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DIRECT LOCATION OF OIL AND GAS BY
THE SEISMIC REFLECTION METHOD.**

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DIRECT LOCATION OF OIL AND GAS BY
THE SEISMIC REFLECTION METHOD

by

Poh-Hsi Pan

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IN PARTIAL FULFILLMENT OF THE
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1. INTRODUCTION

The seismic reflection method has long been used as one of the most effective tools in the search for oil and gas. However, the results obtained by this method merely yield cross-sections of the underlying geological structures. These may, in turn, lead to the finding oil or gas. The unreliability of the present method is shown by the fact that eight out of nine exploratory wells are dry. Almost all these wells were located on the basis of structures. It is, therefore, of the utmost importance to study and develop a method that can directly detect the existence of oil and/or gas at depth.

The methods derived here can be applied to both exploration and production. By exploration we mean the attempt at finding a new oil or gas field, by production the attempt at determining the boundaries of an existing oil or gas field. The method is more accurate in the latter case because more information is available than in the former case.

This thesis is divided in two main parts. The first part discusses the theory. The second part illustrates the application of the idea and methods described in the first part to two practical examples, one from exploration, the other from production.

The economic importance of the method is emphasized in the conclusions.

2. OUTLINE OF THE METHOD

The reasoning behind the method may be summarized as follows:

1) The seismic velocity of sedimentary rocks is determined by the velocities in the matrix and in the fluid, and by the porosity.

2) The velocity in a sandstone or a shale matrix is known; the velocity in gas, oil and water is also known.

3) The velocities in the layers can be measured from the surface.

4) If the only difference at two points is the nature of the fluid in one layer, the ratio of the reflectivities of the layer at these two points determines the nature of the fluid.

5) Once this is determined, the porosity and the size of the reservoir follow immediately.

3. DETERMINATION OF SOME PHYSICAL PROPERTIES OF THE RESERVOIR ROCKS

The three main factors which play the dominant roles in determining the possibility of oil and gas accumulation in the reservoir rocks are: velocity, porosity and density. We will now show how to compute these elements of the formations in an area where no wells exist.

Figs. 1, 2 and 3 show three typical geological structures and the symbols used in the computations. The highly schematic nature of these figures is recognized, but they exhibit all the features needed for the present analysis. The applications to real cases will be made in the second part.

3.1 Calculation of Average and Interval Velocities

Using seismic cross-sections and structural maps as guides, we choose the structural high and low points, and the zones of interest for further analysis.

In the case of anticlinal and synclinal structures (Figs. 1 and 2) we use Dix's (1955, p. 70-78) method for measuring the average and interval velocities at the crest and the trough of the structures. This method uses seismic reflection data.

In the case of pinch-out (Fig. 3), sand-lens and other

ϕ_1 = porosity of shale bed above A

ρ_1 = density of shale bed above A

$\bar{V}_1$ = average velocity of shale bed above A

V_{11} = interval velocity of shale bed

The other three sets of symbols are defined similarly, but at different locations and for different rocks.

Fig. 1. Schematic seismic cross-section of an anticlinal and a synclinal structure.

See Fig. 1 for the definition of the symbols.

Fig. 2. Schematic seismic cross-section of a faulted anticlinal structure.

See Fig. 1 for the definition of the symbols.

Fig. 3. Schematic seismic cross-section of a pinch-out structure.

stratigraphic traps, we use Sattlegger's (1965) method or Dix's method for determining the interval velocities of the interesting zones. The details will be illustrated in the later sections.

3.2 Evaluations of Porosities of Interesting Beds

We will demonstrate the principle of the method on the most common oil and gas traps; these are formed by a shale bed overlying a sandstone bed, the latter contains oil or gas as well as water.

We can apply the "time average equation" (Wyllie, 1963) to the calculation of the porosities of the shale and sandstone beds:

$$\frac{1}{V_{1j}} = \frac{\phi_j}{V_f} + \frac{1 - \phi_j}{V_{1j(m)}} \quad , \quad (1)$$

thus

$$\phi_j = \frac{V_{1j(m)} - V_{1j}}{V_{1j}(V_{1j(m)}/V_f - 1)} \quad , \quad (2)$$

where

V_f = velocity of the fluid, i.e.

V_{sw} : velocity of salt water = 5,000 ft/sec

V_{oil} : velocity of oil $\pm$ 4,300 ft/sec

V_{gas} : velocity of gas $\pm$ 1,420 ft/sec or 430 m/sec

V_{1j} = interval velocity of j-th medium

$V_{1j(m)}$ = interval velocity of the matrix of j-th medium.

