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Petroleum and Natural Gas Section

in cooperation with: The Pennsylvania Natural Gas Men's Association • The Pennsylvania Grade Crude Oil Association • The Bradford District Pennsylvania Oil Producers' Association

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FOREWORD

AFTER a lapse of two years, necessitated by the building program of The Pennsylvania State College, the yearly Petroleum and Natural Gas Conferences have been successfully resumed. The Pennsylvania industry has expressed its satisfaction with the resumption of the conference program which, in its opinion, fills a need for closer contact between the professional man and the State's institution for mineral industries education.

The technical sessions of the conferences are organized in such a manner as to cover problems of the Pennsylvania industry which are particularly pressing. This year, the difficulties experienced in discovering new reserves by the natural gas industry in the northern Pennsylvania and New York gas fields have given particular significance to subsurface studies of deep exploratory wells in Pennsylvania.

Geophysics is finding an ever widening field of application in oil exploration as well as production; therefore results of this work in Canadian oil and gas fields have found a wide interest.

Other problems facing the oil and gas men of Pennsylvania are discussed in this volume.

The success of the conference was due to the help, interest and support of the following groups:
The Pennsylvania Natural Gas Men's Association
The Pennsylvania Grade Crude Oil Association
The Bradford District Pennsylvania Oil Producers' Association, whose co-operation is gratefully acknowledged.

Sylvain J. Pirson, In Charge
Petroleum and Natural Gas Engineering Department
The Pennsylvania State College
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Recent Magnetic and Electrical Geophysical Investigations on the Surface and in Drill Holes in Regions Containing Gas, Oil, and Other Minerals, and the Correlation of the Results of the Investigations

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I. The Delineation of Magnetic Anomalies.

There appears to be two classes of magnetic anomalies:

A. Anomalies in which a large but finite number of consequent poles exist in the material of the subsurface body and for which the body in whole or in part may be represented by a resultant equivalent magnet. Numerous deposits of magnetite, pyrrhotite, ilmenite, and franklinite as well as basic dikes containing disseminated magnetite have been found to provide this condition. Moreover, it is found frequently that the magnetic meridian plane of these bodies has only a small declination from the earth's magnetic meridian plane. If measurements of the vertical, \( \Delta Z \), and horizontal, \( \Delta H \), components of the field intensity due to the body are made at well-chosen points on the surface of the ground in the neighborhood of a magnetic body and contours of these component field intensities are mapped as in Fig. 1a and Fig. 1b the magnetic meridian section of the equivalent magnet of the body may be determined approximately. It is indicated by the dotted line in the figures, which is in the plane \((x, z)\), \(z\) being vertical. If now the measured values of the vertical, \( \Delta Z \), and horizontal, \( \Delta H \), components in this meridian section, are plotted as shown in Fig. 2, the following deductions may be made.

1. If the magnetic body is extensive in the direction perpendicular to the magnetic meridian plane then the following may be determined:

\[
d = \text{depth from the surface of the ground to the upper or south subing pole of the equivalent magnet}
\]

\[
x = \text{angle of dip from the horizontal}
\]

\[
l = \text{length or distance from the upper to the lower pole}
\]

\[
a = \text{half-width of the magnetic body in the meridian plane section, i.e., the plane } (x, z) \text{ in the figure. The origin is taken at a point in the surface directly above the upper pole of the equivalent magnet.}
\]
\[ \Delta Z = \frac{\rho}{d} \left[ \frac{x + a}{\{(x + a)^2 + d^2\}^{1/2}} - \frac{x - a}{\{(x - a)^2 + d^2\}^{1/2}} \right] + \frac{\rho}{d + l \sin \alpha} \left[ \frac{x - a - l \cos \alpha}{\{(x - a - l \cos \alpha)^2 + (d + l \sin \alpha)^2\}^{1/2}} - \frac{x + a - l \cos \alpha}{\{(x + a - l \cos \alpha)^2 + (d + l \sin \alpha)^2\}^{1/2}} \right] \]

\[ \Delta H = \rho \left[ \frac{1}{\{(x + a)^2 + d^2\}^{1/2}} - \frac{1}{\{(x - a)^2 + d^2\}^{1/2}} \right] - \rho \left[ \frac{1}{\{(x + a - l \cos \alpha)^2 + (d + l \sin \alpha)^2\}^{1/2}} - \frac{1}{\{(x - a - l \cos \alpha)^2 + (d + l \sin \alpha)^2\}^{1/2}} \right] \]

where \( \rho \) = average intensity of magnetization of the equivalent magnet.

If now measured values of \( \Delta Z \) and \( \Delta H \) obtained at suitable points are inserted in these formulae, the value of \( \rho \), i.e., the average intensity of magnetization of the equivalent magnet, may be determined.

2. If the magnetic body is not extensive in the direction at right angles to the magnetic meridian plane, the following formula may be taken to represent the vertical component intensity \( \Delta Z_{\text{max}} \) at the point on the surface of the ground where it is a maximum.

\[ \Delta Z_{\text{max}} = 2 \rho \tan^{-1} \left( \frac{b/a}{d} \right) \sqrt{\frac{1}{d^2 + a^2 + b^2}} - 2 \rho \tan^{-1} \left( -\frac{b/a}{d} \right) \]

\[ + \rho \tan^{-1} \left( \frac{b/N}{M} \right) \sqrt{\frac{1}{M^2 + N^2 + b^2}} - \rho \tan^{-1} \left( -\frac{b/N}{M} \right) \]

\[ - \rho \tan^{-1} \left( \frac{b/O}{M} \right) \sqrt{\frac{1}{M^2 + O^2 + b^2}} + \rho \tan^{-1} \left( -\frac{b/O}{M} \right) \]

where:

(a) For a body dipping south
\[ M = d - l \sin \alpha \]
\[ N = a - l \cos \alpha \]
\[ O = -a - l \cos \alpha \]

(b) For a body dipping north
\[ M = d - l \sin \alpha \]
\[ N = a + l \cos \alpha \]
\[ O = -a + l \cos \alpha \]

\( a, d, l \) and \( \alpha \) are indicated in Fig. 3.
Since the vertical component $\Delta Z_{\text{max}}$ due to the magnetic body may be measured and since the depth, to the upper pole, $d$, and the dimensions of the equivalent magnet, $a$, $b$, $l$, $\alpha$ and $\rho$ may be determined approximately from the contours of the measured values of $\Delta Z$ and $\Delta H$, then the value of the average intensity of magnetization, $\rho$, may be calculated. The values of $a$, $b$, $l$, $\alpha$ and $\rho$ are obtained more accurately with the assistance of graphs of $\Delta Z$ and $\Delta H$ for typical illustrative examples of equivalent magnets. The values of $d$, $a$, $b$, $l$, $\alpha$, and $\rho$ for actual field examples are presented in Fig. 3.

If the values of $\rho$ which have been obtained from measurements of $\Delta Z$ and $\Delta H$ over known deposits of magnetic ores are tabulated, the investigator will become able to distinguish deposits of massive magnetite from other ore deposits, and with the assistance of other geophysical evidence, e.g., the electrical conductivity, may be able to distinguish dikes containing disseminated magnetite from massive magnetic bodies such as pyrrhotite, ilmenite, and franklinite. From the values of $\rho$ and the normal value of the vertical intensity in the region, $V_b$, the value of an hypothetical susceptibility of the ore body, $\xi$, may be calculated from $\xi = \frac{\rho}{V_b}$ and the permeability $\mu$ may be calculated from $\mu = 1 + 4\pi \xi$. The
values of \( \varphi, \xi, \) and \( \mu \) for the materials in several ore deposits are presented in Fig. 3.

The maximum vertical intensity \( \Delta Z \) is given by:

\[
\Delta Z = 2\varphi \tan^{-1}\left(\frac{h_b}{b} / \sqrt{d + b^2}\right) - 2\varphi \tan^{-1}\left(\frac{h_a}{a} / \sqrt{d + a^2}\right) \\
+ \varphi \tan^{-1}\left(\frac{h_b}{b} / \sqrt{m^2 + b^2}\right) - \varphi \tan^{-1}\left(\frac{h_a}{a} / \sqrt{m^2 + a^2}\right) \\
- \varphi \tan^{-1}\left(\frac{h_b}{b} / \sqrt{m^2 + c^2}\right) + \varphi \tan^{-1}\left(\frac{h_a}{a} / \sqrt{m^2 + c^2}\right)
\]

WHERE:

- For a body dipping south:
  - \( M = -d \cdot \sin \alpha \)
  - \( N = a \cdot \cos \alpha \)
  - \( \varphi = -a \cdot \cos \alpha \)

- For a body dipping north:
  - \( M = -d \cdot \sin \alpha \)
  - \( N = a \cdot \cos \alpha \)
  - \( \varphi = -a \cdot \cos \alpha \)

\( I = P \cdot \text{magnetic moment/ unit volume} \)
\( V_e = \text{the normal vertical intensity for the district} \)

Magnetic dike dipping to the north

![Diagram of a magnetic dike](image)

1. Length along dip
2. Length along strike
3. \( d \) = depth below surface
4. \( \alpha \) = angle of dip
5. \( \varphi \) = equivalent magnetic susceptibility
6. \( \mu \) = equivalent permeability

| DISTRICT | \( d \) | \( \alpha \) | \( 2a \) | \( b \) | \( \psi \) | \( \varphi \) | \( V_e \) | \( I \) | \( P \) | \( z \) |
|----------|-------|--------|-------|------|------|-------|------|------|------|
| 1      | FALCON BRIDGE | 135° 80° | 30° 100° | 150° | 10° 150° | 0.0142 | 0.008 | 0.213 |
| 2      | 150° 100° | 30° 65° | 90° 120° | 10° | 10° | 0.213 | 0.021 |
| 3      | 100° 45° | 50° 100° | 50° | 10° | 10° | 0.213 | 0.207 |
| 4      | 50° 100° | 10° 100° | 10° | 10° | 0.213 | 0.207 |
| 5      | 100° 45° | 75° 100° | 60° | 10° | 0.213 | 0.207 |
| 6      | 100° 45° | 75° 100° | 60° | 10° | 0.213 | 0.207 |

Fig. 3—Magnetic vertical intensity over a dike.

The comparatively small values of \( V_e \) and the large values of \( \varphi, \xi, \) and \( \mu \) for these deposits give rise to speculations on the origin of the magnetization of these deposits and particularly to the possibility of production of this magnetization by the exciting normal field of the earth.

The values of \( \varphi \) which are given in Fig. 3 were obtained from the formula for \( \Delta Z_{\text{max}} \) but the values of \( d, x, a, \) and \( l \) used in that formula were obtained on the assumption that the magnetic body was extensive in the direction perpendicular to the magnetic meridian of the body.

The values of \( \varphi \) thus obtained are, therefore, roughly approximate. They serve, however, as the basis for a useful delineation of the character of the magnetic body under investigation.

3. The actual problem for investigation in the field is found frequently to be more complex than that which has been considered, owing to the existence of groups of massive magnetic bodies where the dimensions of the individual members of the group and their distance of separation are of the same order as their depth below the surface. The problem is rendered still more complex if disseminated magnetic material exists in the region between the massive magnetic bodies. In order to cope with the difficulties of investigation which have been indicated it is of great assistance to plot the contours of \( \Delta Z \) and \( \Delta H \) and the graphs of the relative magnitudes of these quantities along and perpendicular to the magnetic meridian of numerous hypothetical individual magnetic bodies and groups of magnetic bodies. Well-chosen examples of such typical cases have been found very useful indeed in the interpretation of the results of measurement in the field.

