to its operations. Other auxiliary equipment such as welders, small electric power plants, a small crane, and shop tools were used by the crews. The seismic equipment used varied from crew to crew and from season to season. The above list and description are generalized for the equipment in use during 1949 and 1953, and as such represent the cumulation of experience as to what was necessary.

GEOPHYSICAL PROBLEMS AND EXPERIMENTAL WORK

EFFECT OF PERMAFROST

Permafrost, defined as ground which is permanently below 0 °C., occurs everywhere in the Reserve and adjoining areas except under lakes and rivers that do not freeze to the bottom during the winter season. Because of lack of homogeneity of the ground, the permafrost layer is not physically homogeneous, and the velocity of compressional shock waves through it ranges from as low as 6,000 to as much as 14,000 feet per second. The effect of permafrost, where it has been measured, is to increase the velocity of the compressional wave. The results of velocity surveys of test wells drilled in the Reserve show a surface layer of higher velocity about 800 feet thick, underlain by a zone of lower velocity. This problem was studied in some detail at Lake Minga in the Simpson area. In 1950, a velocity test hole was drilled near the center of the lake. The average velocity obtained near the surface was approximately 5,500 fps (feet per second) and increased to approximately 6,500 fps at a depth of 1,200 feet in Lower Cretaceous rocks. These data, compared with the velocity of the 9,000 to 10,000 fps obtained at Simpson core hole 7, show that the change in velocity is due to the change in temperature of the ground. There is some evidence that the velocity-change effect is sharp near the freezing temperature of water. This velocity change causes a time delay in thawed areas that, if not recognized, may cause an erreoneous interpretation. The problem was largely avoided by locating lines between lakes and swamp areas. No satisfactory method was found to compute a correction for velocity changes due to changes of permafrost thickness.

POULTER METHOD OF AIR SHOOTING

A series of experimental shots was made in 1948 to determine whether or not the Poulter method of air shooting would be effective in the Reserve and adjoining areas. This method involves supporting the charges above the ground, usually in a group of small charges (5 to 10 pounds) arranged in a star pattern. The results of the experiment were negative. Several heights, patterns, and amounts of charge were tried.

The high reflectability coefficient at the air-ground interface tends to allow only a small percentage of the shot energy to be transmitted into the ground. This coefficient is high in permafrost areas because of the larger difference in velocity between air, in which the velocity is about 1,100 fps, and the permafrost, in which the velocity is from 10,000 to 12,000 fps. Also, thawed tundra probably acts as a compressional-wave insulator because of its low velocity and porous, spongy consistency.

WATER SEISMIC WORK

Some experimental shooting in the ocean water was done in 1948. The results were good, insofar as record quality is concerned. The records are comparable, in regard to usability, with records obtained by shooting on adjoining land. Operationally, the experiment was severely hampered by pack ice at or close to the shore, and by storms. The length of time during which open ice-free water was available for this type of study was unusually short in 1948.

MULTIPLE-GEOPHONE EXPERIMENTS

In the northern part of the Reserve one geophone per record trace was used. During the latter stages of the operation, when attempts were made to obtain results in the foothills areas to the south, as many as 12 geophones per trace were used. In the Castle Mountain area (see fig. 1) the records were generally improved with 12 geophones per trace. During 1953, in the Shaviovik River area, four geophones per trace were used. It was found advisable to have sufficient extra geophones, which could be used if necessary, available to crews working in the foothills areas.

CORRELATION

In the Barrow, Simpson, and Topagoruk areas, correlation between pre-Cretaceous sections penetrated in the test wells was well defined on seismic control. These correlations agree closely with those made by the U.S. Geological Survey by study of cores and cuttings from the wells, and also with correlations by means of electric logs. The southernmost test well to penetrate known pre-Cretaceous rocks in Topagoruk test well 1, which was drilled through Jurassic, Triassic, and Paleozoic rocks from 6,600 feet to its total depth at 10,503 feet.

Within the vicinities of the Barrow, Simpson, and Topagoruk test wells and elsewhere in the Reserve and adjoining areas, the various kinds of subsurface information regarding the Cretaceous section do not agree with each other as well as do those for the pre-Cretaceous. A zone of shallow reflectors in the Cretaceous section is of about the same thickness (3,000 to 5,000 feet) throughout most of the northern part of the Reserve. This zone of shallow reflectors corresponds roughly to the *Verneuilinoides borealis* faunal zone of middle Albian age as identified by H. R. Bergquist, U.S. Geological Survey (written communication) in interbedded marine and nonmarine sedimentary rocks.

Seismic correlation involves a study of the overall aspect of the sections and the type of reflection information obtained. As such, the base of the zone of shallow reflectors is not everywhere clearly defined. There is a reasonable correlation between the zone of shallow reflectors and the rocks penetrated in the test wells, as below this zone the wells penetrate a sequence that is largely shale of early and middle Albian age (H. R. Bergquist, written communication). However, within the zone of shallow reflectors, the reflections, particularly those perpendicular to strike, tend to cross the zone. For this reason it was not possible to construct a map of the shallow zone without changing the level of control. As an example, eastward from Oumalik test well 1 the shallow reflections dip to the east at a rate sufficient to place them below the lower limits of the zone of shallow reflections approximately at the Ikpikpuk River. As there was no satisfactory reflection control to continue the map farther to the east at this depth, a shallower level of control was chosen in order to construct the map for the area east of the Ikpikpuk River.

GRAVITY SURVEYS

In 1945 the Seabees began the gravity surveys. A detailed survey of the Cape Simpson area east of Admiralty Bay was completed. In 1946 and later seasons, the gravity work was done by United Geophysical Co., Inc. Table 1 shows the percentage of geophysical work done by the ground and air-transported crews. In 1946 a small area south of Smith Bay and a ground-detail survey of the magnetic anomaly due south of Barrow and between the Meade River and Topagoruk River were completed. Also in 1946 an air-transported gravity survey was made of an area near the confluence of the Titaluk and Ikpikpuk Rivers to check three magnetic anomalies in the area.

In 1947 the airborne survey in the eastern part of the Reserve and the Barrow area was completed, with observations made on an approximate 5-mile grid; it tied together the various surveys of 1945 and 1946 and completed the reconnaissance gravity map of the Reserve east of the Meade River.

TABLE 1.—*Statistical summary of gravity surveys*[1]

Year	Type of transport	Number of stations surveyed	Area covered (sq mi)	Dates of operation	Crew months	Area covered per station (sq mi)
1945	Ground	636	350	June 9–Sept. 1	2.7	0.55
1946	Ground	2,552	928	Apr. 8–Sept. 23	5.5	.36
	Air	252	1,466	July 9–July 26	.6	5.82
1947	Ground	103	60	June 19–July 7	.6	.58
	Air	491	13,500	Apr. 11–Sept. 5	4.8	27.5
1949	Ground	185	90	Apr. 22–May 10	.6	.49
	Air	111	2,700	Mar. 15–Sept. 16	6.0	24.3
1950	Air [2]	1,788	7,000	May 29–Sept. 3	3.2	3.9

[1] All surveys made by United Geophysical Co., Inc., except that in 1945, which was made by the 1058th Construction Battalion (Seabees), U.S. Navy.
[2] Helicopter.

A short gravity ground survey of the Oumalik anticline was made at the same time that the seismic crew was surveying the structure in detail. This was an attempt to determine, if possible, any relation between the seismic and gravity data in the area, but none was found.

No gravity work was done in 1948. In 1949 a survey was made on an approximate 5-mile grid of the area along the coast southwest of Barrow. Also a detailed gravity survey was made of the complex area south of the Barrow camp. The results of this survey aided in interpreting the subsurface data in this complexly faulted area. (See p. 16.)

In 1950 a survey was made by helicopter of the western part of the Reserve, completing the reconnaissance gravity survey north of lat 69°30′ N. This survey, as has been previously noted, established the helicopter as nearly ideal for making satisfactory gravity surveys in areas of this type. The survey was made on an approximate 2-mile grid.

GRAVITY AND MAGNETIC RESULTS

The gravity survey of Naval Petroleum Reserve No. 4 and adjoining areas was limited to that portion of the Reserve north of lat 69°30′ N. The observed gravity is shown in plate 2, magnetic intensity in plate 3 and areas of magnetic and gravity anomalies on figure 3. Only those parts of the gravity and magnetic results which, in the final analysis, proved to be useful are discussed here. Within the surveyed area the highest measured value of gravity is in the northeast-trending high that crosses the cape south of Point Barrow. A few stations define the north flank of this high. The gravity value decreases uniformly south and southeast, defining a slope area, off the Barrow high, that trends from Cape Simpson in a general southwest direction along the coast to the western limits of the survey (pl. 2) at the western boundary of the Reserve. This trend is interrupted by a broadening of the contours in the Wainright area east of Wainright Inlet.

In the western part of the Reserve is a large area of generally low observed gravity. This is terminated in the extreme southwest by a rather sharp increase in observed gravity that corresponds to the trend of a major thrust fault mapped in the vicinity of Carbon Creek as a result of the 1952 seismic work. The area of low gravity corresponds approximately to a depositional basin in which coal beds have been found. The gravity map of the western and Simpson areas thus defines a region which may be divided into three provinces: The Barrow high gravity area, the slope area along the coast from Simpson west to Icy Cape, and the generally low-gravity area in the western part of the Reserve. The apparent boundary of the western low-gravity area is defined along the trend of the Carbon Creek surface anticline, the axis of which is approximately in the creek bed near the confluence of Carbon Creek and the Utukok River.

Of interest is a gravity low that trends northeast from the area north of Carbon Creek to the east side of Cape Simpson. This low crosses the area of increasing observed gravity that limits the western area of low observed gravity.

There is a striking similarity in over-all qualitative aspect between the magnetic map and gravity map (pls. 2 and 3) in the western and northern areas. The gravity anomaly south of Barrow corresponds to a broadening in the magnetic contours and is an interruption in the regional gravity high that extends across the Barrow area. The highest value of observed gravity in the surveyed part of the Reserve occurs outside the Barrow complex to the north. (See p. 16.) An interpretation of this gravity anomaly is that it corresponds to a circular fault complex, and that the low results from the decrease in rock density due to brecciation. The relatively minor nature of the magnetic anomaly indicates that the faults and local gravity high in the center of the complex area are not the result of an intrusive that significantly changed the thickness of sedimentary rocks in the general high-gravity area south of Point Barrow. Drilling and seismic evidence show this section to be 2,000 to 3,000 feet thick, which is the thinnest known sedimentary section (Triassic and younger rocks) in the northern part of the Reserve.