Let $j = 1$ for shale (see Fig. 1), then

$$V_{11(m)} = V'_{11(m)} = \text{velocity of shale matrix} \\ \pm 13,000 - 14,000 \text{ ft/sec.}$$

Let $j = 2$ for sandstone, then

$$V_{12(m)} = V'_{12(m)} = \text{velocity of sandstone matrix} \\ \pm 19,200 \text{ ft/sec or slightly less (Hicks} \\ \text{and Berry, 1956).}$$

In a typical case one might find $V_{11} = 10,000 \text{ ft/sec}$, inserting $V_{11(m)} =$ either 13,000 or 14,000 ft/sec into Eq. (2) we get $\phi_1 = 19\%$ and 22% respectively. This 3% difference in porosity will result a difference in density about 0.05 gm/cc as calculated by using Eq. (3) in the next section. Therefore, the small discrepancy in the estimate $V_{11(m)}$ does not very much affect the results of the calculations of reflectivity ratios and fluid velocities to be discussed later. Also, Haskell's measurements (1941) of velocities of Tertiary slates — about $15,000 \text{ ft/sec}$ — are a good point of reference.

The values of ϕ_1 or ϕ'_1 thus obtained can be compared with the values given in Table 1 (Pettijohn, 1957). These values are only approximate.

Table 1. Porosity of Shale in Relation to Overburden

<u>Depth below surface (ft)</u>	<u>Porosity (%)</u>
0 - 100	50
1,000	30
2,000	23
3,000	18
8,000	8

3.3 Computation of Densities of Salt-Water-Saturated Shale and Sandstone Beds

Having thus found the porosities, ϕ , we can compute the densities, by using Nafe and Drake's (1957) formula

$$\rho_1 = 1.00 \phi_1 + 2.68 (1 - \phi_1) \quad (3)$$

with similar formulae for ρ'_1 and ρ'_2 .

3.4 Calculation of Reflectivity Ratios

The reflectivities at A and B (Figs. 1 to 3) are defined as

$$R_A = \frac{\rho_2 v_{12} - \rho_1 v_{11}}{\rho_2 v_{12} + \rho_1 v_{11}}, \quad (4)$$

and

$$R_B = \frac{\rho'_2 v'_{12} - \rho'_1 v'_{11}}{\rho'_2 v'_{12} + \rho'_1 v'_{11}}. \quad (5)$$

These values of R_A and R_B can not be obtained from the traces on the seismic records. We can, however, measure the reflectivity ratio, R_B/R_A , which is proportional to the ratio of amplitudes, A_B/A_A , measured on the seismic records at the proper times. Thus we have

$$\frac{A_B}{A_A} = \frac{R_B}{R_A} = \frac{\rho'_2 v'_{12} - \rho'_1 v'_{11}}{\rho'_2 v'_{12} + \rho'_1 v'_{11}} \cdot \frac{\rho_2 v_{12} + \rho_1 v_{11}}{\rho_2 v_{12} - \rho_1 v_{11}} \quad (6)$$

3.5 Identification of the Fluids in the Reservoir Rocks

In the case of exploration, knowing the values of the rest of the elements in Eq. (6) we can solve for $\rho_2 V_{12}$, the product of the density and velocity of the sandstone under point A in Figs. 1 to 3.

$$\rho_2 V_{12} = \frac{\rho_1 V_{11} \left(\frac{R_B}{R_A} + \frac{\rho_2' V_{12}' - \rho_1' V_{11}'}{\rho_2' V_{12}' + \rho_1' V_{11}'} \right)}{\frac{R_B}{R_A} - \frac{\rho_2' V_{12}' - \rho_1' V_{11}'}{\rho_2' V_{12}' + \rho_1' V_{11}'}} \quad (7)$$

Since $\phi_2' \neq \phi_2$, and since the densities of the crude oil and gas are known, we can find ρ_2 assuming that the fluid is either oil or gas, and find respectively

$$\rho_{2,oil} = \rho_{oil} \phi_2 + 2.68 (1 - \phi_2) \quad (8)$$

$$\rho_{2,gas} = \rho_{gas} \phi_2 + 2.68 (1 - \phi_2) \quad (9)$$

(note that if the fluid is salt water, the expression, $R_B/R_A \neq$ unity by definition).

We can now insert each of these values of ρ_2 in Eq. (7) and find the two corresponding V_{12} . These two values, in turn, can be inserted into

$$\frac{1}{V_{12}} = \frac{\phi_2}{V_x} + \frac{1 - \phi_2}{V_{12(m)}} \quad (10)$$

which may be written

$$V_x = \frac{V_{12} V_{12(m)} \phi_2}{V_{12(m)} - V_{12}(1 - \phi_2)} \quad , \quad (11)$$

where $V_{12(m)} = V'_{12(m)} \pm 19,200$ ft/sec, to yield two possible V_x , the velocity of sound in the fluid. One of these values will be close to the known value of sound in either oil or gas. The other will be aberrant. The first value then determines the nature of the fluid.