B. Anomalies due to a difference of permeability to the earth's magnetic field of subsurface massive bodies of homogeneous materials extending to a considerable distance in a direction at right angles to the magnetic meridian plane.

1. An example of this is a sedimentary deposit of massive crystalline dolomite containing one-fifth of its volume of oil or salt water. If these materials are free from disseminated magnetic substances such as magnetite, then clusters of consequent poles do not exist and if the body of dolomite is of considerable extent from its upper to its lower surface, its effect on the magnetometer needles placed on the surface of the ground will not in general be that of a finite equivalent magnet with upper and lower poles, but rather that of a homogeneous magnetic body extending downwards to a very great depth in which no position of finite resultant poles exists.

In this case the vertical component \( \Delta Z \) and the horizontal component \( \Delta H \) of the field intensity due to the magnetization of the body at a point on the surface of the ground in the meridian plane of the earth's field directly above the center of the upper surface of the body may be indicated formulatively. In the simpler case
of a body of rectangular section of narrow width in the north-south and extensive in the east-west direction the components of the field intensity due to the body per unit of east-west extent are according to Haalck* represented approximately by the following:

$$\Delta Z = \frac{\xi V_e}{R^3} \left[ x \sin \alpha + d \cos \alpha \right] \left[ R^2 \cos \alpha (x + R \cos \alpha) \right. \\
\left. + x d (x \sin \alpha + d \cos \alpha) \right]$$

$$\Delta H = \frac{\xi V_e}{R^3} \left[ x \sin \alpha + d \cos \alpha \right]^2 \left[ d^3 \cos \alpha - x^3 \sin \alpha - R^3 \cos \alpha \sin \alpha \right]$$

where $V_e$ = the normal vertical component of the earth's field
$\xi$ = susceptibility
$d$ = distance from the origin to the top of the body
$x$ = co-ordinate in the North-South direction
$\alpha$ = angle of dip
$R^2 = x^2 + d^2$

For the extensive body the above values of $\Delta Z$ and $\Delta H$ should be multiplied by a constant.

The form of the graph representing $\Delta Z$ and $\Delta H$ is given in Fig. 4.

If the mass of the porous dolomite is of the form of a rectangular parallelepiped of known dimensions and depth and is of known susceptibility $\xi$ and if the angle of dip is $90^\circ$, the value of the vertical component of the magnetic intensity at a point on the surface of the ground directly above the center of the top of the body may be calculated approximately. In an actual field case in which an extensive mass of porous dolomite containing about one-fifth of its volume of oil and salt water was embedded in non-porous crystalline dolomite with its upper face at a depth of 1600 feet and extending downward to a great depth the value of $\Delta Z_{\text{max}}$ was found to be of sufficient magnitude to warrant the carrying out of measurements of the vertical intensity in the field. In this calculation the values of $\xi$ as given in Table 1 were used.

The greatest difference in values of $\Delta Z_{\text{max}}$ obtained by measurements in the field was about 110 $\gamma$. Since this difference was comparatively small it was necessary in the course of the measurements to take account of

(1) the daily variation in the earth's normal field intensity
d(2) the change in the earth's normal field intensity in a south-north direction.

### Table 1

<table>
<thead>
<tr>
<th>Substance</th>
<th>Spec. Suscep. $\mu$</th>
<th>Density $\rho$</th>
<th>Vol. Suscep. $\xi$</th>
<th>Permeability $\mu$</th>
</tr>
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<tr>
<td>Water (20°C)</td>
<td>$-0.75 \times 10^{-6}$</td>
<td>1.00</td>
<td>$-0.75 \times 10^{-6}$</td>
<td>0.99999056</td>
</tr>
<tr>
<td>Rocksalt</td>
<td>$-0.499 \times 10^{-6}$</td>
<td>2.15</td>
<td>$-1.07 \times 10^{-6}$</td>
<td>0.9999893</td>
</tr>
<tr>
<td>Dolomite</td>
<td>$-0.9935 \times 10^{-6}$</td>
<td>2.90</td>
<td>$+2.88 \times 10^{-6}$</td>
<td>1.0000362</td>
</tr>
<tr>
<td>Petroleum</td>
<td>$-0.83$</td>
<td>0.90</td>
<td>$-0.74 \times 10^{-6}$</td>
<td>0.99999062</td>
</tr>
</tbody>
</table>

Note: The specific susceptibilities $\psi$, were taken from international critical tables. The volume susceptibilities $\xi$, were calculated from $\psi = \frac{\xi}{\rho}$. The permeabilities $\mu$, were calculated from $\mu = \frac{1}{\rho} \times \xi$.

It is apparent that the volume susceptibility, $\xi$, of dolomite and of dolomite containing a considerable amount of gas is somewhat higher than that of dolomite containing either petroleum or saline water. It appeared possible that if the materials were massive and not too deeply situated these differences in susceptibility might be sufficient to produce measurable differences in the vertical component of the earth’s magnetic field intensity at a point on the surface of the earth. The calculated values of $\Delta Z_{max}$ warranted the making of measurements of the vertical component intensity and the work in the field was undertaken.

The results of the measurements are shown in Fig. 5. They indicate systematically higher values of $\Delta Z$ in the north and west directions than in the south and east directions, the change from low to high values of $\Delta Z$ being fairly sharp along the (south-east) — (north-west) lines at points a short distance north of drill hole 45.

### II. The Delineation of Electrical Anomalies Associated with Deposits of Gas, Oil, and Salt Water.

Electrical resistivity measurements were made in the same region in which the magnetic measurement presented in B1 were made. The measurements of resistivity at depth were made by a modification of the layout used by the author in electrically coring a drill hole in 1929, which is given in Memoir 176 of the publications of the Geological Survey of Canada. The modified layout is presented in Fig. 6c and Fig. 6d in elevation and in plan. It was believed from these resistivity measurements that porous dolomite containing gas and oil could be distinguished from porous dolomite containing salt water and in conjunction with the results of the magnetic measurements that both of these could be distinguished from massive crystalline dolomite. Further in conjunction with the results of resistivity measurements made on the surface of the ground it was hoped that some knowledge of the depth from the surface of oil or salt water could be obtained. The basis of measurement and the methods of procedure were as follows:

1. From Fig. 6c it will be observed that the current point electrode at the bottom of the drill hole is a center of symmetry with respect to the line electrodes on the surface not only in space...
but also electrically since the stake resistances all along the line electrodes were equalized. However, it will also be seen that the electrical symmetry of the subsurface region about this central point will depend on the homogeneity of the materials. Further, the vertical plane through the central point electrode and parallel to the vertical planes containing the parallel line electrodes is a central plane of symmetry with respect to the line electrodes. Then by sending the current from the central point to the line electrodes in succession the drop in potential between any two points in the central plane of symmetry is a comparative measure of the conductivity of the materials in any direction from the bottom of the drill hole. This is indicated in Figs. 6a and 6b. If the four parallel line current electrodes are used in parallel as $C_2$, and the central point current electrode as $C_1$, then the approximate value of the average resistivity $\rho$ of the materials in the neighborhood of the central point may be determined from

$$\rho = 4\pi R \frac{a b}{b-a}$$

where $R$ is the interbowl resistance between two bowls of radii $a$ and $b$ respectively. If the calculated value of $\rho$ is below $10^5$ ohms per centimeter cube, the presence of salt water is indicated. If in the region considerable oil or gas or crystalline dolomite exists, the value of $\rho$ will be higher than $10^5$ ohms per centimeter cube.

The results of these subsurface measurements indicated:

(a) Low values of $\rho$ in the region adjacent to the bottom of the drill hole.

(b) the resistance in the west direction slightly higher than in the east direction.

the resistance in the north direction about 30 per cent higher than in the south direction.

2. The layout for the measurement of the resistance on the surface is shown in Fig. 6d. $\rho$ was obtained from $\rho = 2\pi R \frac{a b}{b-a}$ where $a = 1600$ feet, $b = 2200$ feet in distance from the top of the drill hole.

The results of measurement indicated that

(a) the resistance in the north-west direction was about twice as high as in the south-east direction.

(b) the high resistance in the north-west direction was due chiefly to materials less than 200 feet in depth.

3. Consideration of the formula used in the calculation of the specific resistivity, $\rho$, in the neighborhood of the bottom of the drill hole 45, viz.

$$\rho = 4\pi R \frac{a b}{b-a}$$

$$= 4\pi \frac{V}{I} \frac{a b}{b-a}$$
Since the equation of distribution of applied potential for a steady flow in a homogeneous conductor, viz.
\[
\frac{d^2 V}{dx^2} + \frac{d^2 V}{dy^2} + \frac{d^2 V}{dz^2} = 0
\]
implies continuity and the solution of this equation leads to the formula for the specific resistivity, \(\rho\), it is evident that the formula can apply only approximately to the conditions of flow in a nonhomogeneous medium. However, the results of the measurement of the resistance, \(R\), were made chiefly to make comparisons...
of the resistance in adjacent regions and the measured resistance \( R \) was used in the calculation of the average resistivity, \( \rho \), in the immediate neighborhood of the bottom of the drill hole in order to obtain a knowledge of the approximate value of the average resistivity from which the probable existence of saline water might be determined.

4. Consideration of the measurement of \( R \).

The applied potential was alternating, and very low frequencies of alternation were used as well as a frequency of 500 cycles per second. In the use of the latter, care was taken to provide that self-inductance in the current leads and mutual inductance in the potential leads from the alternating current in the current leads were negligibly small. It must be recognized, however, that portions of the earth through which flows an electrical current form in reality a “leaky condenser” of finite capacity and, therefore, reactance as well as ohmic resistance must be taken into account. The measurement of \( V \) was made by means of an alternating potential potentiometer in which compensation for the reactance was made by means of a mutual inductance. The measurement of current \( I \) was made by means of an alternating current milliammeter and a reactance-free standard resistance of known value was used as a comparator.

The value of the ohmic resistance was then calculated by means of the formula

\[
R = \frac{I_0 E_0 + I_p E_p}{I^2} \text{ in ohms}
\]

and the reactance \( X \) from

\[
X = \frac{I_0 E_0 - I_p E_p}{I^2} \text{ in ohms}
\]

where

\[
I_p \text{ is the current in phase}
\]

\[
I_0 = I_p^* + I_0^2
\]

\[
E_p \text{ is the E.M.F. in phase}
\]

\[
E_0 = E_p^* + \sqrt{-1} E_0
\]

\( I_p \) and \( I_0 \) may be determined if the potential drop across a known reactance-free standard resistance is measured.

A study of the results of the magnetometric measurements in conjunction with the results of the measurements of electrical conductivity led to the following conclusions for the areas between lines 1, 2, 3, and 4 shown in Fig. 6d.

Area I (Between Line 1 and Line 2)

Probably contains massive dolomite and may contain a small amount of gas

Area II (Between Line 2 and Line 3)

Probably contains massive dolomite and may contain gas

with the possibility of saline water and a small quantity of oil at the southern edge of the area

Area III (Between Line 3 and Line 4)

Probably contains considerable saline water and possibly some oil near Line 3.

The conclusion was also reached that in the area between Line 1 and Line 2 very little saline water existed above a depth of 2000 feet.

A drill hole, No. 98, was put down at a point about 1200 feet north and slightly west of drill hole 48, (Fig. 6d), that is, in the area between Line 1 and Line 2. The depth of this hole was about 2300 feet.

