New Techniques for Ore Search

Paul L. Allsman
INTRODUCTION

This report is a survey of the newest methods in use for mineral exploration. It will attempt to review the newest techniques in the fields of geophysics, geologic research and theories of ore deposits, exploratory drilling, mapping methods, and other tools of mineral exploration. Then a preview of coming and predicted techniques will comprise a summary.

The mineral exploration techniques in use prior to 1940 might well be termed "primitive" in comparison with those used in 1954. With the exception of a few large mining companies, only the most basic prospecting methods were employed; the same methods used for centuries. Even the most progressive companies, feeling an urgent need for new techniques, were not able to afford the heavy cost for research and development of such methods.

The heavy demand for minerals brought about by World War II, plus critical defense requirements for a nation where expense was no object compared to the need for minerals, probably acted as the main stimulus to the development of more efficient prospecting methods. Another important stimulus is the exhaustion of easily found or outcropping deposits, coupled with an increasing demand for mineral products from an advancing civilization.

The exploration techniques of 1954, while not revolutionary, represent a significant advance over those of 10 or 15 years ago, and seemingly presage a new era where revolutionary techniques of ore search will become common. The main factor in this change should be emphasized; it is that of "incentive". When the potential rewards become great enough the techniques will assuredly be forthcoming.

I. Geophysics and Related Methods

A new tool which might almost be classed as revolutionary is geophysics; measuring the natural or induced physical, chemical, and geologic properties of rock formations with sensitive instruments. Geophysics has become a major field of science in its own right, much too large to be fully discussed here. A few of the newest and currently most important methods used in prospecting ore deposits are given below. The use of geophysics in petroleum, where it has received its greatest development and use, is outside the scope of this report.

Regional geophysical surveys are currently very popular. They
are used to select target areas for intensive exploration. The U. S. G. S. is carrying on such a regional survey for the A. E. C., and the A. E. C. is making available monthly reports of the location of anomalous radioactivity and also is installing supersensitive radioactivity assaying instruments in 25 localities. For uranium prospecting Radiometric methods have undergone considerable improvement. New and improved types of hand-portable meters (Geiger counters), carbon equipment, and gamma ray logging meters are on the market. Scintillation detectors are taking over the area formerly served by Geiger counters. Basic research is being done in gamma ray scattering and in absorption and isotope geology.

Other recent developments were largely in improved methods of bore-hole logging, by gamma ray, self-potential, and resistivity surveys. On the Colorado Plateau seismic methods were tried unsuccessfully, and a resistivity method for direct ore finding is being currently tested.

Geochemical prospecting became an important method during 1953, and at the present time appears to be one of the most promising tools of the future. Its development far surpassed that of any other single prospecting method; the Quebec Department of Mines announced 101 geochemical surveys submitted as assessment work in 1953. Geochemical prospecting might be considered a scientific application of the age-old principle of tracing float. It might include soil, vegetation, and stream testing. Very delicate analytical techniques must usually be developed to detect the minute traces of elements found in streams. On the Colorado Plateau geochemical haloes are being studied as guides to ore.

The most significant success attributed to geophysics in 1953 was in New Brunswick, where immense sulfide zones have been found. More will be said about geophysical surveys later on.

II. Classical Geology

What might be termed "classical geology" still remains probably the most important single method for finding ore. By classical geology is meant the old and established techniques of routine mapping and sampling; studies of structure, mineralogy, and petrography; and geologic reasoning and deduction based on the known principles of ore deposition. The only reason this phase is not given more emphasis is because it is not basically a new technique. There are many new features apparent even in classical geology.

One recent event is increased cooperation by companies. This has been common in the petroleum industry, where as many as 40 companies have joined to share the immense cost of developing a new geophysical method. It is badly needed in the mining industry if any basic research in ore deposition and exploration techniques is going to be forthcoming. On the Mesabi iron range the operators contributed their full geologic knowledge without exception, and produced an areal map which increased the knowledge of structural control and the conditions of sedimentation forming the iron ore.
The problems of ore deposition are still being attacked. The current topics of greatest interest are diffusion and rock permeability. Large scale structural features, such as deep-seated zones of weakness on the Continental scale, are receiving renewed attention. In this connection attention is called to the paper by Billingsley and Locke, "Structure of Ore Districts in the Continental Framework". Once again the Colorado Plateau figures prominently in the news. The major crustal breaks forming the boundaries of the plateau are thought to be very significant as loci of ore deposition.