In the case of production, Eq. (6) can be solved for

$$\rho'_2 V'_{12}$$

$$\rho'_2 V'_{12} = \frac{\rho'_1 V'_{11} \left[1 + \frac{R_B}{R_A} \left(\frac{\rho'_2 V'_{12} - \rho'_1 V'_{11}}{\rho'_2 V'_{12} + \rho'_1 V'_{11}} \right) \right]}{1 - \frac{R_B}{R_A} \left(\frac{\rho'_2 V'_{12} - \rho'_1 V'_{11}}{\rho'_2 V'_{12} + \rho'_1 V'_{11}} \right)} \quad , \quad (12)$$

since $\rho'_2 V'_{12}$ is known from the well-logging data obtained in the well at A'.

The quantity $\rho'_2 V'_{12}$ may be computed at any point, e.g. C or D, and not only at point B. We can then examine this value as was done previously, and determine if point C or D is in the potentially producing area. This means that we can also determine the boundary between the water and the oil or gas from a study of reflectivities, velocities, densities etc.

We may, of course, use the method described under "exploration" to determine the nature of the fluid, and

then use the one described under "production" to determine the extent of the field (if the fluid is oil or gas).

4. APPLICATION OF THE METHODS TO KNOWN

OIL AND GAS FIELDS

Two practical examples of known producing fields were investigated by applying the methods described in the previous sections. In order to take advantage of the existing data, and since the method for the exploration and production are similar (the only difference being in the determination either of $\rho_2 V_{12}$ or of $\rho'_2 V'_{12}$) the data of both fields were analyzed by the production method. The fields are: the Gurley oil field of the Marathon Oil Company in Nebraska, and the Tiehchenshan gas field of the Chinese Petroleum Corporation in Taiwan.

4.1 Analysis of the Gurley Oil Field, Nebraska

The Gurley oil field is located in Cheyenne County, Nebraska. It was discovered by the Ohio Oil Company in 1940 and started producing 36° commercial oil in 1949 (McCanne and Kundert, 1956). It was the result of five years of reconnaissance and detailed seismic surveys concentrated mostly on the eastern flank of the Julesburg Basin in northeastern Colorado and western Nebraska.

The seismic work was carried out by different techniques from correlation shooting to continuous profiling. Two lines, hereafter named N-S and E-W, were shot in 1949

by the continuous profiling method. However, the subsurface coverage of the reflectors was not continuous; the corresponding gap is indicated in Fig. 4. These two lines were located along the boundaries between sections 1, 2, 11 and 12 of T15N and R49W in Cheyenne County, Nebraska.

The overall quality of the records ranges from good to excellent. There was no difficulty in picking reflections, and tying the records although the subsurface coverage was discontinuous. A reflection template made according to the weathering layer pattern was used as a guide when picking the reflections (Dix, 1952, p. 223-229).

4.1.1 Datum Correction

The conventional up-hole-time datum correction method was not applicable to these seismograms since the ray paths of the end traces of two neighboring records were different (see Fig. 4). The refraction method (Dix, 1952, p. 90) with some modifications was used instead.

Dix approximated the refracted ray path by two straight lines, SB and Bg (see Fig. 6) and remarked that the time error caused by considering the paths SB plus Bg or SA plus Bg (since $SB \approx SA$) instead of $SB' + B'g$ was very small. In the present case it was about 0.0001 second for a 200 ft. long spread and 38 ft. deep shot. Nevertheless, in the case of deep shots, and most shots were at a depth of 250 ft. in

Fig. 4. Time (two-way) cross-section, Line N-S, Gurley Field, Nebraska.

Layer I

0.5 Sec—

Sea Level—

Fig. 5. Time (two-way) cross-section, Line E-W, Gurley Field, Nebraska.

Fig. 6. Vertical section showing datum correction when geophone has long offset (after Dix, 1952, p. 90)

S = shot point (shallow)
 S' = shot point (deep)
 D_s = shot depth
 E_s = Elevation of shot hole on surface
 E^{sp} = Elevation of geophone
 E^g = Elevation of datum
 E^d = Elevation of datum
 V_w = velocity of weathering layer
 V_{sw} = velocity of subweathering layer

Fig. 7. Datum correction used when the shot depth is large.

the Gurley field, this approximation should be modified, since S'B is much greater than SB (Fig. 7).