The following results were found:

1. Massive crystalline dolomite existed to a depth of more than 2000 feet.

2. No saline water was found above a depth of 1905 feet.

III. Delineation of Magnetic and Electrical Anomalies Associated with a Deposit of Pyrite and Pyrrhotite.

The methods of procedure in making magnetic and electrical resistivity measurements given in Section I and in Section II respectively were also used in the delineation of anomalies in the neighborhood of a deposit of pyrite and pyrrhotite. The deposit was associated with much-disturbed basic rocks with a considerable content of disseminated magnetite and the magnetic field intensity components were largely due to the presence of magnetite.

Interbowl electrical resistance measurements were made with one current electrode, C, at the bottom of a drill hole commencing on the 1120-foot mine level and extending downward about 800 feet, and four parallel line current electrodes on the surface of the ground as shown in Fig. 7.

The results of the measurements of interbowl resistance in different directions from the bottom each of the drill holes are given in Tables 2, 3, 4, 5, 6. The approximate values of the average resistivity, \( \rho \), were also calculated from the formula:

\[
\rho = 4 \pi \frac{R}{ab} \frac{a}{b-a}
\]

and the location of the deposits of pyrite which are of low resistivity was determined approximately.

The results of the electrical resistivity investigations agreed very well with the known location of the deposits as revealed by drilling and mining. This becomes evident by a study of the Tables 2, 3, 4, 5, and 6 and also of the position of the drill holes with reference to the main ore body as shown on Fig. 8. In the figure there is presented in plan part of the eighth level of the
mine at a depth of 1125 feet below the surface. The position of the top of each of three drill holes Nos. 203, 202, 165 on this level are shown and a dip of each hole is indicated. The drill holes extended downward from this level about 800 feet. The position of the drifts shown in the figure indicate the location of the main ore body on this level. Above this level and to the north and east there was an extensive massive ore body of low resistivity which had a dominating effect on all of the results of the measured resistances.

Two other drill holes which had been drilled from the surface of the ground were investigated by electrical resistance measurements, viz.

D.D.H. No. 28—about 700 feet southeast of the collar of the shaft

and

D.D.H. No. X—about 150 feet northwest of the collar of the shaft.

The low resistivity of the ore body in the upper levels had in these cases also a dominating effect on the results of the measured resistances.

In spite of this effect on the resistivity measurements by the massive ore body on the upper levels, the directions from the drill holes in which lower resistivities were indicated by the results of measurement corresponded in general with the directions in which the greater masses of ore were located. This may be seen by a study of Tables 2, 3, 4, 5, 6. In the tables there are presented
### Table 2

Drill Hole—U 203  
Dip—Vertical at the collar  
58° at the bottom of the hole  
Direction—Unknown  
Collar—1125 ft below surface  
$C_i = 835$ ft down the drill hole from collar

<table>
<thead>
<tr>
<th>Station</th>
<th>Ratio $R_v/R_n$</th>
<th>Ratio $R_w/R_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>785—585</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>738—535</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>785—485</td>
<td>1.00</td>
<td>.95</td>
</tr>
<tr>
<td>635—435</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>585—385</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>535—335</td>
<td>1.03</td>
<td>1.01</td>
</tr>
<tr>
<td>483—285</td>
<td>1.03</td>
<td>1.00</td>
</tr>
<tr>
<td>435—235</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>385—185</td>
<td>1.02</td>
<td>1.01</td>
</tr>
<tr>
<td>335—135</td>
<td>1.07</td>
<td>1.12</td>
</tr>
<tr>
<td>285—85</td>
<td>1.05</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Note: There is a lower resistance in the north and east directions.

### Table 3

Drill Hole—U 202  
Dip—60°  
Direction—South  
Collar—1125 ft below surface  
$C_i = 600$ ft down the drill hole from collar

<table>
<thead>
<tr>
<th>Station</th>
<th>Ratio $R_v/R_n$</th>
<th>Ratio $R_w/R_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>550—500</td>
<td>1.00</td>
<td>.92</td>
</tr>
<tr>
<td>500—450</td>
<td>.98</td>
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<tr>
<td>450—400</td>
<td>1.00</td>
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<td>400—350</td>
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<tr>
<td>350—300</td>
<td>.94</td>
<td>1.04</td>
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<tr>
<td>300—250</td>
<td>1.00</td>
<td>1.14</td>
</tr>
<tr>
<td>250—200</td>
<td>.98</td>
<td>1.00</td>
</tr>
<tr>
<td>200—150</td>
<td>.91</td>
<td>1.03</td>
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<td>150—100</td>
<td>1.00</td>
<td>1.10</td>
</tr>
<tr>
<td>100—50</td>
<td>1.03</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Note: There is a lower resistance in the east and a slightly lower resistance in the south direction.

### Table 4

Drill Hole—U 165  
Dip—55°  
Direction—South 22°W  
Collar—1125 ft below surface  
$C_i = 800$ ft down drill hole from collar

<table>
<thead>
<tr>
<th>Station</th>
<th>Ratio $R_v/R_n$</th>
<th>Ratio $R_w/R_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>700—650</td>
<td>1.06</td>
<td>.80</td>
</tr>
<tr>
<td>650—600</td>
<td>1.00</td>
<td>1.03</td>
</tr>
<tr>
<td>600—550</td>
<td>1.47</td>
<td>1.11</td>
</tr>
<tr>
<td>550—500</td>
<td>3.0</td>
<td>1.00</td>
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<tr>
<td>500—450</td>
<td>1.00</td>
<td>1.13</td>
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<tr>
<td>450—400</td>
<td>.88</td>
<td>1.14</td>
</tr>
<tr>
<td>400—350</td>
<td>1.06</td>
<td>1.00</td>
</tr>
<tr>
<td>350—300</td>
<td>1.02</td>
<td>1.00</td>
</tr>
<tr>
<td>300—250</td>
<td>.76</td>
<td>1.00</td>
</tr>
<tr>
<td>250—200</td>
<td>1.04</td>
<td>1.00</td>
</tr>
<tr>
<td>200—150</td>
<td>1.00</td>
<td>1.10</td>
</tr>
<tr>
<td>150—100</td>
<td>1.59</td>
<td>2.99</td>
</tr>
<tr>
<td>100—50</td>
<td>1.00</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Note: There is a lower resistance in the north and east directions.

### Table 5

Drill Hole—28—700 ft SE. of shaft  
Dip—60°  
Direction—North  
Collar—On surface  
$C_i = 750$ ft down drill hole from collar

<table>
<thead>
<tr>
<th>Station</th>
<th>Ratio $R_v/R_n$</th>
<th>Ratio $R_w/R_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600—550</td>
<td>1.04</td>
<td>1.00</td>
</tr>
<tr>
<td>550—500</td>
<td>1.02</td>
<td>1.00</td>
</tr>
<tr>
<td>500—450</td>
<td>1.06</td>
<td>1.00</td>
</tr>
<tr>
<td>450—400</td>
<td>1.22</td>
<td>1.00</td>
</tr>
<tr>
<td>400—350</td>
<td>1.18</td>
<td>1.00</td>
</tr>
<tr>
<td>350—300</td>
<td>1.02</td>
<td>1.00</td>
</tr>
<tr>
<td>300—250</td>
<td>1.06</td>
<td>1.00</td>
</tr>
<tr>
<td>250—200</td>
<td>1.02</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Note: There is a lower resistance in the north direction.
Table 6
Drill Hole—X, 150 ft NW. of shaft
Dip—55°
Direction—North
Collar—On surface
C₁ = 400 ft down drill hole from collar

<table>
<thead>
<tr>
<th>Station</th>
<th>Ratio Rᵢ/Rₑ</th>
<th>Ratio Rₑ/Rₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>350—300</td>
<td>.98</td>
<td>1.07</td>
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<tr>
<td>300—250</td>
<td>1.00</td>
<td>.98</td>
</tr>
<tr>
<td>250—200</td>
<td>.99</td>
<td>1.00</td>
</tr>
<tr>
<td>200—150</td>
<td>.77</td>
<td>1.00</td>
</tr>
<tr>
<td>150—100</td>
<td>1.00</td>
<td>1.01</td>
</tr>
<tr>
<td>100—50</td>
<td>1.00</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Note: There is slightly lower resistance in south and east directions.

(1) The distances of the interbowl resistances from the current electrode C₁ near the bottom of the drill hole
(2) The ratio of the interbowl resistances.

The results presented in each table indicate the following:
(a) From Table 2 for drill hole 203 there is a lower resistance in the north and east directions.
(b) From Table 3 for drill hole 202 there is a lower resistance in the east and a slightly lower resistance in the south directions.
(c) From Table 4 for drill hole 165 there is a lower resistance in the north and east directions.
(d) From Table 5 for drill hole 28 there is a lower resistance in the north direction.
(e) From Table 6 for drill hole X there is a slightly lower resistance in the south and east directions.

In general then the directions from the bottom of the drill holes in which low resistances were found corresponded to the directions in which the major parts of the ore body were located.

The following tables showing the comparison of earth interbowl resistances (Rₑ) to the south with those to the north (Rᵢ) and resistances to the west (Rᵢ) with those to the east, (Rₑ) at the bottom of drill holes U 203, U 202, U 165, 28 and X.

The figures in the columns headed "station" refer to the distances in feet of the potential electrodes, P₁ and Pₑ, from the current electrode, C₁, near the bottom of the drill hole.

The results of a modified form of electrical drill hole coring are presented in the graphs I, II, III, IV, and V for D.D. holes 203, 202, 165, 28 and X.

Graph I.—Earth resistivities from electrical measurements made in diamond drill holes.

Graph II.—Earth resistivities from electrical measurements made in diamond drill holes.
202, 165, 28, and X. As the distances of the interbowls from the current electrode $C_1$ near the bottom of the drill holes became successively greater during the course of measurement of the interbowl resistances $R$, the average resistivity became the resistivity of material at successively greater distances from the bottom of the hole. The dominating effect of the low resistivity material of the ore body on the upper levels became more pronounced the farther the interbowl was from $C_1$. In spite of this

**Graph III**

Graph III.—Earth resistivities from electrical measurements made in diamond drill holes.

the low resistivities $\varphi$ found for the region near the bottom of D.D.H. No. 203 as shown on Graph I indicate the advisability of deepening this drill hole. The values for $\varphi$ are much lower for this region than for the regions near the bottom of any of the other drill holes. For the region near the bottom of D.D.H. No. 28 the value of $\varphi$ is about one-tenth of that of the regions near the bottom of D.D.H. Nos. 202 and 165.

Still further information could be made available by the ordinary method of electrical coring of the drill holes.

These investigations were carried out in co-operation with K. W. Fritzscbe and members of the mine staff and by A. R. Clark of the department of physics, University of Toronto, by whom the actual measurements and calculations were made.
THE PETROLEUM INDUSTRY has undergone many changes during the relatively few years since its inception and many of these changes have been revolutionary in nature. Fortunately these progressive changes have taken place in all phases of the industry, namely, production, transportation, refining, and distribution with the result that the industry has rapidly developed into one of the most important and essential basic industries.

The life of the industry from its beginning to the present may arbitrarily be divided into three periods. The early years which may well be designated as the “Burning Oil Period,” represented its infancy. During this early period, burning oils, such as kerosene, were the main items of economic value, while naphthas and gasoline were drugs on the market and petroleum lubricating oils were just beginning to “creep.” Ghosts whisper of valves opened at midnight and excess gasoline and naphtha launched into mountain creeks for disposal, and at a loss. This method of “dumping” is not entirely without parallel in more recent years.