The particular tool that has made the most notable recent advances to the understanding of ore deposition is petrology; the study of the rock types associated with ore deposits. It is only one facet of the problem, and eventual solution will probably be attained by close cooperation of the mineralogist, geochemist, petrologist, and economic geologist.

It is remarked that mining geologists are currently being kept so busy that they have no time to develop new theories, and are rapidly using up the "bank of geologic knowledge." Sound geologic inference is yet the basis of finding ore in most operating mines, and unless new theories are continually developed as a basis for inference, all the possible ore bodies will soon be inferred and continual development of the existing mines will be halted. It is hoped that this situation is temporary.

III. Drilling Techniques

Drilling has long been recognized and still continues as one of the major tools of mineral exploration. The present day techniques and the new advances in drilling techniques are deserving of an extended discussion.

In the past one of the main headaches in diamond-drill operation has been in casing through the overburden. It has generally been considered uneconomical to drill through overburden much over 100', but new operating techniques for drilling up to 500 feet of overburden are phenomenal. These techniques include soil-freezing, under-reamings, and mud-fluid drilling. Overburden is no longer considered a problem.

Other recent improvements in diamond-drilling include a light, portable drill easily carried by one man or in a canal. This can be used to cut a true channel sample in a shallow deposit, saving the great labor of trenching and cutting a channel by hand. Similar use of a diamond-drill for many varied prospecting activities makes it the most versatile of prospecting tools. The use of deflecting wedges for directional drilling, long practiced in oil-drilling, is becoming standard practice in diamond-drilling.

New equipment in the drilling field includes the wire-line core barrel. The core-barrel is suspended by a small wire cable on a high-speed hoist. The rods need only be raised to replace the
bit. The core-barrel is fitted with a ball-bearing, swivel type head, with optional positive water shut-off valve. This eliminates the human element and prevents core grinding. Whereas 60 minutes is normal time to raise and lower the core-barrel with conventional equipment, it can be done in 15 minutes with the wire-line barrel. At 3,000 feet the wire-line barrel is changed in 35 minutes, versus 3 to 4 hours with conventional equipment.

A diesel engine for running the drill is now considered more economical than gasoline, even considering its larger first-cost and greater weight. A camera for photographing the inside of a 3 inch bore-hole has been developed by the U. S. Army Engineers.

Numerous new types of drills are constantly being developed. In this connection, rotary oil-well rigs have been tried in mining with insignificant success. Auger drills are occasionally valuable in soft ground. The Carter Oil Company has developed a multi-use drill which can do auger drilling, rotary drilling, or diamond coring. On the Colorado Plateau, tricone bits (oil rigs) have proved 2 to 4 times as expensive as diamonds, and do not yield a core. Churn drilling has also proven too expensive.

One of the greatest prospecting ventures of history is now in progress throughout the world in the search for uranium. In this country the search has concentrated in the Colorado Plateau country, and it is natural that many of the newest developments have come from that area. Currently diamond drilling is used in a 5:5:1 ratio over wagon drilling for exploration on the Plateau. Comparative costs are as follows:

<table>
<thead>
<tr>
<th>Core (diamond) Drilling</th>
<th>Wagon Drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling $2.89/foot average</td>
<td>$.90/foot average</td>
</tr>
<tr>
<td>Core (boxed) 1.48 lb./foot</td>
<td>Sacked cuttings 3.06 lb./foot</td>
</tr>
</tbody>
</table>

The wagon drill has proven the ideal tool for drilling on the Plateau. The only reason for preferring diamond drilling is the purely geologic preference of obtaining a core. The desire for geologic knowledge of the Plateau is the ruling consideration, and cost is not much object to the Government. The wagon drill cuttings are selected, and only a small percentage are sacked and saved, so the apparent advantage in core samples shown above is in reality reversed.