The total travel time, T_t , from S' to G through B is

$$T_t = \frac{[X^2 + (D_s - E_{sp} + E_g - D_w)^2]^{\frac{1}{2}}}{V_{sw}} + \frac{D_w}{V_w} \quad (13)$$

Solving for D_w we have

$$D_w = \frac{\frac{V_{sw}^2 T_t}{V_w} - (D_s - E_{sp} + E_g)}{\left(\frac{V_{sw}}{V_w}\right)^2 - 1}$$

$$+ \frac{\left[\left(\frac{V_{sw}^2 T_t}{V_w} - D_s + E_{sp} - E_g \right)^2 - \left(\frac{V_{sw}^2}{V_w^2} - 1 \right) (T_t^2 V_{sw}^2 - X^2 - (D_s - E_{sp} + E_g)^2) \right]^{\frac{1}{2}}}{\left(\frac{V_{sw}}{V_w}\right)^2 - 1} \quad (14)$$

where the minus sign in front of the square root was used for getting reasonable values.

Consequently, the time correction at the location of the geophone is

$$T_g = \frac{E_g - E_d - D_w}{V_{sw}} + \frac{D_w}{V_w} \quad (15)$$

and the total datum correction, T_c , for each trace is

$$T_c = \frac{D_s - E_{sp} + E_d}{V_{sw}} - T_g \quad (16)$$

if the shot is below the datum.

The line N-S and E-W were corrected to the datum of 4,000 ft. using a weathering velocity of 2,500 ft/sec, and a subweathering velocity of 6,500 ft/sec. These velocities were also used by the Ohio Oil Company. They could be obtained either from up-hole surveys or from analysis of refraction paths.

4.1.2 Picking of Reflections

The topography in this area is rather even. The maximum difference in elevations between the shot holes is 50 ft. However, the minor zigzag pattern of weathering layer does show on most of the reflections on the records. There were no difficulties in recognizing their continuities across the area under study.

Five outstanding continuous reflections were picked. The intervals between the datum and these five horizons were named layers I, II, III, IV and V for convenience (see Figs. 4, 5 and 8).

The evidence of low amplitudes and weak reflections before the recording time 1.0 second, i.e. in the layers I and II, indicates a sequence of shale beds. Layer III shows strong reflections; these reveal the zone of sandstones which is of interest. Layers IV and V are two other massive beds presumably interbedded sandstone and shale

152

NO. 1

151

150

Layer II

Layer III

Layer IV

Layer V

Fig. 8. Record section showing five re

15

owing five reflecting horizons.

S

158

157

156

sequences.

Since the subsurface coverage of the reflections does not tie from one record to its adjacent one, the time-tie of end traces were paid great attention to. In addition wave-form characteristics at the tie between records were carefully scrutinized.

4.1.3 Calculation of Average and Interval Velocities

The velocity of the thick massive shale section shown on the electrical log (Fig. 9) and seismic records (before 1.0 second) can be considered as quite constant. An assumption of straight-ray path was made for calculating the average velocities.

Since the spread lengths were fairly short (most of them were 800 ft.) the following method for determining the average velocities for small parallel dipping beds was used instead of the X^2-T^2 plotting method.

Two values of average velocities, $\bar{V}_{B1}$ and $\bar{V}_{B2}$ were computed from two sides of the split-spread shooting records. A mean value of these two was used for the average velocity between the datum and the chosen reflection under the shot point.

In Fig. 10 the dip angle, θ_1 , of the reflector is greater than zero, i.e. the reflector is dipping to the left. Thus for the left spread B1 we have

$$(\bar{V}_{B1} T_{xB1})^2 = X_1^2 \cos^2 \theta_1 + (\bar{V}_{B1} T_o + X_1 \sin \theta_1)^2 \quad (17)$$

D.M.L. 4420

SCHLUMBERGER WELL SURVEYING CORPORATION HOUSTON, TEXAS	
Electrical Log	
COMPANY: OHIO OIL COMPANY	Location of Well
WELL: MARY EGGING #1	ES ML
FIELD: GURLEY	NE NE NE
LOCATION: SEC. 11-15N-49W	
COUNTY: CHEYENNE	
STATE: NEBRASKA	
FILE NO.: D.M.L. 4420	Section D.F. 4217 or 614208

SHALE

SHALE

Fig. 9. Electrical log of the well Mary Egging # 1 showing shale sections from 1160-4402 ft.

Stratigraphic log of the well Mary Egging # 1 showing thick
sand sections from 1160-4402 ft.

Fig. 9. Electrical log of the well Mary Egging
shale sections from 1160-4402 ft.

Mary Egging # 1 showing thick
402 ft.

SANDSTONE

SHALE

S.S.

D RUN NO. ONB 423

Fig. 10. Determination of $\bar{V}_B$ for $\theta_1 > 0$.

T_{o1}, T_{o2}, T_{o3} = travel times of the center traces

Fig. 11. Determination of θ_2 , the dip angle under SP_2 .