The closing years of the last century brought the automobile and with it a phenomenal and increasing demand for gasoline, a fortunate condition for the industry, for it was now launched into the second period of development, the “Gasoline Period.” In this connection it is interesting to note the relationship between the development of the automotive industry and the petroleum industry, particularly as regards cause and effect, a point that will be emphasized later by specific examples. Suffice it to say at this point that Dame Fortune smiled on the petroleum industry, not as a result of farsighted planning on the part of the leaders of the industry at that time, but solely as a result of the imagination of pioneers in a new and uncertain field—pioneers with the courage of their convictions. The gasoline phase will cover those years wherein motor fuel has been the major commodity of the industry and has carried the major part of the financial load.

For some years past petroleum has been slowly—all too slowly—entering the third and final period, a period which will be recorded by future historians as the “Chemical Period.” The initiation of this permanent change to a major chemical industry was the result, to a large degree, of a demand originating in the consuming field of petroleum products rather than of leadership and pioneering within the industry. This situation is changing rapidly and the industry is awakening to the opportunities in chemical specialties and by-products as evidenced by the petroleum research laboratories.

It would be difficult to find in our social and economic system a single individual whose daily life is not directly, or indirectly,
affected by petroleum products. Most of our petroleum products have become commodities. The field of expansion for the use of these petroleum commodities is therefore limited. It is in the chemical field, developed around the hydrocarbons, that we will find the greatest opportunity for development, expansion of distribution and profits, with more employment and greater stability. Where is it possible to find a wider variety of organic chemicals in larger quantities and at lower costs than in petroleum?

What is this chemical field that is proposed? Chemical and Metallurgical Engineering in describing the chemical industry in the United States has given a fine word picture in the statement that “120,000 wage earners and 24,000 salaried employees produce from $600,000,000 worth of raw materials from the mine, farm, forest, sea, and air in 2800 plants, $1,185,000,000 worth of chemicals for chemical consuming industries, representing $1,192,000,000, to serve the fundamental human needs of Food, Clothing, Shelter, Health, Happiness, Transportation, and Security.”

During the entire history of the petroleum industry there has never been a time when the problem of finding and developing outlets for the by-products of conventional refining of crude oil has not existed. Therefore, it is neither new nor unique. Executives and technologists of the petroleum industry have had the problem before them ever since the industry adopted the “cheese-box” still. There are relatively few of the pioneers of the industry alive today who were not confronted with these problems, and who, if one is fortunate enough to catch them in a reminiscent frame of mind, cannot add many personal and humorous details to the glamorous story. Disposal of by-product gasoline and naphtha has been mentioned.

The solution to many of these early problems indirectly resulted in furnishing the answer to later problems through creating a demand. The development and refinement of automotive transportation created a demand for more and better lubricants. Simultaneously, and with wider distribution of the automobile, came a demand for more and better roads and highways, which in turn created a demand for road-building materials. The result, another by-product of the industry—asphalt—found a profitable outlet. To appreciate what a large and lucrative business this has meant to the petroleum industry in the past few years one has but to look at the total volume of road oils, asphalts, liquid asphalts, and emulsified asphalts purchased annually by the various governmental agencies having to do with highway construction.

The scope of this paper is quite inadequate to enumerate the many problems of the past, or to trace their ultimate solution and relationship to other problems in the industry. Suffice it to say that the pioneers of the industry met these problems courageously and in their ultimate victory laid the foundation for our present major and basic industry.

Progress has no maximum limitation. Technical developments, particularly our chemical knowledge, have affected the petroleum industry to an extent not equaled by any other basic industry. Fortunately, the chemist and the engineer have not been content to solve their current problems and then sit back and bask in their success. The engineer set about in his drafting room and shop to create an engine with greater efficiency, or more power per gallon of fuel and more power per pound of engine. He increased his compression ratios. Concurrently with this research the petroleum chemist had been working in his laboratory to evolve some method of obtaining a greater amount of gasoline per barrel of crude oil to take care of the increased demand for gasoline as a result of the rapidly increasing use of the automobile and to conserve what was then presumed to be a limited amount of crude. The result of this was cracking.

High-compression ratios in internal combustion engines knocked badly with straight-run gasoline. Cracking not only resulted in a greater amount of gasoline per barrel of crude, but eliminated the knock in the higher compression engines. Thus the progress made by the petroleum chemist solved two problems and at the same time introduced a few more problems. All this progress was not so simple. The commercial introduction of cracking not only increased the amount of motor fuel, but also the gas, always produced in cracking operations, thus introducing another by-product to be utilized.

The past few years have witnessed an intensive competitive program in the industry popularly referred to as the "octane race" to produce motor fuel with higher antiknock properties. In the main this has been accomplished by cracking at higher temperatures and pressures. With these increases has come an increase in the amount of by-product gas. The utilization of the tremendous volume of this gas is a most important technical and economic problem of the industry today. A partial solution was found for these highly cracked gases in utilizing their high thermal value for enriching artificial gas for both domestic and industrial heating. Many industrial plants have turned to this gas and in many instances have revamped their plants to burn gas. Completeness of combustion, ease of control, and higher thermal value recommend refinery gases for such use. Unfortunately, large volumes of this gas were produced at points not accessible to gas pipe lines and to a large extent became a complete loss. Certainly those highly unsaturated gases that found a market as fuel had far greater economic possibilities in chemical utilization.

The rapid developments and installation of plants for the polymerization of these highly unsaturated gases for the manufacture of high antiknock fuels as well as basic and intermediate chemicals is at the present dominating the chemical period of the industry.

The logical approach to the future chemical development of specialties and by-products would appear to be through a more
intensive research program to determine what the specialties or by-products of any particular refinery are, followed by a comprehensive survey of the industrial field to ascertain wherein these chemical products might be employed advantageously by industry and supplied profitably by the refiner. It is, of course, obvious that these specialties and by-products must be developed on a sound economic basis.

Research costs money. It has been estimated that during 1939 $200,000,000 was spent on research by industry of the United States, of which approximately $20,000,000 was spent by the petroleum industry. The average expenditure on research by United States manufacturing industries during 1938 was equal to 0.5 per cent—1.0 per cent of net sales revenue. This offers a yardstick for the measurement of a research budget.

In addition to financing a research program it must be borne in mind that unless unusual good fortune attends the project it may well be several years before the research work pays dividends through development of new products and the development of a market. In general any specialties or by-products developed will fall into one of three classes: entirely new products which may require considerable time to develop a market, a product with a developed market that may be produced more economically from petroleum by a new process, or a product that can be produced from petroleum economically for a potential market that has been open but handicapped by high costs of products. This classification applied to the individual refiner's possibilities will establish the limitations of any proposed research problem.

Williams has given an excellent review of modern petroleum research based on petroleum as a basic material of the chemical industry. In addition to reviewing new laboratory methods applicable to actual molecular studies and studies of the mechanism of catalysis, he has given an excellent account of production of synthetic glycerol from propylene from petroleum gas. This is an outstanding example of the chemical possibilities of petroleum. The glycerol is equal to or better than the U.S.P. product and competitive with the average price. Further, he states that the entire world's requirements of glycerol could be produced from petroleum gas.

Wilson has estimated that there are 940,000,000 cubic feet per day, or 14,000,000 tons per year, of cracked petroleum gas available as raw materials for chemicals. Propane in a high degree of purity has been extracted from petroleum as a by-product and returned to the industry for use in solvent refining. He has pointed out that 18 years ago isopropyl alcohol cost $7 per gallon but today through conversion of propylene from petroleum to isopropyl alcohol the cost is only one-twentieth of the old cost. One company makes over one hundred chemicals from ethylene, propylene, and the butylenes, including 24 alcohols and alcohol ethers, 4 ketones, 23 esters, 14 amines, 8 ethers, and 7 chlorinated products. The olefins form the most important group of compounds in cracked refinery gas from the standpoint of chemical raw materials. Practically all isopropyl alcohol, secondary and tertiary butyl alcohols are made from petroleum gas. Most acetone now comes from utilizing petroleum, ethylene is chlorinated to ethylene dichloride for Thiodol, a synthetic rubber, vinyl chloride for resins, and acrylate and methacrylate resins.

Hill has pointed out that if all the ethylene available as a by-product of refining was converted to ethenol, the production in the United States would be over 300,000,000 proof gallons per year, or 50 per cent more than the present total production available from fermentation of grain and molasses.

Ten years ago iso-octane cost $30 a gallon. Today the cost is 1/100 of that amount and Kirkpatrick has estimated that in 1940 there will be produced 125,000,000 gallons of 100-octane aviation fuel.

The economic waste in by-product petroleum gases in the past has been enormous and Howe and Antwerpen have estimated the following quantities are available, which may largely be considered as waste in that they are not utilized for the purpose that yields the highest return.

2500 billion cubic feet natural gas
350 billion cubic feet crude oil distillation gas
350 billion cubic feet cracked gas.

Gabriel has reported one of the most interesting developments in the chemical field covering the research, commercial production, and utilization of the nitroparaffins and their derivatives. Since the original work of Dr. Hass in 1935 over 500 products and derivatives have been made, many of which will be in commercial production in the near future. The commercial products will include nitromethane, nitroethane, the nitropropanes, nitroalcohols, nitroglycols, aminonitril, aminoglycols, aminoalcohol, nitrohydroxy and aminohydroxy compounds. Many of these products have excellent solvent properties and are raw materials or intermediate products for organic chemical synthesis.

Padgett and Degener have indicated the possibilities of detergents in kerosene in the form of sodium alkyl sulfates from straight chain duodecane or the kerosene cuts.

Ohmer and Kern have made a valuable contribution in the manufacture of thioglycol. Their process is predicated on the production of ethylene oxide and hydrogen sulphide, which gives an intermediate in large quantities at low cost. Particularly at this time these possibilities are interesting from the military standpoint due to the fact that mustard gas or dichlordiethyl sulphide can be made from thioglycol.

Thomas, Zimmer, Turner, Rosen, and Frolich have made contributions to the synthetic resin field by polymerizing polybutenes at low temperatures to produce hydrocarbon polymers of high
molecular weight, which should find wide application as additive agents for petroleum products to improve the lubricating properties.

The field of plastics and synthetic resins offers one of the most interesting fields for the utilization of petroleum, and considerable commercial development has taken place in this field. These resins, being hydrocarbons, are acid-, alkali-, and water-resistant. They have found wide application in fields utilizing drying oils and, due to their low cost, have replaced in many instances higher-priced synthetics. Kirkpatrick\(^1\) has reported on the production of resins of high molecular weight produced by propene extraction from Pennsylvania oils. These resins will find widespread application in coatings, such as paints, varnishes, and enamels, as well as finders and adhesives.

A series of high-molecular-weight petroleum resins have been on the market for several years and are being used in about 30 different manufacturing industries. Chemically these resins are olefins of predominantly high molecular weight. Their drying, or curing, parallels drying oil in thin films exposed to the air. The drying is due to oxidation, but the primary advantage that they have is that they can be cured in certain applications by further polymerization entirely. This polymerization can be accelerated by the same driers as used with drying oils, even in the presence of an inert gas.

Most synthetic resins are soluble in the usual organic solvents, including high-solvency naphthas, and are compatible with most of the drying oils. Experience has shown that petroleum resins have two general faults as at present produced. These are the dark color and the brittleness or fragility of the cured resin. In the case of the color this is more apparent than real although the color is too dark for use in grinding vehicles for white or light-colored paints and enamels, for they yellow badly. The brittleness of the petroleum resins can be corrected by the use of plasticizers such as bodyd, either kettle-bodied or oxidized, drying oils or other plasticizing agents.