The wagon drill used on the Plateau is usually truck-mounted for maximum mobility. It is usually operated without water, the cuttings being blown out by compressed air. The U. S. G. S. has designed a sample collector, consisting of a small suction fan which exhausts cuttings into a glass bottle. A cotton sack collects the dust, and the collector is cleaned after each sample. Contamination of dust from hole walls and previous samples is a serious problem, but recovery is 96%, with the loss evenly distributed. This machine costs $500 and maintenance costs are low. Effective depth in wagon drilling is usually 200 feet, and is limited by the ability to blow cuttings from the hole. Certain porous formations give a serious air-loss, and wet formations cause the cuttings to stick.
The samples are immediately tested with a Geiger counter. If a count is registered, the sample is sacked and retested by accurate Geiger methods and chemical analysis. This eliminates many samples at the outset. Samples are taken every 5 feet in regular rock, every 1 foot in ore zones. A big disadvantage is that the driller cannot accurately determine the cut-off points. Average footage is 200 feet/shift, up to 500 feet/shift.

The diamond drills in use on the Plateau are now large, hydraulic rigs. Special designs were necessitated for the requirements of portability, ruggedness, and dependability in an isolated area. Water is a major problem on the Plateau. A large water truck with heater tubes was developed, and storage tanks on the drills were increased from 250 to 600 gallons. Water loss is the biggest problem in core drilling. Casing and cementing methods are too costly. Often drilling to 150 feet is done without water; and 1 or 2 sizes of casing are carried and the hole is reamed to the point of loss. AX proved too small; giving excessive breakage. Currently holes are 81.5% EX and 18.5% NX.

Another recent development in drilling is the use of oriented diamonds in bits, developed at the U. S. Bureau of Mines' experimental mine at Mt. Weather, Virginia. Diamond crystals are isometric, usually cubes, octahedrous, or dodecahedrous. Due to the atomic arrangement, certain directions in relation to the crystal axes are soft, others hard. The soft vectors have been utilized by the diamond-cutter for ages in faceting diamonds. The hardest vectors, if oriented so as to do the actual cutting in a core bit, will outlast the soft vector 10 to 1, and outlasts a random orientation 2 to 1. Tests by the Bureau of Mines show a saving in diamond loss in oriented bits of 50%, reducing overall drilling costs from an average of $3.00/foot to approximately $1.25/foot. The oriented diamonds cut faster, and need not be replaced as often. If the point of an octahedron or dodecahedron is set in the mold indentation, the crystal should be rotated 20 to 25 degrees to the left for proper orientation. This rule only applies in setting stones in the near side of the mold.

An untrained setter can easily become skilled at orienting diamonds, which requires recognition of only one crystal face, or baring that of the crystal growth lines. At present several bit manufacturers are supplying oriented-diamond bits at no extra cost. It is suggested that a combined use of oriented-diamond bits and the wire-line core barrel would revolutionize core drilling.

Further major improvements in drilling can come only from cooperative basic research. The trail has been blazed by Drilling Research, Inc., a foundation financed by some 40 oil companies, which considered a myriad of ideas for drilling including fusion-piercing, shape-charges, etc. Their most promising method was high-frequency drilling, on the order of 300 cycles/second. Another suggestion for the future is study of drilling action in different rocks. Perhaps an interchangeable bit could be switched for different formations. Basic research has been started by the U. S. Bureau of Mines and others. A suggested reference is by W. E. Mather, "Rock Hardness as a Factor in Drilling Problems", A. I. M. E. Trans 90: 173-176; Feb. 1951.
IV. Aerial Surveys and Methods

This is the Air Age, and the present use of the airplane in prospecting has given phenomenal results. The newest technique is color air photography. Vertical, stereoscopic photography shows structure, alteration, and ore relationships better than a ground party could determine them. Hydrothermal alteration seen with difficulty by painstaking ground study becomes evident from the air. It requires considerable experience to evaluate aerial photos, and it is hoped that University courses in this technique will eventually fill the need. Aerial mapping is used most effectively for regional studies, from them selecting target areas of 1 sq. mile on which geochemical and geophysical studies can be made. Photogeologic studies cost $50/sq. mile, whereas geophysical and geochemical studies cost $500 to $5,000/sq. mile. As much additional geologic knowledge as possible is needed. The present status of photogeology is reportedly such that the geologist need not even set foot on the ground. The U. S. G. S. is responsible for this development.