Solving for $\bar{V}_{B1}$ we get

$$\bar{V}_{B1} = \frac{T_o \sin \theta_1 \pm \left[(T_o \sin \theta_1)^2 + (T_{xB1}^2 - T_o^2) \right]^{\frac{1}{2}}}{T_{xB1}^2 - T_o^2} \cdot x_1 \quad (18)$$

The plus sign in front of the square root should always be used.

For the right-side spread, B2,

$$(\bar{V}_{B2} T_{xB2})^2 = x_2^2 \cos^2 \theta_1 + (\bar{V}_{B2} T_o - x_2 \sin \theta_1)^2, \quad (19)$$

and

$$\bar{V}_{B2} = \frac{-T_o \sin \theta_1 \pm \left[(T_o \sin \theta_1)^2 + (T_{xB2}^2 - T_o^2) \right]^{\frac{1}{2}}}{T_{xB2}^2 - T_o^2} \cdot x_2 \quad (20)$$

The plus sign in front of the square root should be used if T_{xB2} is greater than T_o , the minus sign for T_{xB2} less than T_o , since the velocity cannot be negative.

The average velocity from the datum to the reflector under the shot point is

$$\bar{V}_B = \frac{\bar{V}_{B1} + \bar{V}_{B2}}{2} \quad (21)$$

It is clear that Eq. (18) and (20) must be interchanged if the reflector dips to the right.

In the above equations the values of θ are unknown. They can be computed by using Eqs. (22-23-24) (Dobrin, 1960).

(see Fig. 11).

$$\theta_{12} = \sin^{-1} \frac{V_{sw} \Delta T_{o(12)}}{2 \text{ XX1}} , \quad (22)$$

$$\theta_{23} = \sin^{-1} \frac{V_{sw} \Delta T_{o(23)}}{2 \text{ XX2}} \quad (23)$$

and

$$\theta_2 = \frac{\theta_{12} + \theta_{23}}{2} , \quad (24)$$

where $\Delta T_{o(12)} = T_{o1} - T_{o2}$, and $\Delta T_{o(23)} = T_{o2} - T_{o3}$.

The interval velocities between horizons can then be calculated by applying Dix's (1955, p. 73) equation,

$$V_{in}^2 = (\bar{V}_n^2 \sum_1^n \Delta T_j - \bar{V}_{n-1}^2 \sum_1^{n-1} \Delta T_j) / \Delta T_n , \quad (25)$$

where

V_{in} = interval velocity of n-th layer

$\bar{V}_n$ = apparent average velocity between datum and
bottom of n-th layer

ΔT_j = interval travel time in the layer.

The average and interval velocities of the layers chosen from the continuous profiling records were computed on the Burroughs 5500 at Rice University. The program is given in Appendix I.

The average velocities from the datum to the top of the five reflectors are shown in Figs. 12 and 13. The

Fig. 12. Average velocity profiles in ft/sec, from datum (4000') to five horizons, Line N-S, Gurley field, Nebraska.

To Reflecting Horizon I

To Reflecting Horizon II

To Reflecting Horizon III

To Reflecting Horizon IV

To Reflecting Horizon V

Fig. 13. Average velocity profiles in ft/sec, from datum (4000') to five horizons, Line E-W, Gurley field, Nebraska.

interval velocities of the five layers I, II, III, IV and V were mapped in contours as shown in Figs. 14 to 18. In all the maps presented for the Gurley field, control exists only along the N-S and E-W lines. Normal contouring practice has been used in drafting the maps.

It is interesting to note that the trends of increase in interval velocities shown on Figs. 14 and 15 are different from those shown on Figs. 16 and 17. This difference may be caused by different depositional environments; layers I and II are mainly shale, whereas layers IV and V composed of interbedded shales and sandstones.

The interval velocity map of the layer III has a low-velocity region near the top of the structure. From the preceding theory we conclude that it is related to the oil-bearing sandstones in the producing area.

4.1.4 Amplitude and Normalized Reflectivity Maps

It is clear that the reflectivity depends on the angle of incidence of the ray. Near vertical incidence, however, this change is small (Muskat, 1940). We compare the amplitude of the central traces on different seismograms. Even so, however, the geophone nearest to the shot holes in the Gurley field were about 200 ft. away. This corresponds to an angle of incidence of 1.5° for a depth of 4,000 ft., which does not appreciably affect the reflectivity.

R. 49 W.

Fig. 15. Interval velocity contour map of layer II.

MARATHON OIL COMPANY

GURLEY FIELD
CHEYENNE CO., NEBRASKA

T.
15
N.

Fig. 16. Interval velocity contour map of layer III.

MARATHON OIL COMPANY

GURLEY FIELD
CHEYENNE CO., NEBRASKA

SCALE: 1"=2000'

Fig. 17. Interval velocity contour map of layer IV.