The successful development of light-colored flexible petroleum resins will open up a tremendous new market. The resins as known today are all thermoplastic, and research resulting in modifications that will produce thermosetting resins will broaden the field.

Scott and Walker\(^2\) have produced a new series of dihydro-naphthalene polymers by polymerization of the isomeric dihydro-naphthalenes with sodium naphthalene. From 1, 4-dihydro-naphthalene light-colored thermoplastic resins are obtained.

The rapid strides made the past few years in synthetic resins have created a steadily increasing demand for high-solvency naphthas to replace the more costly organic solvents. Straight-chain hydrocarbons have low solvency. Here again thermal and catalytic polymerization has indicated a solution. The production of aromatics from coal-tar is not keeping pace with industrial requirements and the petroleum industry must meet this shortage either by chemically producing them from petroleum or separating the high-solvency fractions from the crude.

The separation by distillation of very close fractions and hydrocarbons of high concentration has been established and will grow rapidly as they offer a reserve supply of basic or intermediate chemicals for the organic chemical manufacturer.

It is entirely beyond the scope of this paper to cover the entire field of technical references applying to the chemical utilization of petroleum, but a complete survey of the literature offers no difficult problems. The few references quoted serve to illustrate specific cases and to suggest further work. In conclusion, when the inherent properties of the Appalachian crudes are considered together with the refining processes in use in the Appalachian fields, the utilization of specialties and by-products from the reining of these crudes appear to have the greatest possibilities in the following fields:

1. Pure hydrocarbons
2. Solvents
3. Plastics.

References

Subsurface Studies in Connection with Deep Oil and Gas Sand Explorations in Pennsylvania*

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Attempts to discover deposits of oil and gas in western Pennsylvania in the more deeply buried formations, that is, those below the extensively drilled and relatively shallow Mississippian and Upper Devonian sands, have been made from time to time ever since the late eighties of the last century. The well of the Presque Isle Natural Gas Company, drilled to a depth of 4450 feet between October 1887 and January 1889 in the city of Erie, was one of the earliest of these. This well was reported to have penetrated the Trenton limestone to a depth of 170 feet and it is still the only well that has reached this formation in western Pennsylvania. The R. A. Geary well of Peoples Natural Gas Company, five miles northwest of McDonald, Pa., at the time it was abandoned at a depth of 7248 feet in strata of Salina age in the summer of 1917, was the deepest well in the United States and the second deepest in the world. In 1925, the same company’s Booth and Flinn No. 2 at McCance, Westmoreland county, also bottomed in the Salina formation, at a depth of 7756 feet, had the distinction of being the deepest well in the world.

Interest in the deeper sands was greatly stimulated by the discoveries of relatively large volumes of gas in the Oriskany sandstone in the Wayne-Dundee field in Schuyler county, New York, in March 1930, and in the Tioga field in Tioga county, Pennsylvania in September 1930. The extensive drilling campaign which followed has resulted in the development of seven Oriskany sand pools of commercial rank in north central Pennsylvania and one Oriskany sand and one Onondaga pool in the southwestern part of the State.

Three wells, to date, have reached depths greater than 8000 feet. The deepest of these, the Crawford Estate No. 1 of the Potter Development Company in Keating township, Potter county, was abandoned after having penetrated 310 feet of Queenston (Juniata) formation at 8482 feet. The upper 6090 feet were drilled with cable tools and the lower 2392 feet by the rotary method. F. C. Deemer’s W. H. Irwin Tract No. 1 well in Gaskill township, Jefferson county, reached a depth of 8227 feet before it was abandoned in strata of lower Salina age, and the Greensboro Gas Company’s John R. Thompson No. 1 in Wharton township, Fayette county, a depth of 8159 feet after it had penetrated approximately 140 feet of magnesian limestone, probably of Upper Silurian age. The latter two wells were drilled entirely with cable tools. The drilling of the Irwin well was started on September 18, 1924 and continued at intervals until September 13, 1931 when the well was finally abandoned because a liner set at the bottom collapsed. In contrast, the Thompson well was commenced on January 26, 1938 and completed on August 12, 1938.

Regional Stratigraphy

The present is an opportune time to study the subsurface stratigraphy of western Pennsylvania on account of the deep drilling for natural gas that is under way. While thus far the Oriskany horizon has been the principal objective, a considerable number of wells in the northwestern portion of the State have been drilled through the Medina and one of the earliest of the deep wells in the city of Erie, as already mentioned, reached the Trenton.
The writer, in recent years, as time permitted and material became available, has been studying samples of drill cuttings from deep wells in the western part of the State and immediately adjacent areas for the Pennsylvania Topographic and Geologic Survey. Thus far on account of the large number of samples involved, sometimes as many as one thousand to a well, attention has been confined largely to their general lithological characteristics. Texture, color, and mineral composition, in particular, have been noted. In the case of many of the limestones, examination with the hand lens and binocular microscope has been supplemented by qualitative analyses for calcium and magnesium and examination of the insoluble residues under both binocular and polarizing microscopes. While macro-fossils are abundant in certain beds, these in the cuttings, as a rule, are too fragmentary to be determined. Micro-fossils, if present, are not sufficiently conspicuous to be observed in the course of the ordinary routine observations. Subsurface correlations, therefore, have had to be based largely upon lithologic characteristics and stratigraphic sequence. Fortunately, almost all of the deep wells in Pennsylvania have been drilled with cable tools. This has made it possible to determine the boundaries of the various beds penetrated within comparatively narrow limits.

The sections show the succession of strata and their thicknesses in as much detail as the scale permits. They have been lined up with respect to sea-level.

Throughout northwestern Pennsylvania the base of the Medina series (restricted) is readily distinguished from the underlying Queenston red shale. The Medinan or Lower Silurian series retains pretty much the characteristics of the western New York section. The gray-to-white Whirlpool sandstone member at the bottom and the red Grimsby member at the top are both present. In places the "Gray band" or Thorold sandstone also occurs immediately above the red member.

Along the outcrop southeast of the Allegheny front in central Pennsylvania, the Queenston red shale is represented by the Juniata formation, the gray-to-white or Whirlpool member of the Medinan series becomes the Tuscarora sandstone, and the attenuated edge of the red or Grimsby member is represented by the Castanea sandstone.
The Niagaran or Middle Silurian series is represented by the Clinton group and the Lockport dolomite. The upper part of the Clinton group, the Rochester shale, becomes dolomitic in western Pennsylvania. The Lockport dolomite thickens and constitutes a readily recognizable horizon throughout northwestern Pennsylvania. It consists of a very fine, crystalline, brownish-gray to very dark grayish-brown relatively pure dolomite. The Cayugan or Upper Silurian series is represented by the Salina formation. The Salina, as developed in western Pennsylvania, consists of a series of interbedded, dense, argillaceous, magnesian limestone ranging in color from light gray to dark grayish-brown, and gray shales and clays, for the most part either calcareous or dolomitic. Beds of anhydrite and salt are abundantly present at least as far east as eastern Tioga, Jefferson, and Westmoreland counties. A magnesian limestone occurs at what has been taken as the upper limit of the Silurian system. It is thought that this may represent the Cobleskill limestone of western New York. In the well sections, it has been included with the Salina.

It is difficult to draw the line between Silurian limestone and limestone belonging to the Helderberg group from sample studies. The former usually is magnesian and nonfossiliferous. Anhydrite appears a short distance below the top. The latter is nonmagnesian, in part cherty, and frequently very fossiliferous.

Representatives of the Helderberg group probably underlie most, if not all, of western Pennsylvania. This and the Oriskany group comprise the Lower Devonian series. The upper or Ridgeley sandstone member of the Oriskany group, usually referred to as the Oriskany sand or sandstone, the principal objective of the deep drilling, with the exception of two areas—one marginal and the other inside the main area of deposition—apparently underlies all of Pennsylvania west of the Allegheny front. Whether or not the Shriver or lower member is also represented has not been established.

The interval between the top of the Oriskany group and the top of the Medinan series is that portion of Pennsylvania thus far explored with the drill, and thickens considerably in a southeasterly direction, as shown on the isopach map of Fig. 3. The rate increases from northwest to southeast and is particularly rapid at the northeastern end of the explored area. In the Crawford Estate No. 1 well of the Potter Development Company, in southwestern Potter county, the interval is 2940 feet, while in the United Natural Gas Company's No. 3737 well, Warrant 3788, in northwestern Elk county, it is only 1676 feet and in the Derrick City deep well in northern McKean county, only 1425 feet. Although it was not possible to determine definitely the boundaries of the Upper and Middle Silurian series from the rotary drill cuttings obtained from the well, it is thought that considerable part of the increase occurs in the Salina formation. Deep drilling, both to the northeast and the southwest, indicates that the well is located in a deep portion of the former Salina basin. The L. E. Shoemaker No. 1 well of the Lycoming Natural Gas Company at the northeastern edge of the Tioga pool penetrated 3218 feet of strata below the top of the Oriskany without reaching the bottom of the Vernon red shale, the lower member of the Salina. Part of the abnormal thickness in the case of the latter well probably is due to an upward flow of the relatively incompetent Salina beds beneath the more competent but much thinner uppermost Silurian, Helderberg, and Oriskany beds beneath the Sabinsville anticline. Possibly the same condition exists in the case of the Crawford Estate well. There is also a possibility that the well may have intersected a fault between the Oriskany and the Medina, which has produced some repetition of strata in the interval measured.

The Middle Devonian series includes the strata between the top of the Oriskany sandstone and the base of the Tully limestone, namely, in ascending order, the Onondaga limestone and the Hamilton group. The Onondaga apparently underlies all of western Pennsylvania, although in the Bellefonte quadrangle section, it is reported to be absent. In Tioga county, it is relatively thin, 10 to 20 feet. The Onondaga limestone thickens in a northwesterly, westerly, and southwesterly direction and for the most part is
decidedly cherty. In Erie county, thicknesses as great as 290 feet are attained and in Washington county, 220 feet. In Fayette and Westmoreland counties considerable portions of it consist entirely of chert with interstratified dark silty, shaly, and glauconitic layers. A thin but persistent seam of brown micaceous shale with abundant pyrite at the top of the Onondaga has been traced from Tioga to Fayette county.  

The Middle Devonian series thins in a northwesterly direction across western Pennsylvania, as shown on the isopach map of Fig. 4. The rate is most pronounced in north central Pennsylvania, still considerable in southwestern Pennsylvania, and more gradual in the northwestern part of the State, where minimum thicknesses apparently occur in Mercer county.

The Tully limestone at the base of the Upper Devonian series has proven to be an excellent key horizon throughout a large part of western Pennsylvania. This limestone, first recognized as being prominently developed in Pennsylvania through examinations of drill cutting samples from the Tioga field, has its greatest thickness on the outercop in Clinton and Lycoming counties, where it consists of more than 200 feet of limestone. It was the encountering of an open flow of 3,500,000 cubic feet of gas per day in the upper part of the Tully in a well on the Gilbert farm, two miles north of Richburg, in the town of Wirt, Alleghany county, New York, by the Belmont Quadrangle Drilling Corporation in September 1928 that inaugurated the recent extensive deep drilling campaign in the northern Appalachian province. In spite of the hundreds of wells that have passed through the Tully limestone since that time, the well remains unique in that it has been the only commercial producer from this horizon.