Airborne geophysical surveys have been astonishingly successful. Anomalies from airborne magnetometer surveys are so revealing that claim parties have been put on the site within 24 hours, and the chief geologist is required to be at the base camp, or even to accompany the plane. In the Colorado Plateau the A. E. C., Anaconda Copper Mining Company, and two small contractors are successfully using light, low-flying aircraft for scintillometer surveys.

Helicopters have proven valuable in prospecting. They are uneconomical for a small reconnaissance prospecting venture, but for supplying a definite exploration project in inaccessible terrain they are practical. They have a definite application in mountains. In British Columbia they were found to have a 15 mile practical limit, a 50 mile range, and are said to have an altitude limit of 6,500 feet. Freight can be carried at the rate of 2,000 lbs./day at a cost of $.12/lb. An approximate cost of $38.50/hr. includes all equipment and supplies, a pilot, mechanic, 4 prospectors, 2 engineers, and a chief geologist.

SUMMARY

V. Integration of Techniques

None of the many new techniques described here is the sole answer for finding new ore bodies. Every possible tool is needed, and if any one technique ever proves best, it will be the integration of several methods.

One combination method now finding success is a regional geologic survey, followed by an areal geophysical survey, and then geochemical techniques to pinpoint the target. Another "integrated" method is an aerial geophysical survey, a geochemical survey of the target area, and finally drilling to prove the deposit. An infinite variety of combinations could prove useful.
A very significant use of an integrated technique was in the discovery of the Pima mine, near Tucson, Arizona. The following list of factors was first set up:

Geological Factors
1. Type of intrusive.
2. Presence of favorable host rocks.
3. Apparent intensity of mineralization.
4. Presence of favorable structures in covered or unexplored areas.

Economic Factors
1. Past production from district or mine.
2. Size, grade, shape, and type of ore deposit in the district.
3. Ease of acquiring mineral rights.
4. General development facility.

Exploration Favorability Factors
1. Results to be anticipated from geological methods alone.
2. Application of geophysical methods, namely-topographic conditions, surface interference, depth-size relation, and physical property contrasts as related to ores or controlling structural features.
3. Drilling factors.

These 11 factors were each given a rating of 1 to 10, based on the best evidence available, and this crude statistical analysis was applied to some 30 possible districts, from which the Mineral Hill area of the Pima district was finally selected. The evaluation of the various factors was done through a concentrated library research on all available sources, plus some field reconnaissance.

The Mineral Hill area consists of a granitic batholith, forming the Sierrita Mountains. A varied section of sediments and extrusives is extensively deformed. A major thrust-fault zone apparently controls ore deposition. The deposits are contact-metamorphic, and are localized in favorable sediments along the thrust zone and near intrusives. The geologic presumption was that the fault zone would continue into the alluvium covered areas and cut other favorable sediments.

Ore and gangue minerals from known deposits in the area were tested for magnetic susceptibility, density, and conductivity. It was found that they would contrast sufficiently with the country rock to support geophysical methods, and theoretical results could also be computed.

A magnetometer was found applicable to 300 feet depth, and trials were made with it first. A standard, temperature-compensated, vertical intensity magnetometer was used for readings along profile lines, and also on a grid system. A main base station was occupied each morning and night.

An anomaly was found where geologic inference indicated possible ore, but as magnetite could occur without ore additional evi-
idence was needed. A gravity survey did not give ore, but an electrical method gave a favorable anomaly at the same place. A natural-potential method also gave a comparable anomaly, showing an oxidized zone existing.

Drilling was then done, and uncommercial ore was hit at 209 feet (calculations predicted ore at 210 feet depth). Additional drilling, controlled by the magnetic contour map, outlined the ore-body. At present 20,000 tons running 6% Cu have been shipped, and limits of the deposit are not yet known. The vein walls show intense chloritic alteration, and ore is directly related to degree of alteration. The deposit is supergene above 300 feet. Ore minerals are chalcopyrite, chalcocite, and native copper in a gangue of epidote, garnet, magnetite, and calcium silicates.