MARATHON OIL COMPANY

GURLEY FIELD
CHEYENNE CO., NEBRASKA

SCALE: 1"=2000'

T.
15
N.

Fig. 18. Interval velocity contour map of layer V.

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CHEYENNE CO., NEBRASKA

SCALE: 1"=2000'

The amplitudes of the central traces of the second reflecting horizon reflected from the top of layer III were measured. The amplitude was measured from the bottom of the trough to the center lines of the traces (Fig. 8). The use of automatic gain control prevent the use of a more sophisticated method. An amplitude contour map was then constructed (Fig. 19). A reflectivity ratio map is then obtained by dividing the amplitudes by the amplitude at the top of the structure (shot point # 19). This reflectivity ratio map was then superimposed on the subsurface structural contour map (McCanne and Kundert, 1956) for comparison (Fig. 20).

4.1.5 Evaluation of Oil Potential

In view of the low velocity and low reflectivity ratio near the top of the structure we can almost immediately conclude that this is a producing structure. Nevertheless, by using Eq. (12) to evaluate the existence of hydrocarbon we will obtain more quantitative results; we will also find the limit of the producing area as demonstrated in the following section.

As previously explained, for exploration purposes one should use Eq. (7) in the last part of the calculations instead of Eq. (12), but the rest of the procedures would remain the same.

Fig. 19. Contour map of amplitudes measured from the central traces at the top of layer III.

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Fig. 20. Normalized reflectivity contour map superimposed on structural contour map.

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SCALE: 1"=2000'

4.1.6 Development of the Field

Generality

After a producing well is discovered the developing work is just as important as the exploratory one: by applying inaccurate velocity functions to the migration of reflections one may produce erroneous structural contour maps; these in turn lead to drilling some unnecessary dry holes, and/or miss a part of the potential area.

Application

The discovery well Mary E. Egging No. 1 in the Gurley oil field is located 330 ft. from the north line, and 330 ft. from the east line of section 11 of Township 15 N. and Range 49 W., Cheyenne County, Nebraska. No density log was available. The continuous velocity log was run from 6,926 ft. to 4,400 ft. by the Seismograph Service Corporation in 1957 (Fig. 21). Routine log interpretation makes it clear that the section from 4,403 ft. to 4,429 ft., which has a velocity about 11,500 ft/sec is oil-saturated sandstone, while the sections from 4,429 ft. to 4,480 ft. and from 4,660 ft. to 4,880 ft. are salt-water-bearing sandstones which have an average interval velocity of about 13,450 ft/sec. From the latter the porosity of this section of sandstones, ϕ_2 , was found by using the "time average equation".

$$\frac{1}{13,450} = \frac{\phi_2}{5,000} + \frac{1 - \phi_2}{19,200} ,$$

CONTINUOUS VELOCITY LOG

 Seismograph Service Corporation

 TULSA 1, OKLAHOMA, U.S.A.

WELL: THE OHIO OIL COMPANY NO. 1 BARY EGGING
 LOCATION: NE NE NE SECTION 11, T 15 N, R 49 W,
 CHEYENNE COUNTY, NEBRASKA
 FIELD: GURLEY

Bit Size: 7-7/8" to T.D.
 Mud Type: Gyp. base
 Total travel time referred to seismic
 datum: 4000 feet above sea level
 Reference Level - Seismic Datum: 217 ft. (Dwd)
 Transducer Spacing: 592 ft
 Geophone Check Level:
 No. of Record at Check Level: ⑤

Reference Level: Kelly bushing
 Well Elevation: 4209' Gr., 4216' D.F., 4217' K.B.
 Total Depth of Well: 6936 ft (Driller) 6937' (SCL.)
 Bottom of Casing: 4402 ft (Driller) 4400' (CYL.)
 Logged from: 6926 ft to 4400 ft.
 Contract Number: WK-155 Run: 1st
 Date: April 16, 1957
 Operator: M. Bregdan

Fig. 21. Continuous velocity log showing the producing zone.

and $\phi_2 = 15 \%$. The values of $\rho_2' V_{12}'$ and V_x were then obtained by assuming $\phi_2 \doteq \phi_2'$ and calculating as previously described. The program is given in Appendix II.

A fluid velocity map was made (Fig. 22). If the velocity boundary between oil and salt water is 4,400 ft/sec (kerosene velocity = 4,343 ft/sec at 25°C), the water line of the field can be found.

The lower velocity region may indicate the mixture of oil and traces of gas — dissolved gas (Levorsen, 1967, p. 558).