The Upper Devonian series includes all of the strata between the base of the Tully limestone and the base of the Mississippian system. The exact position of the Devonian-Mississippian boundary in western Pennsylvania has long been and is still a mooted question. Along the Allegheny front the top of the Catskill red beds has been considered to represent the top of the Devonian. In McKean county, Caster's paleontological studies indicate that the base of the Mississippian occurs at the base of the Knapp formation. In this area about 200 feet of gray marine shale and sandstone occur between the base of the Knapp and the top of the Cattaraugus red beds. In Venango county, in the vicinity of Franklin, 125 feet of dark reddish-brown to purplish-gray shale immediately overlie the Venango First sand. The top of these red beds
lies 60 feet below the base of the Corry or Berea sandstone. If the Venango First sand has been correlated correctly with the Tuna or Kilbuck conglomerate at the top of the Cattaraugus red beds at their type locality, the red beds at Franklin are higher stratigraphically than the Cattaraugus and their top probably represents very nearly the top of the Upper Devonian series as now placed along the Allegheny front. These red beds have been traced in well sections westward almost to the State line in Lawrence and Mercer counties. In Fayette county, on the other hand, the red beds do not reach to the top of the Devonian. In the well sections obtained at Summit, Fayette county, the writer has tentatively placed the base of the Mississippian at the base of a prominent sandstone containing conglomeratic layers which occurs about 200 feet above the top of the red beds. In Beaver county, the bottom of a sand below the Berea, known as the Gas sand, which seems to correlate with the Butler county or Murrysville sand to the east, has been tentatively selected as the base of the Mississippian system.

The Upper Devonian series represents the major portion of the interval which has to be penetrated to reach the deeper sands. The series thins relatively rapidly in a northwesterly direction, as shown on the isopach map of Fig. 5. In the northern tier of counties, most of the deep wells have started in the upper part of this series. The splitting of this thick series into subdivisions and correlating these with their equivalents in outcrop sections in adjacent territory, will require the careful study of a greater number of closely spaced well sections, obtained through the examination of drill cuttings, along lines running from southeast to northwest and northeast to southwest. A large percentage of the important oil- and gas-producing sands of western Pennsylvania occur in the upper one-half of the Upper Devonian series. Completion of work on their proper correlation will go far toward unravelling the stratigraphy of the Upper Devonian.

The Mississippian system comprises the strata between the base of the Knapp formation and the base of the Pottsville sandstones of the Pennsylvanian system. A pronounced erosional unconformity exists at the contact of the Pennsylvania and Mississippian systems, which bevels successively younger and younger southerly dipping Mississippian strata in going from north to south across western Pennsylvania. In northern McKean county, Pottsville (Olean) sandstone rests upon the lower 65 feet of the Knapp formation, the lowest member of the Mississippian system; while in Fayette county, the Pottsville overlies the Mauch Chunk red shale, the highest member. In Washington county, the Mississippian system is represented by from 600 to 650 feet of strata and the Pennsylvanian by 1280 feet. In the extreme southwestern corner of the State in Greene county, in places 1000 to 1200 feet of Pennsylvanian beds overlie the Pennsylvanian.

Regional Structure

Structurally, western and north central Pennsylvania are part of the northeastern one-half of the Appalachian Plateau synclinorium. This is a broad asymmetrical and complex structural trough whose long axis trends northeast and southwest, with the steep limb on the southeast side. The central part of the trough, in southeast Ohio, southwest Pennsylvania, and northwest West Virginia, is floored with beds of Permian age which are surrounded by outcrops of Pennsylvanian beds. Mississippian, Devonian, Silurian, and older strata crop out in sequence along the western, northern, and eastern margins.

On the southeast the trough terminates a short distance south of the Allegheny front, where it adjoins the closely folded Appalachians. Superimposed upon this broad structural trough are a series of minor folds with axes trending approximately parallel with the long axis of the trough. On the southeast limb these consist of strong well-defined anticlines and synclines, but northwestward the intensity of folding diminishes so that the folds become less prominent in the central part of the trough and are hardly perceptible on the northwestern limb.

The regional structural features of the northern Appalachian plateau, as outlined above, have been recognized for a long time. Deep drilling, particularly in north central Pennsylvania and immediately adjacent parts of New York in addition, has revealed that the folds which are superimposed upon the eastern limb of the synclinorium in depth are much more complex structurally than had been conceived from the earlier surface mapping. It has been found that extensive, usually north or northwest dipping, reverse faults intersect and frequently complexly modify the outlines of the more prominent domes along the anticlinal axes. The faults, for the most part, have strikes approximately parallel with the axes of the folds intersecting them at only slight angles. Some of them have throws of at least 700 feet. Recent drilling indicates that the Summit dome along the Chestnut Ridge anticline east of Uniontown, in Fayette county, is probably intersected by a similar fault on its southeast flank.

Deep Oil and Gas Horizons of Pennsylvania

Thus far only two formations older than Upper Devonian have yielded gas in commercial quantities in western Pennsylvania, namely, the Oriskany and the Onondaga, and none have produced oil. Both oil and gas in large quantities, however, have been obtained from several formations below the Oriskany in the adjacent states of Ohio and New York. Inasmuch as these are known to underlie western Pennsylvania also, they are worthy of consideration as possible sources in this State. These deep proven and potential oil and gas horizons will be discussed in descending order.
encountered in the chert a short distance below the gas-bearing zone. Booth and Flinn No. 2, located about 500 feet from No. 1, encountered only a show of gas and no water in this zone. Although these wells are located on the Chestnut Ridge anticline, they are not favorably situated with respect to the domes along its axis.

Wm. E. Snee and Potter Development Company’s Indiana Savings and Trust No. 1 well on the Laurel Hill anticline in Fairfield township in eastern Westmoreland county also encountered an open flow of about one-half million cubic feet of gas per day in the cherty Onondaga formation. A little salt water entered the well from the lower part of the formation. After the Oriskany sandstone had been penetrated, the flow of water increased greatly.

The Summit pool is located on the crest of an elongated dome along the axis of the Chestnut Ridge anticline with a closure of approximately 1000 feet as mapped on the surface beds. At this locality, the uppermost 3 to 30 feet of the Onondaga formation consist of a dense, very dark brownish-gray argillaceous limestone. The rest of the formation is made up largely of a light-to-dark brownish-gray chert in part silty and to a considerable extent noncalcareous. In the lower portion, considerable dark brownish-gray to black shale occurs interbedded with the chert. Occasional glauconitic zones are present. The total thickness of the formation ranges from 184 to 199 feet.

The first gas is obtained anywhere from 40 to 70 feet below the top of the formation, and the flow increases at intervals until the bottom is reached. Several of the wells have not been completed through the entire thickness. Unfortunately, no cores of the pay portions of the Onondaga have been obtained and the drill cuttings are too fine to yield any definite information in regard to the nature and amount of the pore space. Some of the silty chert particles appear to contain minute pores. Occasionally some show slickensides and others are intersected by minute quartz veinlets, both of which suggest a certain amount of fracturing and the existence of minute crevices. It seems probable, therefore, that the pore space is partly primary and partly secondary. The permeability must be relatively low, as the initial open-flow capacities of the wells are low when compared with the Oriskany sand wells of north central Pennsylvania and south central New York.

It is not likely that the Summit pool represents the only occurrence of commercial quantities of gas in the Onondaga formation. Other prominent domes along strong folds, such as the Chestnut Ridge and Laurel Hill anticlines in the area in which the Onondaga retains its cherty character and sufficient thickness, can be looked upon as favorable territory to prospect. Since it is highly probable that the Onondaga acts only as a suitable reservoir rock where it is creviced due to fracturing, the weaker folds to the northwest of the Chestnut Ridge anticline are less likely to
contain commercial quantities of gas. The John Marshall well of the Peoples Natural Gas Company, located on a prominent dome along the Grapeville anticline in Penn township, Westmoreland county, encountered no gas in the Onondaga, although the formation was 205 feet thick and had very much the same characteristics as at Summit.

**Oriskany Sandstone**

With the exception of two areas, the Oriskany sandstone apparently underlies all of Pennsylvania west of the Allegheny front. One of the areas in which it is missing is marginal, as shown on the map of Fig. 7. This embraces portions of southeastern Erie, northeastern Crawford, northern Warren, and northwestern McKean counties. Within the main area of sandstone, drilling has outlined only one large area in which the Oriskany sandstone is probably absent. This includes considerable portions of middle and western Potter, southeastern McKean, and northwestern Cameron counties, most of Elk, Forest, and Clarion counties, and large parts of northwestern Jefferson, northeastern Armstrong, and southeastern Venango counties.

The greatest thicknesses northwest of the Allegheny front have been encountered in Tioga county, where some wells were drilled through as much as 60 feet of sandstone at the Oriskany horizon and in Fayette and Washington counties, where thicknesses of 95 to 110 feet occur. In the latter two counties, however, most of the sandstone is calcareous and portions of it consist of sandy limestone rather than true sandstone.

The major Oriskany gas developments in Pennsylvania have been confined to northern Tioga and Potter counties. Northwest of the Allegheny front in north central Pennsylvania, the Sabinsville anticline, the fourth of the prominent folds in that direction, distant about 40 miles from the front, is the first one along which commercial production has been obtained. The Sabinsville and Tioga fields are located along it about 10 miles apart. One pool in Pennsylvania, the Harrison, has been developed along the Harrison anticline, the next anticline northwest of the Sabinsville. Along the Hebron anticline, the next northwest of the Harrison, two major pools, the Hebron and the Ellsburg, and three minor pools have been opened up. Along the Smethport anticline, the next northwest of the Hebron, two fields, the Sharon and the State Line, have been developed. The major portion of the latter, however, lies in New York state. Each of the above fields occurs on a well-defined dome, in some instances complexly modified by faulting. Although a number of tests have been made on equally well-defined structures along the anticlines southeast of the Sabinsville in Bradford, Tioga, and Potter counties, none of them has produced. The Oriskany sandstone was found, but it was so tightly cemented and recrystallized that it was no longer capable of acting as a reservoir rock for the retention of fluids.

Exploration along the Sabinsville, Harrison, Hebron, and Smeth-
Fig. 7.—Oriskany sand gas development in Pennsylvania.
port anticlines has extended into the area in which the sand is absent. There is, therefore, little likelihood that any additional pools of the rank of those already developed remain to be discovered in the Oriskany sand in north central Pennsylvania. The discoveries of additional reserves of gas in this area, if any, will be confined largely to the borders of the fields already developed where some detached fault blocks with sufficient closure may still remain to be discovered.

In western Pennsylvania, the South Beaver gas pool in western Beaver county is the only one that has been developed thus far in the Oriskany sandstone. The discovery well in this pool was located on a low dome discovered by contouring the top of the Berea sand. This dome, which had a closure of from 20 to 30 feet on the top of the Berea sand, showed some closure when projected onto the Oriskany sandstone after making allowance for the convergence between the two horizons. Later drilling revealed an effective closure of about 20 feet on the top of the Oriskany. Although good shows of oil have been encountered in the Oriskany in several wells in Beaver township, northwestern Crawford county, no commercial production has been developed. Slight shows of oil have been reported also in two of the three wells drilled through it on the Knapp Creek dome in the Bradford field. It will be noted on the map of Fig. 7 that a number of other wells in northwestern Pennsylvania have encountered shows of gas and many of salt water in the Oriskany.