East of Wainwright Inlet in the Wainwright area (fig. 3) a magnetic high corresponds to a broadening in the gravity contours. The total thickness of Triassic and younger rocks, as shown by the seismic work in the area, is approximately 10,000 feet.

The area of regionally low gravity in the western part of the Reserve corresponds to an area in which magnetic intensity increases eastward; a northeast-trending magnetic low crosses an area of more abruptly increasing observed gravity and magnetic intensity east of the Meade River and continues to the coast, emerging at Cape Simpson. The axis of this magnetic low is

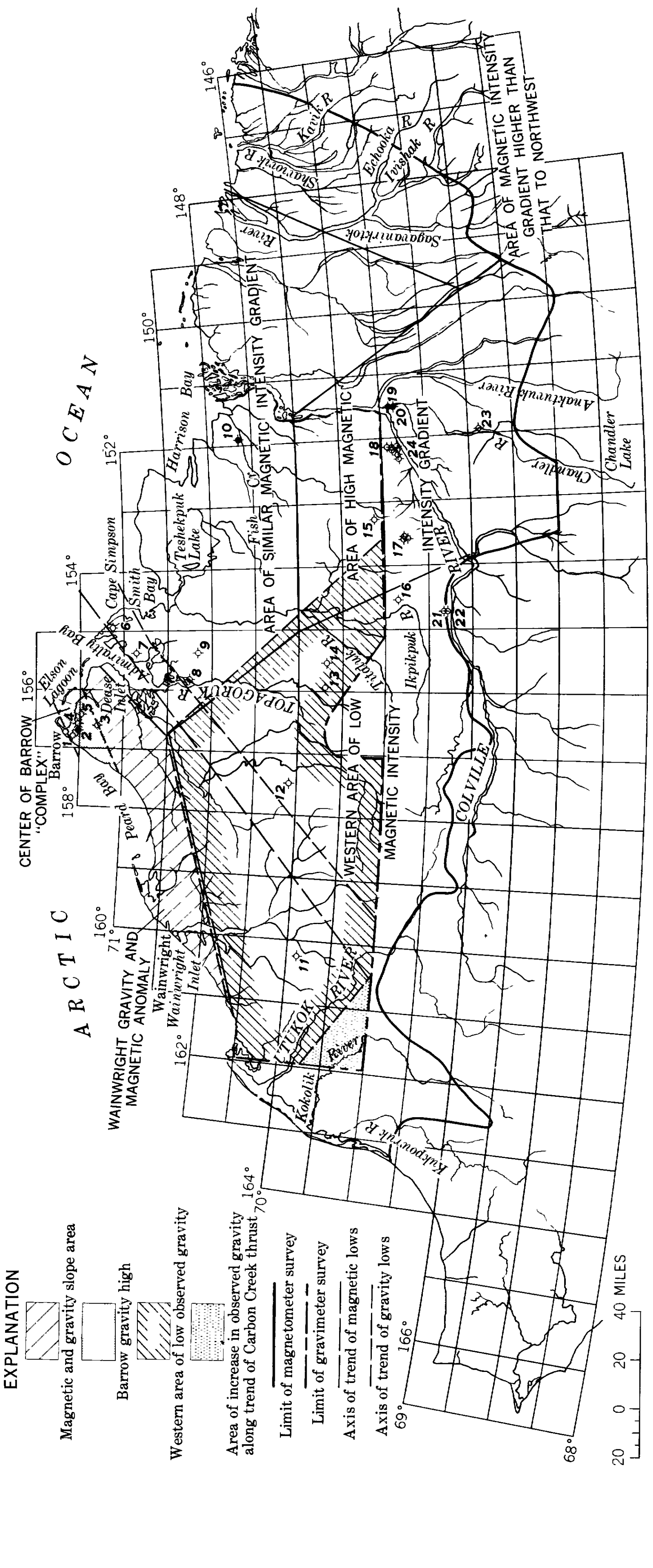


FIGURE 3.—Limits of magnetic and gravity surveys and outlines of anomalous areas. Numbers indicate wells listed on figure 1.

parallel to and north of a similar low trend in observed gravity (fig. 3).

The gravity low in the western area is terminated in the extreme southwest by an increase in observed gravity. This increase occurs along the trend of the Carbon Creek thrust fault, as interpreted from seismic evidence; there is no corresponding increase in magnetic intensity. This lack of conformity would indicate that the Carbon Creek thrust becomes a bedding-plane fault at depth and does not occur as a major fault in the rocks of high magnetic susceptibility underlying the sedimentary rocks.

It is thus possible to divide the western part of the Reserve, as defined by magnetic intensity and observed gravity, into areas which have the same boundaries. (See fig. 3.) These are the Barrow high-gravity area, the slope area trending along the coast, and the western low-gravity area separated from the eastern part of the Reserve by a zone of increasing magnetic intensity and observed gravity.

The northern and western parts of the Reserve are separated from the eastern part by an area of sharply increasing observed gravity and magnetic intensity which trends approximately N. 30° W. from the southern limits of the survey to a point west of Topagoruk test well 1, where it intersects the low-gravity trend discussed in the preceding two paragraphs (fig. 3).

The eastern part of the Reserve is characterized by higher values of observed gravity and greater magnetic intensity. A part of the increase in magnetic intensity is due to closer proximity to the earth's magnetic pole; however, the increase that divides the eastern and western parts of the Reserve is greater than the regional increase. The magnetic map of the eastern area as far east as the Itkillik River and south of lat 70° N. is characterized by a sharper gradient in magnetic values. Because of the approximate correspondence between the Umiat anticline at the surface and a large magnetic anomaly, considerable effort was made in the course of the exploration of the eastern part of the Reserve to determine the relation of these sharp magnetic anomalies to possible structures in the sedimentary section. The evidence is not complete, and it was not possible to establish any well-defined relation.

No gravity work was done south or east of the Colville River. Thus, only a part of the magnetic anomaly at Umiat can be compared with the observed gravity. The area north of the Colville at Umiat is a gravity low.

A trend of high values of gravity terminates north of Umiat. This trend begins south of Smith Bay and is parallel to the zone of change from low observed gravity in the western part of the Reserve to higher observed gravity in the eastern part.

There is no demarcation in gradient of gravity at lat 70° N. corresponding to that in the magnetic intensity. Also, in the entire eastern area there is no correlation between magnetic and gravity highs and lows. Partly on the basis of seismic evidence, it is concluded that the anomalies in the eastern part of the Reserve are the result of magnetic-susceptibility and density changes, which do not affect structure in the sedimentary rocks.

The decrease in observed gravity and magnetic intensity from east to west is unexplainable from present evidence. In general, the Cretaceous rocks in the western area are more coaly than those in the east. However, the differences in density of coal, shale, and sandstone are insufficient to account for the difference in observed gravity. It is therefore necessary to use the pre-Cretaceous rocks to explain the change. Seismic evidence shows a difference in structural development from east to west. Those structures that are east of a north-south line through Barrow show dominant east plunge, and those west of it show dominant west plunge, principally in the Meade-Oumalik trend of structures (pl. 4). Also, a map of a deeper seismic horizon (pl. 5) shows a low-grade arch along this same line. Thus there is a difference in structural development in the Reserve from east to west. Evidence is insufficient to firmly correlate this structural change to the previously discussed changes in magnetic intensity and observed gravity.

Only magnetic information is available for the area east of the Colville River. The area of high magnetic-intensity gradient, of which the Umiat anomaly is a component, ends approximately at the Itkillik River. The gradient of magnetic intensity is less east of the Itkillik River. A line may be drawn along lat 70° N. north of the area of high magnetic-intensity gradient to the Colville River, thence southeast to the Kuparuk River at lat 69° 30′ N., and thence northeast to the mouth of the Sagavanirktok River. By use of magnetic-intensity gradient as a determinant, this line would place the area north of it in the same type of area as that from the Colville River west to Simpson. Southeast of this line the magnetic-intensity gradient is higher.

An attempt has been made to divide the area of magnetic and gravity surveys in northern Alaska into smaller areas where the information shows contrasts in overall aspect. This qualitative approach was used because of the failure of more detailed analysis to relate the gravity and magnetic anomalies to seismic structure. The Barrow high and slope area south can be fairly definitely related to seismic structural evidence. The degree of conjecture increases as the interpretation is extended away from Barrow and Simpson, the areas of maximum subsurface control from drilling and seismic evidence. The fact that the overall qualitative aspect of the magnetic and gravity information can be related to the subsurface information in the Barrow area and the slope area south of Barrow would indicate that a relation south of these areas should exist. It is, however, not deducible from the information available. This is the nature of magnetic and gravity surveys, as they measure fields of force that could be caused by a multiplicity of subsurface conditions. They cannot be interpreted without using subsurface data from other sources.

SEISMIC SURVEYS

TECHNIQUES AND PROCEDURES

From 1945 through 1953 a constant effort was made to improve the quality of the reflection and refraction data. The Arctic Slope of Alaska is, in general, an area yielding usable seismic data. More often than in most areas of comparable size, it was possible to obtain interpretable records. The typical reflection record consisted of a group of shallow reflections of fair quality that were, in general, not continuous and a group of deeper reflections that were continuous and often correlative over considerable distances. The group of shallow reflections (pl. 1), as established by test-well control, originates from a sandstone-and-shale sequence of Early and early Late Cretaceous age, and the group of lower reflections originates from the oldest Lower Cretaceous and pre-Cretaceous rocks. As the shallow sandstone-and-shale sequence is truncated northward by an unconformity, the lower Upper Cretaceous strata are cut out, and this sequence in the northern wells consists only of Lower Cretaceous rocks. In the extreme southern and eastern area, this general description becomes invalid; however, it is true for the major part of the work done. Of the areas explored by geophysical methods, the Barrow area has the least thickness of Triassic and younger sedimentary rocks. It was necessary to increase the size of the charge as the thickness of section increased, from an average of 25 pounds in the Simpson and Barrow areas to 150–200 pounds in the south. It was also necessary to lower and broaden the peak-response frequency of the instruments in an effort to develop maximum amplitude of the reflections as they became deeper to the south.