This discovery is extremely significant, both because of the new "integrated technique" used, a combination of statistical analysis, geologic inference, geophysics, and drilling; and because the deposit was found beneath alluvium of the Basin and Range province, an immense area known to be favorable to mineralization which contains hundreds of thousands of alluvial covered square miles not previously explorable. As a forerunner of the coming trend in mineral exploration, it is highly significant. (Reference: Mining Engineering, Feb. 1954, pp. 197-202).

As a projected look into the future status of ore search, the words of James Boyd are important:

"Exploration can become a business with predictable costs; but can only be done profitably in the long run by groups with sufficient backing to average successes against failures. Planned research is needed." This is beyond the resources of the individual corporation, and must depend either on cooperatively financed foundations, or on the activities of the U. S. Government. The latter is at present the only important contribution in this field, and the National Science Foundation has been established, as a result of the Paley report, to do basic research in geological sciences.

The day of the individual prospector does not seem to have completely passed. Again quoting James Boyd: "The factor that really influences the trend of new mineral ventures is that of cost of search and discovery. There is room for both large and small operators. The individual prospector would have had small chance at San Manuel, for it took far more financing than is usually available to uncover and explore it. (San Manuel obtained an $87 million loan from the R. F. C.). On the other hand the organization required for large-scale operations is seldom efficient when dealing with a multitude of related problems where a mineral is required in relatively small quantities."
REFERENCES


OIL FIELDS OF CENTRAL MONTANA
Investigation by Government Geologist.

During the summer of 1920 an area of about 850 square miles in Central Montana was studied by Frank Reeves, of the United States Geological Survey, Department of the Interior, for the purpose of determining whether it contained oil.

This area includes the greater part of a plunging geanticline—a large sloping flexure of the earth's crust—which is an eastern extension of the Big Snowy and Judith mountains uplift. Along the northern and southern flanks of this geanticline there are two pronounced anticlinal folds, and along the axes of these folds there are several oval domes. The strata between these two folds are flexed into a series of low-plunging anticlines or spurs, which extend eastward from the mountain uplift.

The area is now attracting considerable attention because of the discovery during 1919 and 1920 of oil in two of the folds, known as the Devils Basin anticline and the Cat Creek anticline. The drilling that followed these discoveries has yielded three small oil wells in the Devils Basin area and a commercial pool in the Cat Creek area.

Exports on the geology and oil resources of the area, with maps showing the structural geology, will be published later in Survey bulletins, but a preliminary account of the principal results of the investigation is now presented.

Anticlines in South-Central Fergus County.

Area.—The area here considered consists of Tps. 12, 13, 14, 15, and 16 N., Rs. 25 and 26 E., and parts of T. 17 N., R. 25 E.; T. 16 N., Rs. 27 and 28 E., and Tps. 13, 14, and 15 N., R. 27 E. The area forms a more or less rectangular block of about 14 townships that lies west of the Cat Creek anticline and north of the Devils Basin anticline and covers the greater part of the geanticline at the east end of the Big Snowy and Judith Mountains uplift.

Kootenai and Brush Creek domes—Along the axis of the pronounced fold on the north flank of the geanticline mentioned are two domes known to the oil men as the Kootenai and Brush Creek domes. Farther east on this same fold is the Cat Creek anticline. The axis of this marginal fold crosses the area as follows: From sec. 25, T. 17 N., R. 24 E., it extends eastward in a sinuous line, crossing sec. 18, T. 16 N., R. 26 E.; sec. 19, T. 16 N., R. 27 E.; and secs. 30 and 34, T. 16 N., R. 28 E. The dips on the north side of the axis of this fold are more pronounced than the dips on its south side. For the first half mile north of the axis they range from 2° to 12°
and in the next mile from 120° to 75°. Farther north the dips flatten out in a short distance, so that 2-1/2 miles north of the axis they are only 20° to 30°. South of the axis the dips average about 20°. The Brush Creek dome, the eastern one of the two domes on the axis of the fold, centers in the northwest corner of sec. 26, T. 16 N., R. 27 E. The Kootenai dome centers in the eastern part of sec. 18, T. 16 N., R. 26 E. The lowest point in the saddle between the Brush Creek dome and the next fold on the east (the Cat Creek anticline) is in sec. 2, T. 15 N., R. 28 E., and the low point between the Brush Creek and the Kootenai dome is about 250 feet and that of the Kootenai dome is about 700 feet.