Although the results obtained to date in western and northwestern Pennsylvania have not been encouraging, the possibilities of the area cannot be considered to be exhausted. The existence of a body of sandstone at the Oriskany horizon which retains a fair percentage of porosity, as witnessed by the amounts of salt water encountered in it, is the factor most favorable to the possible occurrence of commercial quantities of gas and possibly oil. The most important question, however, is whether or not there are structures present that acted as traps and brought about a segregation from the associated salt water of gas and oil migrating up the monoclinal slope. In the area in which sand conditions appear to be favorable, such structures are most likely to be present in Beaver, northwestern Allegheny, Lawrence, western Butler, and southern Mercer counties. In this area, good key horizons are available for surface mapping, and in portions of it a sufficient number of shallow wells have been drilled to permit contouring on shallow oil and gas sand horizons. Finally, the top of the Onondaga limestone affords an excellent horizon for subsurface mapping by the reflection seismic method. Although surface structure maps of considerable parts of the area have been published, it is doubtful whether these are sufficiently detailed to reveal all the significant features. In order to be considered favorable, a structure must show some closure when projected onto the Oriskany. This need not be very great, however. Twenty to thirty feet sufficed in the case of the South Beaver pool.
Good shows of gas have been obtained in the top of the Oriskany in one well in western McKean and in two wells in eastern Warren county which were drowned out by salt water. There is a possibility that a small commercial gas pool may be present in this area up the dip from the wells drilled inasmuch as the sand feathers out in that direction. This may have formed a stratigraphic trap for such an accumulation.

In southeastern Pennsylvania in Fayette, Westmoreland, and Washington counties tests completed to date have shown the Oriskany sandstone to possess thicknesses of from 70 to 100 feet. It was found to be so tightly cemented, however, by calcite and secondary quartz that it did not constitute a suitable reservoir rock for the retention of fluids. Considerable portions consist of a sandy limestone rather than a true sandstone. Two core samples from the upper four feet in the John Marshall well of the Peoples Natural Gas Company in Penn township, Westmoreland county, possessed porosities of only 1.5 per cent and two similar samples from the upper 10 feet in the same company's Piedmont Coal Company No. 1 well in the Summit pool, Fayette county, 1.5 and 1.6 per cent respectively. Although it was reported that some additional gas was obtained after the J. H. Sorg No. 1 well in the Summit pool had penetrated the upper five feet of the Oriskany sandstone, it is likely that the observed increase came from the lower part of the Onondaga. Two other wells in this pool that have penetrated the Oriskany apparently obtained no additional production in it. On the other hand, in the Snee and Potter Development Company's Indiana Savings and Trust well No. 1 in the Laurel Hill anticline in eastern Westmoreland county, a large flow of salt water was encountered in the upper 3.5 feet of the Oriskany sandstone. Drilling was discontinued after 7 feet of sandstone had been penetrated.

Lockport Dolomite—Newburg Sand

Gas and some oil were discovered in 1911 in a granular, porous dolomite in the Niagara limestone, which corresponds closely in geologic age to the Lockport dolomite of western New York and northwestern Pennsylvania, at South Newburg in the southern part of Cleveland, Ohio. This horizon has since been called the Newburg "sand." In Ohio, the Newburg has yielded good flows of gas in Cuyahoga and Summit counties, but only minor quantities of oil. Scattered production of small volume is found at this horizon across the state from Lake Erie to the Ohio River.

In Pennsylvania in the R. C. Jamison well in South Shenango township, Crawford county, a little gas and a good show of oil were encountered at a depth of 4080 and 4096 and considerable salt water between 4115 and 4211 feet in the Lockport dolomite. The top of the dolomite occurs at about 3925 feet and it is 285 feet thick. This horizon probably corresponds rather closely to the Newburg of Ohio. Small shows of gas in the Lockport have been reported in several other deep tests in Crawford county, and most of the wells drilled through the Lockport in Erie, Crawford, Mercer, and Warren counties have encountered considerable quantities of salt water in it. There has not been an opportunity thus far to examine a sufficient number of complete sets of drill cutting samples to determine whether occasionally associated shows of gas and oil always occur at the same stratigraphic horizon or not. In most cases it is impossible to pick the top of the Lockport from the drillers' records.

The Lockport can be considered to offer some possibilities as a potential source of gas and possibly oil in northwestern Pennsylvania. As in the case of the Oriskany, a favorable structure was necessary for any commercial accumulation to have taken place.

Medinan Series

The sandstones of the Medinan series have been a great source of gas in western New York and central Ohio. In central Ohio some oil has also been obtained from them. The Medinan series, therefore, has been the objective of a considerable number of the deep tests undertaken in western Pennsylvania. As shown on the map of Fig. 8, wells have reached it in Erie, Crawford, Mercer, Beaver, Warren, McKean, Elk, and Potter counties. While no gas
or oil pools have been discovered in it thus far in northwestern Pennsylvania, a fair show of gas has been encountered at several widely separated localities. In the F. J. Miles well of the Netherlands Gas and Fuel Company in Springfield township, Erie county, an open flow of about 600,000 cubic feet per day was reported in 1932. A little water occurred below the gas. An offset well encountered only 55,000 cubic feet. The Chauncey Blount well of the Wittmer Oil and Gas Corporation and Mellon-Pollock Oil Company in McKean township, same county, encountered an open flow of 75,000 cubic feet natural which increased to 1,250,000 after a shot but soon exhausted itself. In the UIL well of the Fidelity Petroleum Corporation at Tidioute in Warren county, approximately 15,000 cubic feet of gas per day was encountered in the red member and 100,000 cubic feet in the white member, and in the James Naylor Lands well of the United Natural Gas Company in Vernon township, Crawford county, approximately 30,000 cubic feet in the white member. Smaller shows of gas and small quantities of salt water have been reported in several other wells in Erie, Crawford, and Warren counties.

The Medinian series in northwestern Pennsylvania occupies the northwestern limb of the Appalachian structural trough. It will be observed (Fig. 8) that while the regional strike is essentially parallel to that of the overlying Oriskany (Fig. 7), the series dips more steeply toward the southeast because the intervening beds thicken in that direction (Fig. 9).

The important Medina pools occur in a broad arcuate belt which extends across western New York and central Ohio. The belt starts in Ontario county, New York, extends west to the shores of Lake Erie, where it swings southwest and in the form of a great arc continues underneath the lake to enter Ohio in the vicinity of Cleveland. From thence, it continues across middle Ohio south almost to the Ohio River. South of the main belt in New York and east of it in Ohio, extensive prospecting has resulted in the opening of a few scattered pools of relatively minor importance. The main belt of Medina pools misses Pennsylvania, as it lies a short distance to the northwest under the waters of Lake Erie. Erie, Crawford, and northwestern Warren counties, however, are as favorably located with respect to it as are areas in New York and Ohio in which local production has been encountered in the Medina.

The Medinian series constitutes the lower division of the Silurian system in the Appalachian area. Its deposition followed the Taconian disturbance which raised the land along the eastern border of the Appalachian geosyncline high above sea-level. Great alluvial fan and flood plain deposits were spread out over the Appalachian geosyncline along its eastern border which stood slightly above sea-level at the time. The belt of Medina sand pools marks the approximate shore line where these continental sediments intertongue with the marine. In this belt the Medina represents a shore line deposit. Variations in porosity, texture, permeability, as well as lensing and lateral gradations, were the important factors in the accumulation of the gas and oil. Structure played only a secondary role. The Medina underneath much of western Pennsylvania was deposited under a different environment than that of the productive areas in New York and Ohio. This makes the potential possibilities of this horizon appear doubtful.

**Trenton Limestone**

Large quantities of oil and gas have been obtained from the Trenton limestone of Middle Ordovician age in the Lima-Indiana field in northeastern Indiana and northwestern Ohio. No production of consequence, however, has been discovered in the Trenton limestone in Ohio outside the above-mentioned field. In New York, gas flows, relatively small but of sustained volume, have been found in the Trenton limestone in Lewis, Oneida, Onondaga, and Oswego counties in the central part of the state.

All of the above occurrences are far from western Pennsylvania and hence afford little information about the possibilities of finding commercial quantities of gas or oil in the Trenton limestone in this area. The Trenton horizon probably is represented by a limestone. Whether any of it is sufficiently porous to have acted as a reservoir rock for the accumulation of gas or oil, is problematic. The deep tests to this horizon in New York, Ohio, and West Virginia, nearest to western Pennsylvania, have not been encouraging.

**References**


**DISCUSSION BY DR. R. E. SHERRILL, Professor of Oil and Gas Geology, University of Pittsburgh, Pittsburgh, Pa.*

It is generally recognized that an understanding of the sub-surface stratigraphy is fundamental to the success of oil and gas exploration. It is difficult, therefore, to overemphasize the importance to our search for deep production in Pennsylvania of

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stratigraphic studies on well samples of the type described by Dr. Fettke.

Stratigraphic relations are usually more complex than at first appears and this is true in Pennsylvania. It is also true that stratigraphy and structure are closely related, and that we cannot fully determine the tectonic history except as our knowledge of the stratigraphy is complete.

For many reasons I am of the opinion that the structures of western Pennsylvania were periodically folded during the Paleozoic and that we must appreciate and apply this if our deep exploratory program is to be successful. We cannot determine all the periods of folding nor evaluate their intensity, however, except through stratigraphic data. On the other hand, a lack of appreciation of the probability of recurrent folding may readily lead to incorrect stratigraphic conclusions. Numerous instances of this occurred during the earlier development of the Mid-Continental oil fields.

I have been asked to include in this discussion a brief consideration of the work of the State Geological Survey on the old shallow oil and gas pools of the State. The purpose of this shallow-sand survey is to determine as minutely as possible the subsurface distribution, character, thickness, structure, and content of the productive or potentially productive sand bodies. It is felt that, in addition to preserving the data still available, such a survey may assist in the selection of areas for additional oil recovery, in the development of these areas, in the estimation of reserves, and in locating new shallow and deep pools.

In this work every available well's record is collected, each well located on a 4-inch to 1-mile topographic map and the well elevations determined. Where possible, samples of the strata penetrated are collected and studied and core records are assembled.

Two quadrangles—the Hilliards and the Tidioute—have been completed and published as advance reports. Two more quadrangles—the Titusville and the Franklin—will be completed early this summer, and it is hoped to finish the Middle District by the fall or early in 1941. The plan is to assemble, correlate, and interpret all the data and to prepare a complete report on the Middle District. Except for the Bradford pool, no part of Pennsylvania has previously been geologically surveyed in such detail. It is necessarily a slow procedure but it has become increasingly clear that it must be as detailed as possible if it is to be reliable.

These are stratigraphic pools, hence sand-thickness and trend maps are the most readily applicable in suggesting favorable undrilled areas. In their interpretation the origin of the sand bodies and their relation to the ancient seas in which they were deposited should be borne in mind. The data thus far assembled indicate that most of the sand bodies were deposited as off-shore bars separated by lagoons from the shore to the southeast. Some of the sands—notably the First—appear to represent deposition in stream channels and in tributaries at the front of deltas.
In recent years, particularly since drilling below 5000 feet became common, a number of fields that produced small quantities of distillate were discovered and more or less abandoned as gas fields with no market since there was, in most cases, no demand for the gas. Few producers realized that these fields could, if properly operated, be very profitable.

The phenomenon of retrograde condensation which results in production from these so-called distillate wells is very important in studying what happens in these reservoirs. Consider a field in which the pressures and temperatures are high enough that all the fluid is in the vapor state. It is an immense advantage to have the crude in a vapor state because the percentage of recovery from this field, if properly operated, can be extremely high. It can be seen from Fig. 1 that, in order to keep the crude in vapor state, all that is necessary is to maintain the pressure above the point at which condensation begins. If the pressure is allowed to drop and the liquid condensed, a large portion of it becomes irrecoverable because it will wet grains of sand and will not flow into the well bore.