Because of the lack of continuity of the shallow reflections, a system of spread overlap to give continuous 100 percent subsurface coverage was used to obtain reflection control for the shallow section. Most shot points were spaced 1,320 feet apart. This distance was shortened to 660 feet as standard practice in the Barrow complex in an effort to obtain better information. Refraction profiles were usually shot with 8,000-foot spread lengths. Shot depths also increased from Barrow and Simpson to the southern areas. In part, owing to the necessity of loading larger charges in the southern areas, shotholes were drilled as much as 200 feet deep.

Areas covered by refraction and reflection surveys are summarized in tables 2, 3, and 4.

VELOCITY DETERMINATIONS

TEST-WELL VELOCITY DETERMINATIONS

In order to convert time to depth for the purpose of plotting seismic sections, information on velocity must be available or must be assumed. The most satisfactory method of obtaining vertical-velocity information is to lower a geophone into a test well and detonate charges of explosives at the surface. This procedure was used in eight test wells, South Barrow test wells, 1, 2, and 3, Simpson test well 1, Fish Creek test well 1, Topagoruk test well 1, Oumalik test well 1, and Umiat test well 2, the locations of which are shown on figure 1. A summary of the velocity information resulting from these surveys is shown on plate 6. These curves show that the velocity results are correlative with the known subsurface geology, in that the wells in the Barrow area show a higher rate of increase of velocity with depth, which is due to the higher interval velocities in Jurassic and Triassic rocks that occur at shallower depths. The lowest measured velocities were at Fish Creek test well 1, where the thickness of Upper Cretaceous rocks is greatest.

TABLE 2.—*Statistical summary of seismic surveys, 1945, 1946, 1947*

Survey data	1945	1946			1947	
	Party 43, Cape Simpson area	Party 46, Umiat area		Party 43, Simpson area	Party 43, Smith Bay-East Ikpikpuk area	Party 46, Topagoruk-Oumalik area
	Reflection	Reflection	Refraction	Reflection	Reflection	Reflection
Number of recording days	66	57	4	113	147	144
Profiles shot	297	139	21	711	797	615
Average number of profiles per day	4.5	2.4	5.3	6.3	5.4	4.3
Number of shots	734	410	26	2,119	1,653	1,518
Dynamite used (pounds)	10,310	13,865	3,080	35,781	61,963	32,374
Caps used	800	481	72	2,196	1,864	1,637
Number of drill tours	64	82	0	203	249	185
Number of shotholes drilled	147	58	----------	638	721	494
Total footage drilled	8,683	4,492	----------	40,388	46,366	30,715
Average depth of hole feet	59.1	77	----------	63.3	64.3	62.2
Average footage per tour	135.7	55	----------	199	186.2	166
Crew months	2.8	3.0	0.1	4.0	5.5	5.2

TABLE 3.—*Statistical summary of seismic surveys, 1948, 1949, 1950*

1948

Survey data	Party 47			Party 43			Party 46, Fish Creek area	Party 47W, Elson Lagoon area (water work)
	South Barrow area	Barrow-Meade area	Barrow area	Oumalik area	Fish Creek-North Teshekpuk area			
	Reflection	Refraction	Reflection	Refraction	Reflection	Refraction	Reflection	Reflection
Number of recording days	40	40	71	13	117	7	138	8
Profiles shot	76	157	404	52	565	37	809	90
Average number of profiles per day	1.9	3.9	5.7	4.0	4.8	5.3	5.9	11.2
Number of shots	196	342	676	59	1,352	31	1,414	176
Dynamite used ... pounds	9,575	35,392	19,003	16,175	37,510	11,850	63,497	11,195
Caps used	423	485	773	73	1,405	41	1,553	179
Number of drill tours	92	47	116	16	183	5	249	
Number of shotholes drilled	86	67	372	23	570	13	743	
Total footage drilled	14,550	4,860	24,858	1,735	43,697	1,560	57,488	
Average depth of hole ... feet	169.2	72.5	66.8	75.4	76.7	120	77.4	
Average footage per tour	158	103.4	214.2	108.4	239	311	230.9	
Crew-months	1.8	2.7	2.4	0.6	4.8	0.2	5.4	0.9

1949

Survey data	Party 47, Inaru-Meade-Topagoruk area		Party 46, Barrow-Dease area		Party 45, Meade area		Party 44	
							Topagoruk and N. Oumalik	Topagoruk area and south
	Reflection	Refraction	Reflection	Refraction	Reflection	Refraction	Reflection	Refraction
Number of recording days	171	1	145	2	129	18	131	12
Profiles shot	1,010	8	783	3	652	24	746	42
Average number of profiles per day	5.9	8	5.4	1.5	5.1	1.3	5.7	3.5
Number of shots	1,684	14	1,292	10	1,806	35	1,724	86
Dynamite used ... pounds	40,452	3,045	36,327	3,465	60,727	50,315	67,131	28,255
Caps used	1,774	14	1,637	26	2,000	279	1,969	116
Number of drill tours	335	3	278	2	311	28	267	9
Number of shotholes drilled	990	4	748	2	640	39	774	19
Total footage drilled	71,637	240	66,244	220	48,684	4,043	53,167	1,950
Average depth of hole ... feet	72.4	60	88.6	110	76.1	103.7	68.7	102.6
Average footage per tour	213.8	80	238.3	110	157	144.3	199.1	217
Crew-months	6.1	0.1	5.5	0.1	5.3	0.8	4.8	0.8

1950

Survey data	Party 144, Fish Creek-Colville River and Titaluk areas	Party 145, Meade area	Party 146, Wainwright-Utukok area	Party 147, Topagoruk area	Party 148, Driftwood area	
	Reflection	Reflection	Reflection	Reflection	Reflection	Refraction
Number of recording days	125	139	135	169	1	15
Profiles shot	677	746	925	1,151	2	15
Average number of profiles per day	5.4	5.4	6.9	6.8	2	1
Number of shots	1,113	1,974	1,563	2,421	2	23
Dynamite used ... pounds	56,722	75,600	79,455	84,555	200	54,450
Caps used	1,547	2,488	1,750	2,601	4	54
Number of drill tours	214	269	290	345	----	30
Number of shotholes drilled	703	947	925	1,163	----	8
Total footage drilled	50,190	53,131	64,608	61,146	----	756
Average depth of hole ... feet	71.3	56.1	69.8	52.6	----	94.5
Average footage per tour	234.5	197.5	222.8	177.2	----	25.2
Crew months	6.0	5.6	5.4	6.4	0.1	0.8

REFLECTION-VELOCITY SURVEYS

The velocity information has been augmented, particularly in the southern and central parts of the Reserve and adjoining areas, by surface-velocity profiles. These consist of a group of records, usually seven, which are symmetrically arranged with the shot points along the line of geophones at standard distances from the spread. The records are shot in such a manner that the subsurface coverage is common for all seven records. By analyzing the results of these records, it is possible to obtain average velocities through the section to the various reflecting interfaces. It is largely on the basis of this type of surface-velocity profile that the cross sections have been plotted. Most of the cross sections were plotted before velocity data from test wells were available. The differences were usually negligible between the velocity values obtained by the two methods. Where there was a significant difference, the cross sections were replotted.

TABLE 4.—*Statistical summary of seismic surveys, 1951, 1952, 1953*

Survey data	1951	1952					1953
	Party 144, Gubik-Teshekpuk-Sentinel Hill and Square Lake areas	Party 144, Castle Mountain-Chandler River area		Party 145, East Gubik and Umiat areas	Party 146, Driftwood and Kokolik areas		Party 144, Shaviovik area
	Reflection	Reflection	Refraction	Reflection	Reflection	Refraction	Reflection
Number of recording days	90	79	13	109	83	11	45
Profiles shot	790	258	17	675	372	15	141
Average number of profiles per day	8.8	3.3	1.2	6.2	4.5	1.4	3.1
Number of shots	1,098	535	18	1,414	627	15	305
Dynamite used pounds	73,670	62,655	37,610	78,196	53,080	98,450	52,470
Caps used	1,778	739	64	----------	670	15	316
Number of drill tours	305	238	----------	436	358	----------	136
Number of shot holes drilled	799	330	----------	692	466	----------	132
Total footage drilled	69,904	54,804	----------	35,550	42,142	----------	24,322
Average depth of hole feet	87.5	151.7	----------	51.4	97	----------	184.3
Average footage per tour	299.2	210.3	----------	81.5	126	----------	178.8
Crew-months	6.1	4.2	0.6	4.9	4.3	1.0	2.3

A constant velocity of 10,850 feet per second (fps) was widely used in the southern and central regions in constructing the cross sections. It apparently is a valid average velocity for the Cretaceous section and was checked from the Wainwright area across the Reserve, as far east as the Kuparuk anticline area east of Umiat. It was also verified by the test-well velocity surveys at Oumalik and Umiat.

REFRACTION-VELOCITY SURVEYS

Velocities as obtained by refraction methods are the horizontal components of velocity in various subsurface velocity interfaces. The horizontal component of the compressional-wave velocity is commonly higher than the vertical component. It is, therefore, not satisfactory for use as a plotting velocity for reflection cross sections.

Refraction shooting in the Reserve and adjoining areas has been used in an attempt to solve two problems: The depth to the first high-velocity (approximately 16,500 fps) interface in the northern part of the Reserve, and the depth to limestone of the Lisburne group of Mississippian age in the central and southern parts of the Reserve and adjoining areas.

In the Barrow and Simpson areas the method was successful. The 16,500-fps velocity, correlated with depths determined in various test wells, originates from or near Triassic rocks. In South Barrow test well 3 the top of the Triassic is at 2,610 feet, and in Simpson test well 1 it is at about 6,300 feet. It is thus possible to obtain a measure of the regional aspect of the Triassic by study of the depths of the approximate 16,500 fps velocity interface, which are shown on plate 7 in lines 1–48–47, 1–49–47, 2–48–47, and 13–48–47.