4.1.7 Discussion

We wish to insist on the fact that the velocities V_{12}' obtained from Eq. (25) and the map shown contoured in Fig. 16 can not be used for finding V_x . The reason is that these velocities are an average of the velocities of sandstones and shales because of the thinness of the sandstone. They also depend on the thickness of the bed that are picked on records while the reflectivity ratio method of evaluation is dependent only on the top zone of a sequence of formations, and independent of the thickness of the layer.

In comparing the reflectivity ratios and the structural elevations at the interface between layers II and III under shot points # 151 and # 2 in Fig. 20 a remarkable fact can be noticed. At shot point # 151 the structural elevation is 20 ft. higher than that under shot point # 2, indicating

Fig. 22. Fluid velocity contour map showing possible edge-water line.

MARATHON OIL COMPANY

GURLEY FIELD
CHEYENNE CO., NEBRASKA

SCALE: 1"=2000'

that shot point # 151 should be in the producing zone, but a hole drilled to the southwest of it was dry. On the other hand the reflectivity ratio at shot point # 151 is 3.25, an unfavorable value which is 2.5 times larger than that at the shot point # 2, a favorable location for producing oil. This shown clearly the advantage of using the reflectivity ratios. It is, of course, true that the determination of the fluid velocities based on these ratios yields an even more direct answer to the location of oil.

4.2 Investigation of the Tiehchenshan Gas Field, Taiwan

The Tiehchenshan gas field is located about 100 km. southwest of Taipei, the capital of Taiwan, China. It is composed of two structures with a surface expression: the Tunghsiao anticline in the north and the Tiehchenshan anticline in the south (Fig. 23). It is the largest gas field yet discovered on the island of Taiwan.

The first seismic survey was conducted by the writer and a crew under his direction in 1956 (Pan, 1957). Following the seismic work the TH-1 well (Fig. 28) was drilled to a total depth of 2,330 m. This was about the maximum depth which could be reached by the small drilling rig then available (the TH-1 well was deepened to 2,890 m. and became a producer after the discovery of TCS-1 well), (Chang et al., 1965).

Fig. 23. Index map showing the location of the Tiehchenshan gas field, Taiwan.

The second stage of the seismic survey carried out by the Taiwan Petroleum Exploration Division of the Chinese Petroleum Corporation in 1961-1962 covered an extensive area of about 200 km² (Chang and Chen, 1963). Natural gas was first found in the discovery well, TCS-1, in 1962. More than a dozen wells have been drilled in that area since then.

The producing zone is a section of whitish gray, medium- to coarse-grained protoquartzitic sandstone lens in the middle of the Talu shale of Miocene age. It is named zone TT-1, and is divided into four subzones, namely: TT-1A, TT-1B, TT-1C and TT-1D. This study covers only the top zone, TT-1A, which produces most of the gas, and is the thickest of the four subzones (Fig. 24). Its average thickness is about 60 m. The electrical log section indicates that the producing bed thicken slightly from south to north. This may be due to subsidence in the south of the structure after folding and deposition.

The procedures used in analyzing this field are analogous to those used in the preceding case.

4.2.1 Selection of Data and Picking of Reflections

The topography of the Tunghsiao-Tiehchenshan area is rough and rugged. Most of the seismic lines were laid out along narrow country roads or on hilly slopes. The uneven surface conditions certainly greatly affected the quality of

Fig. 24. Electrical and SP log showing the producing sandstones.

the seismic records.

Some four hundred continuous profiles were recorded by either one of two sets of portable recording units, G-33 and P-11, manufactured by the Southwestern Industrial Electronics Company in Houston, Texas. The filter setting were: high cut 2-65, low cut 2-27. The average charge size was about 10 kg. in each hole.

The overall quality of the records was from fair to good. In order to eliminate errors introduced either by unreliable information or by the use of asymmetric split-spread, only records of good quality with straight-line split spreads across the shot holes were analyzed. If there was minor difference in spread length the farthest traces at the same distance from the shot point were used.

From the results of the well-velocity survey in well TCS-2 (Fig. 25) it was noticed that the velocity of the gas-saturated sandstone zone was lower than that of the overlying shale beds. This was taken into consideration when picking the reflections at the top of the gas sandstone on the seismic record # 14-30, which is near the producing well, TCS-2. In this record the peaks of the reflections were picked rather than the troughs; on a normal exploration record a downward motion of the trace corresponds to an upward motion of the ground. This is clearly seen in the first arrivals on the record.

Fig. 25. Well-Velocity surveying results obtained from well TCS-2, Tiehchenshan gas field, Taiwan.

As the picking of reflections was carried out across the boundary between the producing and non-producing zones the polarities of the reflections were seen to change back to normal (Fig. 26). Such a change constitutes a further help in the determination of the water line, thus supplementing the methods described in the previous sections.