It naturally follows that the way to maintain this pressure is to recompress the gas and return it to the sand. For the most economical recovery, the liquid should be extracted from the gas at the highest possible pressure so that the minimum amount of horsepower will be required to return the gas to the sand. Again referring to the curve, it will be seen that this pressure will be the retrograde point or approximately 1000 pounds. The operation of a distillate field essentially consists of reducing the pressure to the retrograde point and the lowest reasonable temperature, extracting the fluid and returning the remaining gas to the formation.

The amount of distillate recovered per 1,000,000 cubic feet of gas processed is the criterion of whether or not the operation would be financially profitable. This determines the amount of production that will constitute the revenue from the field against which must be deducted the costs of drilling, recovery plant, and maintenance.

The first matter to be settled once the distillate field is drilled in is to determine the quantity of distillate that can be produced, to determine the fluid ratio, the optimum working pressures, and the pressure to which it will be necessary to recompress the gas to return the residue gas to the formation.

The curves which will be shown are the plotted test data showing the performance of a distillate well in East Texas. The bottom-hole pressure in this field was 2334 pounds per square inch. It was found that, to return 10,000,000 feet a day to the formation, a differential pressure of 150 pounds per square inch was required. However, due to the density of the column of gas over a mile high and the pressure exerted by the weight of this column, the compressor discharge pressure was 2225 pounds. Semiportable equipment for test purposes, large enough for full-scale operation, was moved in on the lease and all the equipment necessary for meas-
A hypothetical case of retrograde condensation characteristics of a hydrocarbon system.

Fig. 2—A hypothetical case of retrograde condensation characteristics of a hydrocarbon system.

Fig. 3—Effect of first stage separation temperature and pressure variations upon the specific gravity of vent gas.

Fig. 4—Effects of first stage separation temperature and pressure variations upon natural gasoline content of the residue gas.

The effect of retrograde condensation and the need for the lowest possible operating temperature for the maximum recovery of liquid. During these tests, the specific gravity of the gas was measured because the lower the specific gravity the drier the gas; in other words, the greater the quantity of the heavy hydrocarbons removed.
The tests of the vent gas, such as shown in Figs. 4 and 5, although they do not yield any design data, do definitely confirm results of the tests on the accumulation of liquid.

In gasoline-plant practice, the usual method of determining the efficiency of extraction is to measure the gasoline content of the residue gas by the charcoal method.

Fig. 6 is a plot of the gasoline content of the residue gas from the separators, showing definitely that at the retrograde point the maximum amount of fluid is removed from the gas. This curve also helps to determine the actual location of the retrograde point as it shows a much steeper curve than the other forms of plotting data. This shows that 1100 pounds would be a very good pressure at which to operate.

Fig. 7 shows the amount of liquid accumulated in barrels per million cubic feet at the various pressures and temperatures. It illustrates the trend toward greater recovery at low temperatures but does not, as would normally be expected, give very much information about the location of the retrograde point, consequently, the need for the other tests.

The measurements conducted with this test give sufficient information to allow the plotting of the gas solubility, and Fig. 8 shows the number of cubic feet per barrel at various pressures and temperatures. The effect of retrograde condensation is, again, apparent. The liquid produced by retrograde condensation, not only includes the more desirable heavy hydrocarbons but contains in solution large quantities of propane, ethane, and methane which are undesirable and which must be stripped from the gas to make a salable product. Normally this would be accomplished
by means of a stabilizer but, in some cases, the stabilizer is ineffective due to the large quantities of methane in the solution. It has been found that stage trapping is nearly as efficient and considerably cheaper. Combinations of stage trapping and stabilizers are also used. Having determined the quantity of fluid that may be recovered, the next step is to find out how much of this fluid will remain to be pumped into the pipe line after the undesirable parts have been removed.

Fig. 9 is a plot of the percentage of recovery by a single-stage and three-stage trapping and the effect of the storage pressure on the recovery. It is obvious that single-stage flashing is undesirable, as it is apparent that in removing the lighter hydrocarbons some of the more desirable components also are carried away. This curve also illustrates that lowering of the recovery temperature, while it increases greatly the gross recovery of distillate, does not necessarily recover the maximum amount of net distillate because of the lower temperature condensing greater proportions of the lighter components, chiefly propane and methane. This is a fact that must be very carefully looked into in determining the economics of the case.

Having conducted the tests, the next step is to design the recovery plant. The tests show specifically that a mean pressure of about 1050 pounds will give the optimum results. The next step is to determine the operating temperature. Because of the danger of freezing due to formation of hydrates which at 1050 pounds are liable to form at any temperature below 65 degrees, this would be a minimum temperature at which the plant could operate unless some method is used for removing the moisture from the gas. It is also the lowest temperature which would normally be expected without resorting to mechanical refrigeration.
This question is again entirely one of economics and cannot be determined by ordinary field tests, but it is necessary to take samples of the gas and make fractional analysis and determine by calculation whether or not the increased recovery due to lower temperatures will pay for the additional equipment required. The general consensus at present is that mechanical refrigeration and drying are necessary parts of a complete recovery system. Another method for recovering higher percentages from the gas is the use of absorption, which will probably be the most useful method in the future due to its ability to give high recoveries at pressures above the retrograde point.

The majority of the plants installed have been without refrigeration primarily because of the simplicity and low investment. The most common method in use today where refrigeration is used is a process in which calcium chloride brine is used both as a refrigeration agent and an inhibitor of hydrate formation. In the experimental plants, this process has worked at temperatures as low as plus 10°F. Several articles have been published recently describing the results obtained.

The plant for the recovery of distillate is relatively simple although it involves the compression of gases at high pressures. The pressures being handled are no longer considered excessive and it is merely necessary to be careful in the design to make sure that sufficient strength is available in all the materials and that the proper safety precautions are taken.

Having discussed the proper procedure in the developing and operating of a distillate field, it might be well to consider what will happen in an improperly developed field. A classical example of how to ruin a distillate field is illustrated in Patten and Ivey's discussion of this problem. They have plotted the data on a sand in the LaBlanca field in South Texas. In this sand the condensate content of the gas at 3800 pounds per square inch was 9 barrels per 1,000,000 feet. Due to blowing gas in the air, both accidentally and wastefully, the pressures declined to 2180 pounds at which pressure the condensate contained in the gas is only 2.6 barrels per 1,000,000 feet because retrograde condensation has reduced the content of the gas to this extent. It originally was estimated that at 4200 pounds, the initial field pressure, the gas contained approximately 18 barrels per 1,000,000. Because of failure to maintain the original pressure in these fields, it is estimated that 82 per cent of the original content will be lost due to retrograde condensation.

The operation of distillate fields is the highlight of discussion in the production industry today because:

First—Distillate type crude has a market premium.

Second—Being classified as gas wells, they are not subject to rigid proration.

Third—The possibility of long life and quick payout makes it interesting from a financial standpoint.

Fourth—Unusually high recoveries can be expected.

Fifth—Even after depletion of the liquid content, an immense reservoir of marketable fuel is available.

Sixth—It is distinctly possible that with the increased efficiency in treating lighter hydrocarbons to recover high-grade gasoline, that the future development of distillate fields may become even more important than it is today.

Wells in Eastern United States

In the eastern part of the United States, the outstanding distillate field has been the Oriskany sand area around Charleston, West Virginia. The gases from a number of wells in this area have been analyzed by the West Virginia Geological Survey and all these analyses show relatively large quantities of pentane, hexane, and heptane. Two analyses, the first taken on April 29, 1936, and the second on August 7, 1936, on the same well show a change in the proportion of the heavy components as time goes on:

<table>
<thead>
<tr>
<th>WELL</th>
<th>No. 423A</th>
<th>No. 423B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>82.11</td>
<td>84.35</td>
</tr>
<tr>
<td>Ethane</td>
<td>7.53</td>
<td>6.61</td>
</tr>
<tr>
<td>Propane</td>
<td>2.54</td>
<td>2.04</td>
</tr>
<tr>
<td>Isobutane</td>
<td>.13</td>
<td>.17</td>
</tr>
<tr>
<td>Normal Butane</td>
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<td>.61</td>
</tr>
<tr>
<td>Isopentane</td>
<td>.12</td>
<td>.15</td>
</tr>
<tr>
<td>Normal Pentane</td>
<td>.25</td>
<td>.21</td>
</tr>
<tr>
<td>Disopropyl</td>
<td>.02</td>
<td>.00</td>
</tr>
<tr>
<td>Dimethylpropylmethane</td>
<td>.06</td>
<td>.08</td>
</tr>
<tr>
<td>Normal Hexane</td>
<td>.11</td>
<td>.10</td>
</tr>
<tr>
<td>Isoheptane</td>
<td>.03</td>
<td>.03</td>
</tr>
<tr>
<td>Normal Heptane</td>
<td>.04</td>
<td>.04</td>
</tr>
<tr>
<td>Octanes +</td>
<td>.04</td>
<td>.03</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.40</td>
<td>1.60</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>4.70</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Most of the wells in this area produced from 500 to 800 gallons of distillate per 1,000,000 cubic feet of gas and this distillate production has definitely fallen off as the field has become older and the pressures have dropped. After an average of about four years of operation, the distillate production on the average has been reduced to about 50 per cent of the original.

In some of the older portions of the Oriskany sand fields of West Virginia, it is believed that retrograde condensation has made it necessary to introduce some new methods of producing these wells.

The Columbian Carbon Company has found it necessary to blow some of their wells in order to keep up the production. Wells are blown from periods of 30 to 45 minutes. When the differential pen on the meter shows a very low rate of flow, some of these read-
ings are interesting. In the case of one particular well, it was blown once a day for about 45 minutes and during that time only 10 gallons of fluid was produced. The differential on the meter chart on seven consecutive days read as follows:

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&quot;</td>
<td>14&quot;</td>
</tr>
<tr>
<td>3&quot;</td>
<td>14&quot;</td>
</tr>
<tr>
<td>2&quot;</td>
<td>14&quot;</td>
</tr>
<tr>
<td>1&quot;</td>
<td>14&quot;</td>
</tr>
<tr>
<td>20&quot;</td>
<td>20&quot;</td>
</tr>
</tbody>
</table>

It apparently takes about a day for the bottom of the well to load up with liquid to the extent that it is sealing off the gas. It is believed that this is liquid that condensed in the sand when pressure was taken off by flowing the wells. This fluid is now entering the well bores and sealing off the productive sand, as blowing the wells causes them to return to normal flow as seen above.

This fluid is being produced in the low-pressure wells in the Charleston area as a result of retrograde condensation occurring earlier in the life of the field and this points out a possible explanation as to why some of the gas fields which have been used for pressure storage have produced more gas than was injected into them.

It is possible that when gas is pumped back into a depleted sand, raising the pressure may vaporize some of the heavy hydrocarbons that have lain idle in the fluid state in the sand itself. By returning the pressure to somewhere near the original state, these hydrocarbons may again be vaporized and, when the gas is taken from the sand, a noticeable increase in volume has taken place. This has occurred in a number of repressuring and storage projects and it is distinctly possible that the phenomenon of retrograde condensation may account for the increase in output.

Acknowledgment

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Research results of the Experiment Station are disseminated through the following publications: (1) Bulletins which present the proceedings of technical conferences and the detailed results of the experimental studies of a problem which may be more comprehensive than a single project. (2) Information Circulars which present in nontechnical language the results of studies which are given in greater detail in other publications, statistical data or pertinent information gathered from other sources. (3) Technical Papers consisting of bound copies of papers published in scientific journals (reprints), of progress reports, and of results of experimental studies which represent isolated phases of research and which will be summated later in bulletin form.

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