South of Topagoruk test well 1, a high-velocity of approximately 17,000 fps occurs at 5,030 feet in lower Cretaceous rocks. Comparing this with results of the velocity survey of Topagoruk test well 1, it is reasonable to interpret that this velocity originates from a sandstone in the shale of the Oumalik formation of Early Cretaceous, lower Albian age, which is present in the well between 3,900 and 6,600 feet. An indicative correlation has been made between the approximate 17,000 fps velocities in Lower Cretaceous rocks measured by three refraction-velocity surveys in the Topagoruk area. They are shown in lines 1–49–44, 2–49–44, and 3–49–44, on plate 7. A vertical-velocity measurement of 21,000 fps was obtained for chert conglomerate of Triassic age in Topagoruk test well 1, where the Triassic is present between 8,640 and 9,380 feet.

No 17,000-fps velocity was found during the velocity survey north of Teshekpuk Lake. It, therefore, does not fit the correlation outlined above. This refraction survey was shot in an area in which there was some difficulty in making subsurface-reflection maps of the zone in which the 17,000 fps Lower Cretaceous refractor might be expected to occur. Evidence is insufficient to make a reliable interpretation.

A deeper refractor occurs in the Barrow area on some of the refraction profiles. This has a velocity ranging from 18,000 to 20,000 fps. This refractor is about 2,000 to 4,000 feet below the 16,000-fps refractor (Triassic) and has not been penetrated by any of the test wells. It may possibly define the base of the altered sedimentary rock (pre-Mesozoic) that was found in the Barrow area and is present in Avak test well 1 from 2,300 feet to the total depth of 3,463 feet. The lithologic character, steepness of dip, presence of fractures and quartz veins, degree of secondary alteration, and stratigraphic position as indicated seismically, strongly suggest that this section of altered sedimentary rocks is as old or older than the lowest sequence (Devonian) penetrated in Topagoruk test well 1, at 10,040 feet. Data are insufficient to make a reliable interpretation.

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In the Skull Cliff and Wainwright areas, there is no evidence of a velocity interface as high as 16,000 fps in the Lower Cretaceous. This is interpreted to mean that the 17,000-fps refractor (Oumalik formation) in the Topagoruk area does not extend into the areas to the west. This would require only a minor change in lithologic character.

The second purpose of the refraction shooting was to determine the depth to the Lisburne group. This group of limestone formations of Mississippian age crops out in the Brooks Range south of NPR–4. In the Meade-Oumalik area, four unsuccessful attempts were made to obtain a high-velocity break. The highest velocities obtained were on the order of 13,000 fps. These velocities apparently originated from the sandstone and shale sequence of Early Cretaceous and early Late Cretaceous age. The spreads were extended to sufficient length to have allowed the higher velocity from limestone to occur as primary breaks, if the limestone had been within approximately 10,000 to 12,000 feet of the surface. However, because of unsolved questions of energy penetration, the conclusion that the high-velocity interface must be deeper than a certain depth is not justified.

In an attempt to help solve the problem of depth to the Lisburne group, a set of portable instruments was flown to Chandler Lake in the Brooks Range in 1949. These instruments were used to shoot a velocity spread, essentially a refraction survey, on the out cropping Lisburne group. A velocity of 17,200 fps was obtained; considering that the vertical velocity of 21,000 fps was obtained for the Triassic chert conglomerate at Topagoruk test well 1, it is probable that the Lisburne would be masked by the higher velocity Triassic rocks, and that any high-velocity refraction would originate from the Triassic. The limestone of the Lisburne group that crops out at Chandler Lake probably has a somewhat lower velocity than the same limestone at a depth of several thousand feet, but it is unlikely that the velocity would be higher than that of the Triassic rocks at Topagoruk. Unsolved problems of thickness of various members and their separation by lower-velocity layers would complicate any attempt at solution.

In the area of the Driftwood anticline, four attempts were made to obtain high-velocity breaks. Considerable difficulty was encountered in attempts to force a strong enough compressional wave into the section to obtain satisfactory data. A velocity of approximately 17,000 fps was obtained from rocks at approximately 7,000 feet. This is a nondefinitive velocity in that it could, for example, be obtained from a sandstone, a hard shale, or a limestone. The Triassic sequence that crops out south of Driftwood is described as a siliceous or calcareous shale containing chert (E. G. Sable, and M. D. Mangus, U.S. Geological Survey, written communication, 1951) and probably has a higher velocity than 17,000 fps. Vertical components of velocity of the order of 20,000 fps were obtained from similar material at Topagoruk test well 1. No velocity of the order of 20,000 fps was obtained from any of the Driftwood refraction lines. The conclusion, based on the lack of a high-velocity break, that the depth to Triassic and older rocks is greater than some calculated depth should not be made because of questions of energy penetration.

SEISMIC RESULTS

Results of seismic surveys, integrated with data from drilling and surface geologic mapping, indicate the Arctic Slope of northern Alaska to be a single large sedimentary basin. This basin is markedly asymmetric, similar in general structure to certain other sedimentary basins having one flank formed by thrust-block mountains. The deepest part of the basin, representing the principal sedimentary rocks forming the basin, is in the foothills north of the Brooks Range, or perhaps under the range itself. Extreme depth and the complexities of overriding thrust faults prevented determination of the exact location of the axis of the basin. The axis, in general, trends east, parallel to the mountain front.

The principal sedimentary rocks of the basin are Cretaceous in age and range in thickness from approximately 1,600 feet in the Barrow area, at the apparent northern edge of the basin, to 15,000 to 20,000 feet near the mountains to the south. Plate 1 illustrates, by means of a group of diagrammatic sections superimposed on a map of the shallow Cretaceous rocks, the general aspect of the sedimentary basin north of the Brooks Range. It illustrates the two principal structural aspects of the region: The marked asymmetry of the basin, and, in the shallow Cretaceous rocks, the band of anticlinal folds, which are the dominant structural features from the central part of the area south to the mountains. Near the mountains these elongated east-trending folds are exposed. However, through most of the central part of the Reserve they are covered by Pleistocene and Recent sediments. The diagrammatic sections of plate 1 follow lines of seismic control into the foothills of the mountains.

Because of thrust faults that bring pre-Cretaceous rocks to or almost to the surface, it is possible that the Cretaceous basin has no well-defined axis. The basin may continue to increase in depth to the place where the thrust-fault system of the Brooks Range caused the pre-Cretaceous rocks to override the younger Cretaceous rocks. Only a limited amount of subsurface structural information was obtained by seismic exploration methods in the foothills area. However, considering the information obtained and in the light of surface geologic interpretation of the mountains and foothill provinces by the U.S. Geological Survey, the above interpretation, as illustrated by plate 1, best fits the data.

Throughout much of the northern part of the Reserve the reflection records obtained exhibit a group of shallow reflectors in the first 3,000 to 4,000 feet of section; an intermediate zone of few reflections of poor quality and irregular dip; and a deeper zone of continuous reflections. These reflecting zones can be correlated with sections penetrated by the test wells. The shallow zone corresponds to sandstone and shale of Early Cretaceous to Late Cretaceous (middle Albian to Cenomanian) age that is essentially the *Verneuilinoides borealis* faunal zone, as determined by H. R. Bergquist, and the deeper reflecting zone can be correlated with the oldest Lower Cretaceous (early Albian) shale penetrated by Topagoruk test well 1 and Simpson test well 1, and with the pre-Cretaceous section in which a reflecting horizon originates in Triassic rocks.

The reflections used to construct the structure-contour map of the shallow section (pl. 8) are discontinuous. In the northeastern part of the Reserve, it is possible to use the same reflection for control for as much as 6 to 8 miles of line; however, more often a single reflection will exist for only a mile or less. These reflections were used to draw a phantom horizon or line parallel to the reflections as a basis for contouring. From the Barrow area to the east and to the southeast, the shallow reflectors dip at a greater rate to the south and southeast than the zone of shallow reflectors. It is thus not possible to use a single phanton horizon within the zone of shallow reflectors to construct maps of the entire northern part of the Reserve. As an example, from Skull Cliff southeast to a point near Topagoruk test well 1, the shallow reflectors dip to the east to a depth of about 4,500 feet; however, the zone of shallow reflectors increases in thickness from approximately 3,000 feet at Skull Cliff to approximately 4,000 feet near the Topagoruk test well. For this reason it is necessary to successively raise the level of control in constructing a map of the shallow reflecting horizon.

The southernmost control for the map (pl. 5) of the deeper reflecting horizon is Topagoruk test well 1; the reflection on which the map is based is interpreted to originate from sandstone beds immediately above the Jurassic-Cretaceous contact. Because of changes in aspect of this reflection and the lack of well control to the necessary depth south of Topagoruk, it is not certain that the control has not been lost. Study of the reflection as it appears on the records and the sections indicates that, if to the south the deeper reflection does not originate from the oldest Lower Cretaceous, it is deeper in the section (that is, within the Jurassic).

Seismic data reveal that the entire central portion of the Reserve is characterized by a series of anticlinal folds that persist to a depth of 4,000 to 6,000 feet (pl. 4). These folds are elongated east-west and are apparently the result of thrust action from the south and the sinking of the Cretaceous basin. The axial planes of those examined in detail by seismic methods (pl. 9) were found to be approximately vertical. The first 4,000 to 6,000 feet of rocks of Early Cretaceous and early Late Cretaceous age (middle Albian through Cenomanian) is characteristically a sandstone and shale sequence. In the extreme northern part of the Reserve, near Point Barrow, the shallow sandstone and shale sequence thins to less than 1,000 feet and is Early Cretaceous in age. This sandstone and shale sequence is underlain by a shale section (early and middle Albian) in the Lower Cretaceous that also thins to the north.

The shallow folds in the central and southern parts of the Reserve are separated by a low-relief arch that trends approximately north through Point Barrow. Folds east of this arch have a dominant plunge east whereas those to the west have a dominant plunge west. The arch also is present in the older pre-Cretaceous formations.