In the area south of the major anticline just described the strata are folded into a series of three minor plunging anticlines, none of which have any closure in the area mapped. They apparently are spurs extending from Button Butte, a circular area of uplift centering in the western part of T. 14 N., R. 24 E., which is a part of the Big Snowy uplift. These anticlines are here called the McDonald Creek, Flat Willow, and Pike Creek anticlines.

McDonald Creek anticline.—In T. 15 N., R. 25 E., about a mile north of McDonald Creek there is a plunging anticline which is here called the McDonald Creek anticline. This fold approaches nearer the form of a dome than the Flat Willow or Pike Creek anticlines. There is a pronounced terrace along its axis in secs. 27, 28, 29, and 30, T. 15 N., R. 25 E. From sec. 27 the anticline plunges rather abruptly eastward and disappears in sec. 30, T. 15 N., R. 26 E. The dips along the northeastern flank range from 2° to 6°, on the southeastern flank from 1° to 2°.

Flat Willow anticline.—The fold called the Flat Willow anticline represents only a slight buckling of the strata, the folded belt being narrow and the dips not greater than 20°. The axis of the fold, however, is longer than the axis of the McDonald Creek or the Pike Creek anticline. It extends from sec. 30, T. 14 N., R. 25 E., eastward in nearly a straight line to the center of T. 14 N., R. 29 E., where the fold disappears as it merges into the south flank of the Cat Creek anticline. The eastern end of the Flat Willow anticline was mapped by Bowen in 1912 (see U. S. Geological Survey Bulletin 541-H, pp. 329-337), hence the name that he adopted has been used for the western extension of the fold in place of the term "Yellow Water Structure" by which this part of the fold is known among oil men.

Pike Creek anticline.—A broad, pronounced anticline with a short, steeply plunging axis extends across secs. 19, 29, and 33, T. 13 N., R. 25 E. The dips on the north flank of this anticline are about 50° and those on the southeast flank are approximately 1-1/4°. Pike Creek flows eastward along the crest, closely paralleling the axis of the anticline; hence the fold has been named the Pike Creek anticline. It is separated from the Devils Basin anticline on the south by the Flat Willow syncline, which extends up Flat Willow Creek beyond Tyler, forming a structural and topographic valley between the Big Snowy and Little Snowy mountains.
Sedimentary rocks.

Exposed rocks.—The rocks that outcrop at the surface in this area consist of a series of 3,700 feet of strata ranging from the Bearpaw shale, of Upper Cretaceous age, to the Kootenai formation, of Lower Cretaceous age. The formations of the Montana group — the Bearpaw shale, Judith River formation, Claggett shale, and Eagle sandstone outcrop along the north flank of the major anticline that extends along the northern part of the area, and the Bearpaw and Claggett shales form belts of low relief above which the sandstones of the Judith River and Eagle formations project as a series of parallel rock ridges. The Eagle sandstone also extends along the east side of the area mapped. The Colorado shale covers the greater part of the area, having been entirely removed only from the crest of the Kootenai dome. This formation consists of 1,800 feet of strata, made up chiefly of dark marine shales. In its upper half there are calcareous and sideritic concretionary members and beds of bentonite. At 750 feet from the top of the formation there is a thin, sandy fossiliferous limestone. This limestone, called the Mosby sand in the Cat Creek field, is a good key rock and forms more prominent outcrops than any other bed in the Colorado shale. At the top of the lower half of the formation are the grayish-white fish-scale beds of the Mowry shale, in which there are sandy beds that form escarpments. The Mowry shale is underlain by 600 to 700 feet of black fissile shales, in which there are a few thin calcareous sandy beds. Beneath these shales there is a fluggy ripple-marked, fine-grained yellowish-gray sandstone, from 30 to 60 feet thick, containing fossils of fresh-water unios and marking resembling worm tracks. This sandstone forms prominent escarpments where it is exposed in the crest of the Kootenai dome and on the flank of Button Butte in the eastern part of Tps. 13 and 14 N., R. 24 E. It is the chief oil-producing bed of the Cat Creek oil field. Beneath this sandstone there is about 100 feet of red shales, at the top of which is a thin bed of grayish-white clay that is here considered the top of the Kootenai formation. These shales outcrop over an area of about a square mile in sec. 17 and sec. 18, T. 16 N., R. 26 E., in the crest of the Kootenai dome, forming a basin with a red soil. West of the area mapped the Kootenai outcrops over a wide belt around the flanks of Button Butte and the Big Snowy and Judith mountains, forming a sandy red soil. In Tps. 13, 14, 15, and 15 N., R. 25 E., igneous rocks are intruded into the sedimentary rocks in the form of dikes, sills, and laccoliths.