The Meade and Oumalik anticlines are two of the principal closed anticlines discovered and examined in some detail by seismic methods (pl. 4). They are at the northern limit of the group of shallow structures described above. North-south reversal across these anticlines is about 1,500 feet. They are separated by the arch described in the preceding paragraph. Test wells were drilled on both of these anticlines. Some gas was discovered in Oumalik test well 1 drilled near the apex of the Oumalik anticline and in Meade test well 1 drilled on closure along the eastern high of the Meade anticline (pl. 4); East Oumalik test well 1, drilled on the eastern nose of the Oumalik anticline, was dry.

Beneath the shallow sandstone and shale sequence and the northward-thinning shale section, the oldest Lower Cretaceous and pre-Cretaceous sections form a regionally south-dipping homocline, which is interrupted by structures like those developed in the northern part of the Reserve (pl. 4). In the central part of the Reserve, the oldest Lower Cretaceous and older rocks are uniformly south-dipping and exhibit no evidence of the hundreds of feet of north-south reversal that characterize the group of shallow anticlinal folds. The overlying shallow sandstone and shale sequence in the Cretaceous appears to be folded completely independently of the oldest Lower Cretaceous and pre-Cretaceous rocks.

Both seismic and gravity evidence indicate that the thinnest section of sedimentary rocks occurs in the northern part of the Reserve immediately south of Point Barrow (pl. 5) in a regional high that trends slightly north of east. This high is interrupted by a cryptovolcanic structure discussed in detail below. Several closed anticlines were discovered by seismic methods on the southeast flank of this regional high (pl. 5). Only in the area of the Barrow regional high and southwest along the coast to the Wainwright area are the shallow Cretaceous sandstone and shale sequence and the pre-Cretaceous rocks conformable. The pre-Triassic section is unconformable with the Triassic rocks.

In the Topagoruk and Simpson areas, the shallow Cretaceous sandstone and shale section is unconformable with the oldest Lower Cretaceous rocks. In these areas and westward across the Reserve, the oldest Lower Cretaceous and Jurassic reflectors are conformable with the Triassic. Angular unconformity between the Triassic and older rocks is indicated. South of the gravity and magnetic "slope" area the Triassic section is deeper than 10,000 feet, and only a few reflections were obtained from the pre-Triassic.

In the western part of the Reserve, the system of parallel folds in the shallow sandstone and shale sequence of Early Cretaceous and Late Cretaceous age ends at Carbon Creek. At that place a series of thrust faults brings the pre-Cretaceous section to within 10,000 feet of the surface (pl. 1). South of Umiat, toward the mountains, there is some evidence of similar structure, although there is no evidence that the pre-Cretaceous is as near the surface as it is in the west. The existing evidence indicates that the pre-Cretaceous section is at depths of at least 15,000 to 20,000 feet.

In the easternmost part of the White Hills area (fig. 1), a limited study of the Shaviovik anticline showed that a complex pattern of thrusts in Lower Cretaceous rocks underlies the comparatively simple surface structure.

BARROW AREA

The regional high in the Barrow area trends slightly north of east; the thinnest known section of Lower Cretaceous and pre-Cretaceous rocks of the Arctic slope of Alaska is present over the high. Cretaceous through Triassic rocks range from 2,000 to 3,000 feet in thickness. The several test wells drilled here verified the seismic interpretations. On the north flank of the high, all reflectors dip north as far as the extreme northern limits of the surveyed area. The Barrow "complex", a circularly shaped fault complex, is south of Elson Lagoon and slightly north of the axis of the regional high. It is about 5 miles in diameter and is shown on plate 2 as a circular gravity low surrounding a centrally high area that interrupts the regional high. The gravity high corresponds almost exactly with the seismic high shown in Triassic rocks (pl. 10). The seismic work shows that the fault complex consists of a highly disturbed peripheral zone, corresponding to the gravity low, and a less disturbed central core. The combined magnetic, gravity, and seismic results indicate that the core contains about the same thickness of sedimentary rocks as the area immediately beyond the complex, and that highly faulted and distorted sedimentary rocks form the periphery (gravity low). Total fault displacement from the central high across the peripheral zone is probably about 500 feet, downthrown toward the center. Faults within the core are small and downthrown toward the outer margin of the complex. In addition, radial faults extend from the complex. The gas wells, South Barrow test wells 2 and 4, which supply gas for Barrow Camp, were drilled on the north and upthrown side of a radial fault west of the complex.

Avak test well 1, drilled on the north flank of the central high, verified the seismic interpretation. The test well pentrated argillite at 2,302 feet and drilled approximately 1,700 feet into it. The age of the argillite is unknown; it is older than Mesozoic and may possibly be Precambrian (Payne, 1951). The highest measured gravity within the part of the Reserve surveyed by gravity methods is in this regional high. Detailed gravity-survey maps of the Barrow complex show a central high surrounded by a circular shaped low that corresponds to the peripheral zone of maximum fault disturbance. The maximum value of gravity is outside and north of the Barrow complex, on the south shore of Elson Lagoon.

There is no significant magnetic anomaly in the area of the Barrow complex. The slight decrease in magnetic gradient is not believed to be significant. This is interpreted to mean that the forces that caused the Barrow complex did not bring rocks of higher magnetic susceptibility closer to the surface. It also indicates that the complex is not of meteoric origin.

The Barrow complex is similar in structure to the cryptovolcanic structures described by Eardley (1951, p. 237–240). The surface of this area is flat and all shallow formations are covered by Pleistocene sediments. As the rocks penetrated by test wells showed no evidence of either volcanism or dynamic metamorphism, it is not clear if the term "cryptovolcanic" is properly applied to the Barrow complex; the relation is a structural similarity to complex phenomena which have been referred to in the literature as cryptovolcanic. The highly disturbed peripheral zone and the fact that no evidence of volcanism has been found suggest that the complex was caused by a large deep-seated plug that rose and fell periodically throughout Jurassic time.

South Barrow test well 3, a dry well, was drilled on a closed high south of the Barrow complex. Local closure is approximately 300 feet over an area of about 5 square miles in the oldest Lower Creteaceous rocks, a similar amount in the Jurassic, and slightly less than 100 feet in the Triassic rocks. The well data verified the seismic interpretation.

The refraction-velocity surveys in the Barrow area show a velocity of about 16,000 fps occurring at depths which correspond to the Triassic section as mapped by reflection seismic methods.

Underlying the Triassic section in the Barrow area is a highly complex zone with steep and erratic dips that are generally unconformable with the Triassic. Study of Avak test well 1, the only test well that penetrated a significant thickness of this section, indicates that this section is not lithologically homogeneous and thus one from which reflections are likely. The results of the refraction surveys show velocity interfaces in this section. One of the refraction surveys indicated a refractor with a velocity of approximately 20,000-fps, 4,100 feet below the Triassic refractor. This may be the base of the highly disturbed and altered pre-Mesozoic argillite sequence.

The Barrow area presents the most complex subsurface aspect of the northern part of the Reserve and adjoining areas. The area is also one from which gas has been produced and shows of oil have been obtained. Because of the apparent thinning of sediments into the area and the presence of faults, indicating the possibility of pinch out and fault-trap accumulation, the area can be evaluated only by more detailed seismic work and more test-well drilling.

SIMPSON AREA

The Simpson area (fig. 1) was the locale of the earliest seismic work in the Reserve during the summer of 1945. The presence of oil seeps in the area had been known for many years, and work was begun to determine the reason for these seeps. Activity was continued in 1946 on the basis of the gravimetric survey.

Results of seismic surveys and test-well drilling defined a marked angular unconformity in the Cretaceous section. The section in the northern part of Cape Simpson, above the unconformity, is largely shale. This was indicated by the comparatively poor quality of the reflections and was verified by results obtained from North Simpson test well 1, which was drilled on a reflection seismic reversal above the unconformity, in what proved to be largely shale of the Colville group of Late Cretaceous age.

The unconformity is shown on plate 11, which was constructed by using the highest available reflection control. The entire zone of shallow reflections (Early Cretaceous) dips east. The depth at which the shallow reflections ceased was used to define the unconformity, which is not a reflecting interface. As indicated by the core tests, the shallow reflections originate at sandstone-shale contacts in Lower Cretaceous (middle Albian; H. R. Bergquist, written communication) rocks. Closure of the shallow sandstone and shale section against the unconformity is shown on plate 11. The oil seeps both in the east and west appear to be related to this unconformable contact between the Colville group of Late Cretaceous age and the underlying rocks, as seepage has apparently occurred along the unconformity. An extensive core-drill program verified the unconformity as shown on plate 11. A long narrow oil field was defined by core drilling in the eastern part of the area. The trend of this field follows the unconformity.

The reflection characteristics of the records show that the condition at North Simpson test well 1 is true throughout the area, namely, that the section above the unconformity is largely shale. In marked contrast, Simpson test well 1, southeast of North Simpson test well 1, penetrated only Lower Cretaceous rocks below the mantle of Gubik formation.

The seismic maps of the deeper section (pls. 10 and 12) illustrate the oldest Lower Cretaceous and Triassic rocks. These maps show predominantly southeast dip and show no evidence of the gravimetric highs that the 1946 seismic work was designed to test. Plate 11 shows approximately 100 feet of closure against the unconformity, covering an area of about 2 square miles near the seeps on the west side of Cape Simpson; because of differences in permafrost thickness, which are large in the Simpson area, this closure can not be clearly established. The problem of the relation of permafrost to seimic results is discussed on page 6. Simpson test well 1 was located on the closure, and penetrated Lower Cretaceous, Jurassic, and Triassic rocks. Some shows of oil and gas were obtained in this test well.

There is an interesting overall similarity between the gravity highs (pl. 2) and the trend of the unconformity. Density analysis of cores from Simpson test well 1 and North Simpson test well 1 indicates that there is not sufficient density contrast above and below the unconformity to account for the gravity anomalies. Along the seismic line through North Simpson test well 1 and across one of the gravity highs there is a marked but rather poorly defined high in the pre-Triassic section, which indicates that the gravity highs are probably related to the pre-Triassic.

TOPAGORUK AREA

A detailed seismic survey of the northern part of the Topagoruk area (fig. 1) was completed in 1949 and 1950. The principal feature of this area is the marked thickening of the sedimentary section off the Barrow regional high. Strike of the shallow sandstone and shale section (Early Cretaceous, middle Albian) is approximately north; and regional dip in the oldest Lower Cretaceous (Oumalik formation) and older rocks (Jurassic and Triassic) is south to southeast. The pre-Triassic rocks of Permian through probable Devonian age are locally mappable in this area and show a marked angular unconformity with the Triassic and older rocks. The maps of the oldest Lower Cretaceous (pl. 12) and the Triassic rocks (pl. 10), used to illustrate this and other areas in the northern part of the Reserve, have their best velocity and test-well control here and in the Simpson area to the north. The reflections are thus reliably interpreted to originate from reflecting interfaces in the oldest Lower Cretaceous and the Triassic rocks.

In the deeper section (6,000 to 10,000 feet) the Topagoruk area is a terrace off the Barrow regional high. The area contains several seismically well defined faults, most of which have less than 500 feet of throw; the faults decrease in amount of throw upward from the Triassic control reflection through the oldest Lower Cretaceous control reflection. There are major faults in the pre-Triassic rocks.

Several folds in the area are similar in size and amount of closure to the one on which Topagoruk test well 1 was drilled. This well was drilled on a closed high found as a result of the 1950 seismic program, in turn based on a seismic reconnaissance of the area in 1949. The structure has approximately 300 feet of closure in the Triassic section and 150 feet of closure in the oldest Lower Cretaceous (pls. 10 and 12). No closure was mapped in the shallow Cretaceous horizon. The results of the test well checked very closely with the seismic interpretation of the area. The well had shows of oil, but not in commercial quantity.

East of Topagoruk test well 1, the shallow Cretaceous sandstone-and-shale section flattens broadly (pl. 8). Because of some "good looking" sand found at Topagoruk test well 1, where no seismic structure occurs in the shallow section, East Topagoruk test well 1 was drilled in an attempt to find the sand on structure. Such a broad flat structure as was found at East Topagoruk can only be approximately defined by seimic methods. Shows of oil and gas were found in the well, but not in commercial quantity.

One of the main purposes of drilling Topagoruk test well 1 was to determine whether the Lisburne group of Mississippian age was present off the Barrow high. Although the well penetrated about 500 feet of Devonian rocks below 660 feet of Permian beds, the Lisburne group was not found. The age of the Devonian section was determined by J. M. Schopf. These beds, below a marked angular unconformity at 10,040 feet in the test well, are complexly folded and faulted, and commonly dip 30° to 45°. Seismically, this section has more continuity than the basement at Barrow, but its regional status remains largely undetermined.

SKULL CLIFF AREA

In the Skull Cliff area, southwest of Barrow (fig. 1), the regional dip is east to southeast in the shallow Cretaceous sandstone-and-shale (pl. 8) section and south in the oldest Lower Cretaceous and older rocks (pl. 12). The reflections which showed the marked angularity between the Triassic and pre-Triassic in the Topagoruk area area to the east do not occur with the same frequency in this area. The limited evidence does show, however, that the pre-Triassic is more conformable with the Triassic here than it is in the Topagoruk area to the east.

The Jurassic and Triassic sections thicken more abruptly into this area near the Barrow regional high than they do into the Topagoruk area.

No significant reversals of dip or closure were found in the Skull Cliff area. As there is, however, only limited seismic control, the results are primarily useful for stratigraphic purposes only.

WAINWRIGHT AREA

Seismic work in the Wainwright area (fig. 1) was intended to investigate several gravity highs in the area and to obtain general stratigraphic control in the western part of the Reserve. Both the Cretaceous and pre-Cretaceous rocks dip south in this area (pls. 4 and 5). By correlation and interpretation from continuous reflection records, the sedimentary section at Wainwright is similar to that in the Skull Cliff area and to that off the Barrow high. The Triassic is interpreted to be at approximately 10,000 feet in the northern part of the Wainwright area above a marked angular unconformity below which many reflection dips are on the order of 20° to 30°. Northeast of Wainwright Inlet is a south-plunging nose that is present in all reflecting horizons and corresponds to a gravity and magnetic anomaly. Fuel available at the time the seismic crew was in the area was insufficient to allow an adequate amount of detail work on this anomaly.

The seismic tie from the Wainwright area is continuous through the Meade-Oumalik area to Barrow. The trend of shallow folds does not extend into the southern part of the Wainwright area, as would be expected if they were projected along trend as defined by the Meade and Oumalik folds.

TESHEKPUK AREA

The Teshekpuk area (fig. 1) is in the northeast part of the Reserve and is named for Teshekpuk Lake. Regional dip is east in the shallow Cretaceous sandstone and shale section (pl. 8) and south to southeast in the oldest Lower Cretaceous or Jurassic (pl. 12).

The total reflection section thickens southward in this area. No closed anticlines were delineated by seismic methods. An attempt was made in 1951 to find shallow closure in several places south of Teshekpuk Lake where changes in gradient along the 1948 reconnaissance line indicated the possible presence of structures. The project was abandoned after determining that closure greater than 100 feet was improbable. A fanning-out of the contours on the extreme Lower Cretaceous or Jurassic rocks in the area west of Harrison Bay (pl. 12) indicates this to be an area in which structures may be present.

A single line, 12 miles long, was shot across a magnetic high in the southern part of the Teshekpuk area. This magnetic high is located within the high magnetic-intensity gradient, of which the Umiat magnetic high is a component. The line was shot in an attempt to determine whether this type of magnetic high had any relation to the sedimentary rocks; no relation was found. The reflections mapped indicate a sedimentary section at least 15,000 feet thick and the regional dip conforms to other seismic information for this part of the Reserve.

FISH CREEK AREA

The Fish Creek area is in the northeast part of the Reserve immediately west of the mouth of the Colville River (fig. 1).

Regional dip is east in the shallow Cretaceous sandstone and shale section and south to southeast in the oldest Lower Cretaceous or Jurassic and older rocks. The Fish Creek area contains the youngest Cretaceous (Turonian through Senonian, H. R. Bergquist, written communication) rocks known in any of the test wells drilled. The evidence for this is also corroborated by the seismic data, which show a shallow section of different aspect from that found elsewhere in the Reserve. The reflections used for control in mapping the shallow Cretaceous sandstone and shale (middle Albian) are more continuous in this area than they are to the west—that is, in the Simpson area—and the sequence is also thicker.

The deeper reflection on which the map of the oldest Lower Cretaceous or Jurassic is based indicates local faults, particularly in the area north of Fish Creek test well 1 (pl. 12). The pattern of these faults was not completely delineated with the data available. The faults have only a small amount of throw, commonly about 300 feet or less.

Because of the presence of an oil seep in the area, Fish Creek test well 1 was drilled at the apex of a large gravity high and along a seismic line that gave no evidence of significant closure or a structural trap. The well produced oil on pump at the rate of approximately 10 barrels per day from a zone within the Early Cretaceous (middle Albian) at a depth of approximately 3,000 feet. A reexamination of the seismic records indicated the possibility of a small normal fault with approximately 200 feet of downthrow to the east. This fault would intersect the well near the point from which oil was obtained, and by projection would come to the surface southwest of the test well near the oil seep. It is believed that the oil discovered at Fish Creek test well 1 is seepage oil along the fault or from a sandstone a short distance away from the actual fault plane.

This interpretation of faults in the shallow Cretaceous section in the Fish Creek area adds significance to the interpreted fractures and faults in the deeper section. As has been noted previously, data were insufficient to make an adequate interpretation of the complex pattern of disturbance in the deeper section, which, at approximately 10,000 feet, was not penetrated by Fish Creek test well 1 (total depth, 7,020 feet).

MEADE-OUMALIK AREA

The Meade and Oumalik closed anticlines are the northernmost expression of the series of anticlinal folds that are the principal structural features of many thousands of square miles in the central area of the Reserve. Neither anticline is exposed at the surface, but both have been examined locally by seismic methods. They are neither gravimetric nor magnetic anomalies. Photogeologic and field studies made by the U.S. Geological Survey indicate that the type of structure that was examined in detail at Meade and Oumalik persists to the south into the foothills of the Brooks Range and from the western boundary of the Reserve across the Colville River to the east. This interpretation of general structural aspect of the Meade-Oumalik area agrees with the seismic interpretation of the Umiat-Maybe Creek area and of the Kokolik area to the west.

Plate 13 shows the zone of shallow reflectors in Lower Cretaceous rocks in the Meade-Oumalik area. They persist as folds through approximately the first 4,000 feet of section. Below this, as established both by drilling and by weak energy return, erratic dips, and lack of reflections of consistent character, is a thick shale section (lower and middle Albian). The Oumalik anticline has a minimum of 450 feet of closure encompassing an area of approximately 43 square miles. The Meade anticline has a minimum of 250 feet of closure over an area of approximately 53 square miles. The actual closure is probably greater.

The shale section is underlain by the homoclinal south-dipping control reflector of oldest Lower Cretaceous or Jurassic rocks. There is evidence that this interface may have been subject to small faults or fractures. Nowhere, however, does it indicate the hundreds of feet of north-south reversals of dip which characterize the shallow sandstone and shale sequence.

The reflections defining these structures in the shallow Cretaceous sandstone and shale section persist on the seismic records for only relatively short distances. This is interpreted to mean that these reflections originate from sandstone beds that persist in the sandstone and shale section for correspondingly short distances. This section thus appears to be made up of a group of lenticular sands, as is in part verified by the lack of well-defined electric-log correlations between the three test wells drilled in the area.

Meade test well 1 (total depth, 5,305 feet) was drilled on the eastern part of the area of closure of Meade anticline. The separate closure on which the location was made was established during the 1949 season, and the work that proved the larger area of closure to the west was done the following season. This well was drilled to 5,305 feet and at about 4,200 feet penetrated the upper part of the predominantly shale sequence that separates the shallow sandstone and shale section from the regionally south-dipping homocline of oldest Lower Cretaceous or Jurassic rocks at a depth of approximately 10,000 feet. Meade test well 1 found gas, but the amount is unknown.

Seismic work on the Oumalik anticline was done in 1947. The anticline was discovered during a seismic reconnaissance of several magnetic anomalies. In the area of the magnetic anomalies the seismic surveys show east dip in the shallow Cretaceous sandstone and shale section and south dip in the underlying oldest Lower Cretaceous or Jurassic.