Unexposed rocks.—In a well drilled in the Kootenai dome about 1,600 feet of strata have been penetrated below the lowest outcropping rocks of the area. These strata may be grouped into three series, which have been tentatively classified as follows:

500 feet of red, brown, and gray shales, gray sandstones and gray and pink limestones, representing the Kootenai formation.

400 feet of gray and blud limy shales and 500 feet of alternating beds of yellow and red sandstone,
limestone, and shale, representing the Morrison (?) and Ellis formations; of Lower Cretaceous (?) and Upper Jurassic ages, respectively.

200 feet of black shales and gray sandstones, probably belonging to the Quadrant formation of Carboniferous age.

Strata representing the above formations outcrop a few miles farther west, around the flank of the Big Snowy Mountain, but as they are characterized by no definite succession and contain no pronounced member that can be recognized in a well log, and as there are probably one or more erosional unconformities in the series, it is impossible without detailed study of the well drillings to assign the strata penetrated in wells to their proper formations. It is probable, however, that below the series of 1,600 feet penetrated by the well in the Kootenai dome there are from 1,000 to 1,200 feet of shales, sandstones, and limestones, which overlie the Madison limestone, a formation consisting of about 2,000 feet of limestone that lies at the base of the Carboniferous and forms the ridges of many of the mountains of central and western Montana.

Oil prospects in the area.

As most of the oil fields of the world, especially those in the Rocky Mountain region, occur in anticlines or domes it is to be expected that if the area examined contains oil it should be looked for in the anticlines or domes here described, and as the oil in the Cat Creek field -- the only field of commercial importance in Central Montana -- comes from a sandstone at the base of the Colorado shale, it is assumed that the oil is most likely to be found in the crest of the domes in which this sandstone lies within drilling distance of the surface. These conditions are fulfilled by the Brush Creek dome. A well drilled in the northwest corner of the NW. 1/4 sec. 26, T. 16 N., R. 27 E., on the crest of this dome, obtained nothing but water in the Cat Creek sand, which was penetrated at a depth of 627 feet. The well was drilled 1,150 feet deeper and a number of sandstones were penetrated but in these also only water was found. In a sandstone near the base of the Kootenai an artesian flow of fresh water, estimated at 10,000 barrels a day, was obtained. Three other wells located on the east end of this dome in secs. 28, 29, and 33, T. 16 N., R. 28 E., have been drilled through the Cat Creek and Kootenai sands, but they obtained only water. So what seems to be structurally the most favorable area for obtaining oil in the whole area mapped has been drilled and yet no oil was found. Some of the other folds have also been tested without favorable results.

A well in sec. 18, T. 16 N., R. 26 E., on the crest of the Kootenai dome, has been drilled to a depth of over 1,600 feet but found only water. This well was started at a horizon about 50 feet below the Cat Creek sand and probably penetrated the Van Duzen sand of the Devils Basin at a depth of about 1,230 feet.
Another well, in sec. 28, T. 13 N., R. 25 E., on the crest of the Pike Creek anticline, was drilled through the Cat Creek and Kootenai sands but obtained only water.

The results of these tests show that there is little prospect of finding oil in the area. The Cat Creek and Kootenai sands apparently are saturated with water. If more tests are made in the area they should be confined to the crests of the folds and carried down to the lower Quadrant sands. A well drilled 2,500 feet below the Cat Creek sand would probably reach the top of the Madison limestone, which is the lowest of all the possible oil-bearing horizons in the area.

As oil has not accumulated in the known oil sands in the domes of the region, it has probably not accumulated at or behind the dikes. A well drilled apparently on purpose, near a dike in sec. 10, T. 13 N., R. 25 E., encountered strong flows of water in the Cat Creek and Kootenai sands.