Two test wells were drilled on the Oumalik anticline, Oumalik test well 1 (total depth, 11,872 feet) at the apex and East Oumalik test well 1 (total depth, 6,035 feet) on a separate closure downdip along the axis east of the apex. Oumalik test well 1 found gas of unknown quantity; East Oumalik test well 1 was rated a dry hole. Oumalik test well 1 penetrated a sandstone and shale sequence (middle to upper? Albian) to approximately 3,500 feet and a monotonous shale section (lower to middle Albian; H. R. Bergquist, written communication) from 3,500 feet to its total depth of 11,872 feet.

Reflectors on the flanks toward the apex of these structures are markedly truncated, which is interpreted to mean that sandstone beds on the flanks are truncated before reaching the apex. This condition is particularly apparent on the northeast flank of Oumalik anticline and on the northwest flank of the Meade anticline. The parallel folds in the shallow Cretaceous sandstone and shale sequence are separated by a north-south structural high that passes between these two anticlines. West of this high, west plunge is dominant and east of it east plunge is dominant on the folds, which are the principal structural features of the entire central part of the Reserve. Two of the three test wells found gas. None of the wells tested the flanks of structures. The flanks of these structures, however, are of interest because seismically they show a marked thickening of section and truncation of reflectors toward the apexes.

At approximately 10,000 feet is a uniformly south-dipping reflector that appears to be locally fractured but that exhibits no apparent relation to the folds of the shallow section. The deep reflector does not occur at Oumalik; however, data from an area east of the well suggest that the deep reflector (oldest Lower Cretaceous and Jurassic) is south-dipping in this area.

A closed anticline south of the Meade anticline has a minimum of 300 feet of closure in an area of 32 square miles. Several other anticlines were defined by the reconnaissance seismic survey line that extended southward from the detailed work done near the Meade test well. The apexes of these anticlines follow surface geologic trends, as mapped by the U.S. Geological Survey.

Several tests were made in an effort to find a high-velocity refractor, presumably Mississippian (Lisburne group) or Triassic, but none was found. The reflection information indicates that the Lisburne group, if present in the area, probably is at least about 15,000 feet deep and is probably in a south-dipping homocline. The lack of a high-velocity break is negative information; and because of unsolved questions of energy penetration, no conclusions regarding minimum depths to a possible high-velocity refractor can be made.

An extensive but unrewarding effort was made to use the gravity data to develop the detail of the Meade anticline and other structures to the west. The gravity work was more detailed from Meade test well 1 west to the western boundary of the Reserve than in other areas of the Reserve.

KOKOLIK AREA

The Kaolak anticline was discovered in the course of the 1950 seismic reconnaissance of the western part of the Reserve. Kaolak test well 1 was drilled on the Kaolak anticline. It was rated a dry hole and was drilled through a much greater thickness of coal-bearing sediments than Meade test well 1 to the east. Several shows of oil were found. The section in the Kaolak well is interpreted by H. R. Bergquist (1958) to be one of intertonguing marine and nonmarine beds of middle Albian age. The Kaolak anticline is the northernmost of a series of folds that were found in the northwest part of the Kokolik area (pl. 8). These structures, only two of which were mapped in detail by seismograph, are similar to those in the Meade area. The Kaolak anticline is dominated by west plunge of the axis and by south regional dip, which tends to make each reversal structurally lower than the one immediately to the north.

These folds occur only in the shallow Cretaceous section, as in the Meade-Oumalik area. They are underlain by a south-dipping Lower Cretaceous or Jurassic reflector that has no apparent structural relation to the overlying folds (pl. 5).

The type of structure outlined persists as far south as the confluence of Carbon Creek and the Utukok River. At this point an area of major disturbance and faulting was crossed (section, pl. 1). This is in the vicinity of the Carbon Creek surface anticline, whose axis is along the stream bed of Carbon Creek. To the north of Carbon Creek, the Lower Cretaceous or Jurassic reflector was at a depth of about 15,000 feet and reflections from it became intermittent. On the south flank of the anticline, reflections were obtained that, in character and quality, are similar to those obtained from pre-Cretaceous rocks in the Topagoruk area, and they are dissimilar to reflections obtained from the Cretaceous. On the basis of this evidence, on surface mapping by C. L. Whittington, U.S. Geological Survey, and on data from Kaolak test well 1, a thrust fault with approximately 10,000 feet of throw has been interpreted to be present. The lower plate of this thrust is to the north. The interpretation of a major thrust at Carbon Creek is reliable; the amount of throw and the angle of the thrust are conjectural, because it was impossible to make a direct seismic correlation across the fault.

UMIAT-MAYBE CREEK AREA

Two reflection lines on the Umiat anticline (pl. 14) in 1946 were the first seismic work to be done in the Umiat-Maybe Creek area. One line was shot across the anticline and the other from the apex off the north flank. The lines show a fault on the north flank (see pl. 14), which was apparently drilled through at 2,010 feet in Umiat test well 1. A seismic correlation made across the fault was checked closely with well data from Umiat test well 11. A refraction line shot in 1946 failed to indicate the fault, because the fault does not cut rock of sufficiently high velocity to act as a refractor. Near the apex of the Umiat anticline, reflections were obtained only to depths of about 1,500 feet. Umiat test well 2 demonstrated that the section below 1,500 feet to its total depth of 6,212 feet is largely shale of middle Albian and possibly, in part, of early Albian age and contains few lithologic variations to act as reflecting interfaces. The structure-contour map (pl. 14) was constructed by C. H. Mohr, of Arctic Contractors, using seismic data and surface geology as mapped by C. L. Whittington and Karl Stefansson, as well as results of test-well drilling.

In 1950 a reconnaissance line was shot from the Fish Creek area south to Umiat. The regional dip of the shallow Cretaceous sandstone and shale reflecting zone is east to southeast in this area. The reconnaissance line shows that the regional dip of the deeper reflectors is south (pl. 5). It was possible to follow the deep reflector to a point immediately north of Umiat, where it reached a depth of about 15,000 feet. This reflection was not observed at Umiat nor at the Gubik anticline northeast of Umiat. It dips uniformly southward under such structural features as the eastward-plunging Sentinel Hill nose north of Umiat and an anticline between Umiat and the Sentinel Hill nose which occur in the zone of shallow Cretaceous reflections.

The Square Lake closed anticline in the Umiat-Maybe Creek area was mapped by seismic methods in 1951. Approximately 200 feet of north-south reversal was demonstrated on an east-plunging nose northeast of Square Lake. An attempt was made to find significant closure along the Sentinel Hill east-plunging nose, but none was found.

In 1952, east plunge was demonstrated along the eastern part of the Umiat anticline. The axis of this east plunge is offset slightly south from the trend of the Umiat anticline. It was not clearly demonstrated whether this east-plunging nose is en echelon to the Umiat anticline or whether the axis of the Umiat anticline swings to the south.

The closed Gubik anticline northeast of Umiat was mapped in 1950 and 1951 as a follow-up of surface geologic work in the area by W. A. Fischer and A. N. Kover, U.S. Geological Survey. A minimum of 400 to 500 feet of closure was demonstrated. Gubik test wells 1 and 2, drilled on the anticline (pl. 15), were gas wells. A close correlation was made between the group of shallow reflectors and the sandstone and shale sequence (middle Albian through Cenomanian), which is present between depths of 3,300 to 4,000 feet in the wells and beneath 3,300 to 3,500 feet of the Colville group. Below depths of about 4,000 feet no satisfactory reflections were obtained, as the wells were drilled predominantly in middle Albian shale to total depth.

In the western part of the Umiat-Maybe Creek area, a small amount of work was done to check west closure on the west nose of the Titaluk anticline, which was mapped by C. L. Whittington and W. P. Brosge, U.S. Geological Survey. The work showed 150 to 200 feet of west plunge. A reconnaissance line to the north of the Titaluk anticline showed approximately 400 feet of closure on the Wolf Creek anticline.

AWUNA AREA

A small amount of work was done in the north-central part of the Awuna area in 1949 (pl. 8) and a series of folds was mapped. These correspond to structures defined by surface geologic mapping of the area by C. L. Whittington, U.S. Geological Survey. Insufficient work was done to determine whether or not any of the anticlines were closed. A refraction line was shot in an effort to find a high-velocity break but none was found.

The Awuna area was carefully examined in an effort to relate residual-gravity anomalies to the shallow anticlinal reversals. No relation was found.

No data were obtained on the deeper reflecting horizon, which dips south under the Meade anticline to the north.

DRIFTWOOD AREA

An approximately north-south reconnaissance line was shot in 1952 from the Carbon Creek anticline south to the Driftwood anticline (pls. 5 and 16). This area in the southwest of the Reserve is considerably different in structural aspect than other areas in the Reserve examined by seismic methods.

The Carbon Creek fault is a large thrust fault with vertical displacement of about 10,000 feet and horizontal displacement of about 2 to 3 miles. It is the northernmost of a series of thrust faults that are present as far south as the major thrust faults of the Brooks Range. The southernmost seismic control was approximately 4 miles south of the Driftwood surface anticline.

These thrust faults bring a reflector of lower frequency and clearer character to within 10,000 feet of the surface. This type of reflection is more characteristic of pre-Cretaceous rocks than of the Cretaceous, as seen in areas where test-well control is available. Available data from surface mapping and seismic correlation suggest that this reflection may originate from within Jurassic rocks.

Several reflection lines were shot across the Driftwood anticline. The reflections obtained were poor and discontinuous, except along one line from which reflections within the first few thousand feet show that a very steep syncline underlies the Driftwood surface anticline. This type of reflection was not observed on the other parallel lines across the anticline. The limited data obtained from the four lines across the anticline and one line parallel to the surface axis present no consistent aspect nor continuity of information. Based on the fact that reflections of consistent character were obtained immediately north of this anticline and that the dominant structural feature in the section to the north is a series of thrust faults, the most reasonable conclusion is that the Driftwood surface anticline is the result of multiple thrusting and that the formations at depth are complexly folded and faulted.

Attempts to determine the depth to a possible high-velocity formation (presumably Triassic or Mississippian) by refraction methods were not successful. Velocities of about 18,000 feet per second were obtained, but velocities of this magnitude were obtained from the Cretaceous section in the northern part of the Reserve. The results are thus inconclusive.

CHANDLER RIVER AREA

East plunge was mapped on the Schrader anticline immediately east of the Chandler River and south of the Umiat anticline (pls. 4 and 9). Reflections were obtained only from approximately the uppermost 4,000 feet of section near the apex. A continuous line from Schrader anticline to Gubik anticline shows that the Schrader anticline is approximately 2,100 feet structurally higher than the Gubik anticline. North of the Schrader anticline, in the Prince Creek syncline, a few reflections were obtained from the 12,000- to 16,000-foot zone. These are approximately flat lying and do not exhibit the synclinal structure that is present in the shallow section to a depth of about 6,000 feet. This section has some of the characteristics of the deeper section north of Umiat. Insufficient data were obtained to make a correlation.

In 1952 a line was shot from a place as far south on the Tuktu escarpment as it was possible to move the equipment and thence north across the Grandstand surface anticline (pl. 9). The line crosses the Grandstand anticline about 6 miles east of Grandstand test well 1. This line showed conformity between the surface geology and subsurface structure to a depth of approximately 8,000 feet (pl. 1). Below this depth there is an unconformity in dip, which is most clearly exhibited in Ayiyak Mesa syncline immediately south of the Grandstand anticline. Grandstand test well 1, on the anticline, was drilled to 3,939 feet, and penetrated only middle Albian beds.

On the south flank of the Ayiyak Mesa syncline there is a group of reflectors that when projected southward, correspond to the Tuktu formation, which crops out along the Tuktu escarpment, as mapped by R. L. Detterman, U.S. Geological Survey. This section thickens into the syncline where it appears to be underlain by approximately horizontal reflectors, which define the unconformity mentioned above. These reflections decrease in quality and continuity into the syncline, where they would normally be expected to improve in quality. Thus it is interpreted that the Tuktu formation of Early Cretaceous age at Tuktu Bluff grades into shale to the north.

Scattered reflections were obtained along this profile to depths of approximately 20,000 feet. These reflections are of much poorer quality and do not have the continuity of reflections from the pre-Cretaceous obtained in the northern part of the Reserve.

CASTLE MOUNTAIN AREA

Seismic work in the Castle Mountain area was started in 1952 north of Castle Mountain in an area of complex structure that, as mapped at the surface by W. W. Patton, Jr., and I. L. Tailleur, U.S. Geological Survey, is an anticlinorium in the Torok formation of Early Cretaceous, early Albian age. The first line shot across the Ayiyak anticlinorium yielded no usable information. The second line from the north slope of Castle Mountain north to the confluence of the Chandler and Kiruktagiak Rivers was, in general, rather poor, particularly the southern end. At the southern part of the line, from the axis of the anticlinorium south, the reflections have no consistent aspect (fig. 4). The average dip is very low, but some recorded dips are as high as 60°. The section appears to be crumpled. In the northern part of the line good reflections were obtained showing a north dip of about 65°. The shallow seismic dips correlate closely with the north dips at the surface that define the north flank of the Ayiyak anticlinorium. The north-dipping section is underlain by a south-dipping section at approximately 4,000 to 16,000 feet (fig. 4). The reflections from this deeper section are of such quality as to make it unlikely that the same reflectors occur farther to the south. The seismic results demonstrate clearly that a simple anticlinal fold, corresponding to the surface anticlinorium, is not present in the underlying pre-Cretaceous section. The interpretation that major thrust faulting occurred in this area is the most probable way to account for the highly complex section observed. It is also probable that a fault occurs near the southern limit of the steep north-dipping reflectors, as shown on figure 4.

The cross section of the third line shot across the Ayiyak anticlinorium is similar in aspect to the second. On this third line, some reflections were obtained to 4.5 seconds reflection time. This would indicate that the section has a minimum thickness of 25,000 feet.

WHITE HILLS AREA

EAST UMIAT AREA

The East Umiat area, as the name implies, extends along the Umiat anticline as far as the Kuparuk River. The work began with an east-trending reconnaissance line through the syncline that separates the Gubik and Umiat anticlines. The results from this line indicate that the regional east dip of the Umiat-Maybe Creek area continues to the Kuparuk River. The Kuparuk anticline between the East Fork of the Kuparuk and the Itkillik Rivers was surveyed in detail (pls. 8, 9, and 17). This anticline is an easterly extension of the Umiat fold and to the east appears to be along the trend of the Kuparuk anticline as mapped at the surface. It was not clearly established by seismic survey whether this anticline has significant closure independent of the Kuparuk anticline. The zone along the axis is complicated by faults and steeply dipping beds.

A surface-velocity profile shot on the north flank indicates, because of the low velocities found, a minimum of 14,000 feet of Cretaceous rocks in this area.

SHAVIOVIK AREA

The Shaviovik area is between the West Fork and the Juniper Fork of the Shaviovik River, approximately 140 miles east and slightly north of Umiat. This area was examined early in 1953 in an attempt to check the relation between the subsurface and the Shaviovik anticline as mapped on the surface by A. S. Keller, R. H. Morris, and R. L. Detterman of the U.S. Geological Survey. The reflection data from this area are much better than those from the Castle Mountain or the Driftwood areas. These are the only areas in which seismic work has been done in southern parts of the Reserve and adjoining areas where it is possible that pre-Cretaceous rocks are within reach of the drill.

The principal result of the work at Shaviovik was to show that the anticline as it appears at the surface does not have a similar subsurface counterpart. Only limited data were obtained from the first 6,000 to 7,000 feet of section. Between 7,000 and 10,000 feet below sea level an intermediate group of reflections indicates the presence of a complex system of thrust faults, the upper plates of which are to the south (pl. 18).

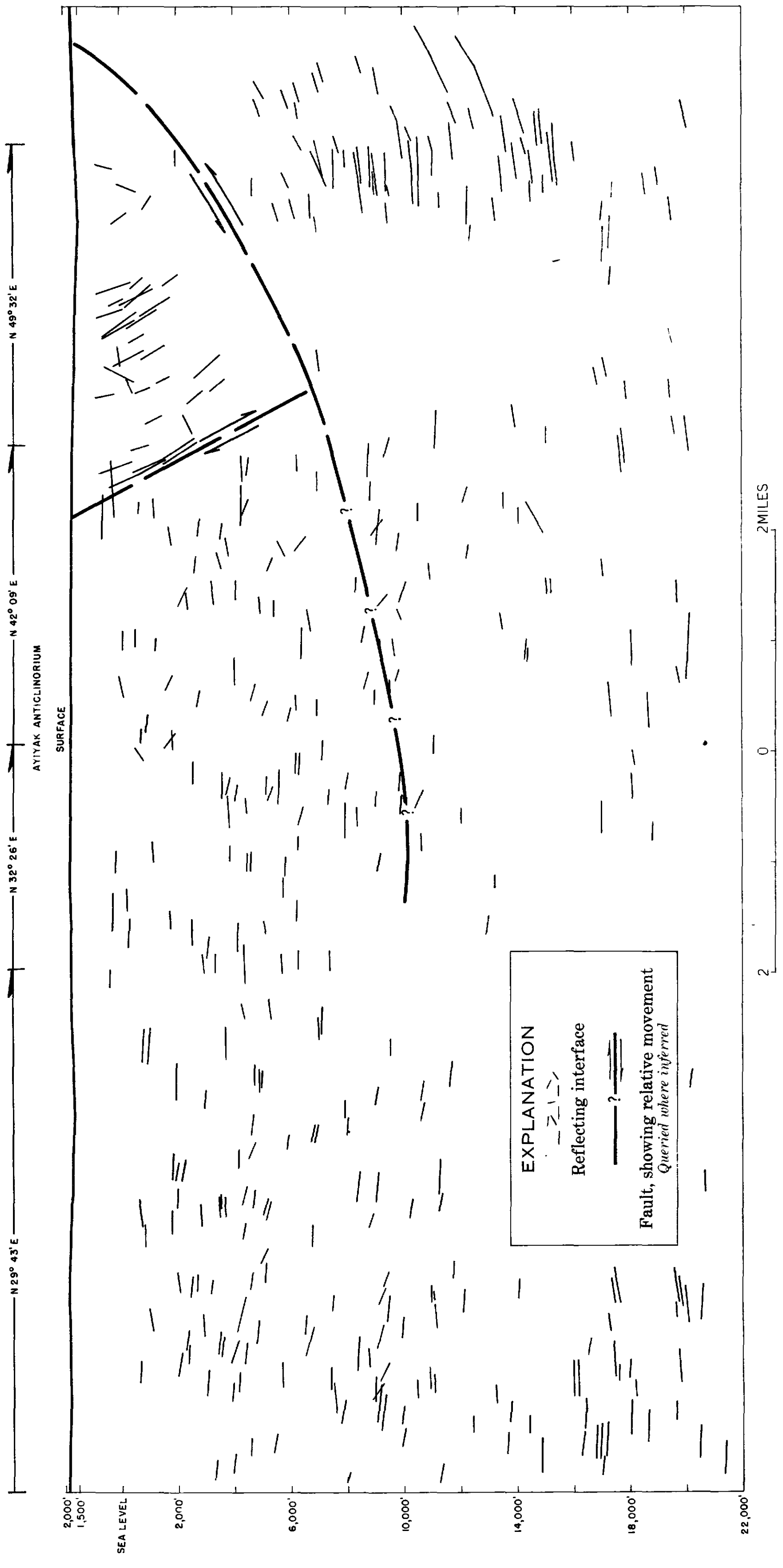

FIGURE 4.—Diagrammatic section of Ayiyak anticlinorium, Castle Mountain area.

A deeper reflection at approximately 13,000 feet, indicates a north-dipping homocline (pl. 19). Insufficient work was done to establish regional dip.

A correlation was made between outcrops south of the Shaviovik area and the seismic cross sections in the Shaviovik area. This indicates that the zone of reflections, which shows thrust faulting, is Lower Cretaceous and that the deeper reflection originates from within a subsurface zone between the top of the Triassic and the top of the Mississippian, which is estimated to be 1,200 to 1,400 feet thick in outcrop. Because of the structural complications, lack of velocity control, and the necessity of projecting data into the area from outcrops, this correlation is conjectural.

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U.S. GOVERNMENT PRINTING OFFICE: 1962 O—644439