To tie the reflecting times of three interesting reflections, namely, the top of the Talu shale and the top and bottom of the sandstone lens, with the well log data a 0.020 second of instrumental filter-delay was subtracted from the recording times. These three reflecting horizons were marked on all the seismograms (Fig. 27). About twenty-five good records were investigated.

4.2.2 Computations of Velocities

Since the datum corrections were already made according to the conventional up-hole-time method, and since the subsurface coverage of the reflections was continuous, no further corrections were needed for timing the reflections on the center and the end traces.

The average and interval velocities between horizons were computed by using a program (see Appendix III) similar to the one shown in Appendix I. The only modification is in the method of computing the dip of the reflectors. Dix's formula (1952, p. 129) was used.

S.P. 14-28

S.P. 14-27

Fig. 26. Seismic records showing polarity change across producing boundary, Tiehchenshan gas field, Taiwan.

Fig. 27. Record section of a part of the Line # 14 showing three picked reflecting horizons.

$$\theta = \sin^{-1} \frac{V_{sw} \Delta T}{2X}, \quad (26)$$

where

θ = dip angle

V_{sw} = subweathering velocity = 1,900 m/sec

ΔT = difference in reflecting times between two end traces.

The need to use of this formula is an immediate consequence of the geometry of the shot hole and geophones.

Two interval velocity maps were made: one for the layer between the top of Talu shale and the top of the sandstone lens (Fig. 28), the other for the top and bottom of the sandstone lens (Fig. 29). In the present case the control points are marked on all maps with circles. Fig. 28 shows a small velocity high of the order of 250 m/sec at the crest of the anticlinal structure. This may be due to compaction of the shale beds near the crest during folding, thus causing high velocities.

The sandstone, on the other hand, shows a pronounced low velocity region (of the order of 1,500 m/sec) in the center of the structure (Fig. 29). It is definitely related to the existence of the gas-bearing sandstones which have lower velocities than the water-bearing sands in the outer region.

TIEHCHENSHAN GAS FIELD

CHINESE PETROLEUM CORP, TAIWAN

SCALE : 1 : 25,000

Fig. 28. Interval velocity contour map of the shale bed.

TIEHCHENSHAN GAS FIELD

CHINESE PETROLEUM CORP, TAIWAN

SCALE : 1 : 25,000

Fig. 29. Interval velocity contour map of the sandstone.

4.2.3 Subsurface Structural Contour Map and Reflectivity

Ratio Map

As has been done previously, a reflectivity ratio map of the interesting interface was constructed and superimposed on the subsurface structural contour map made on the basis of the same interface (Fig. 30). A general agreement between the low reflectivity ratio and the low velocity sandstone zone is obvious.

4.2.4 Fluid Velocity Map and Water Edge Map

A program (Appendix IV) similar to the one given in Appendix II was written, and used for calculating the fluid velocities of the TT-1A sandstone zone.

The following minor differences between the two programs concern only the determination of the values of the sandstone porosities, and the method of identifying the nature of the fluids. Since the porosity of the sandstone increases southward from 15 % in well TH-1 to 20 % in well TCS-6 (Kuan, 1965), the interpolated values of porosities in this area were used instead of the values computed from the formulae. Such a method is consistent with the fact that maximum use should always be made of the data in order to eliminate the errors arising due to unexpected changes in the geology.

Since the velocity of sound in methane is 432 m/sec

TIEHCHENSHAN GAS FIELD

CHINESE PETROLEUM CORP, TAIWAN

SCALE : 1 : 25,000

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Fig. 30. Reflectivity ratio contour map superimposed on structural contour map (unmigrated depths).

and in salt water 1,530 m/sec, the fluid was determined to be gas if the velocity was between 300 and 900 m/sec, and salt water if between 1,300 and 1,900 m/sec. The effects of pressure and temperature on sound velocity can be gaged by the fact that the velocity of sound in air is 331.7 m/sec under one atmosphere, 350.6 m/sec under 100 atmosphere; 344 m/sec at 20°C and 700 m/sec at 1,000°C. Correspondingly, the velocity of sound in methane will stay in the 300-900 m/sec range under the pressure and temperature conditions encountered at a depth of 4,000 ft. A fluid velocity map (Fig. 31) was then made for the sandstone zone, and was superimposed on the map of the water line drawn from structural considerations (Chang, 1965; Kuan, 1965). It is clear that the water lines obtained from the structural and the fluid velocity maps are very similar. A more detailed analysis of the differences should be made after this field is further developed and more research seismic surveys have been conducted.

TIEHCHENSHAN GAS FIELD

CHINESE PETROLEUM CORP, TAIWAN

SCALE 1 : 25,000

Fig. 31. Fluid velocity contour map superimposed on edge-water map.

5. CONCLUSIONS AND RECOMMENDATIONS

The seismic reflection method has long been used for finding oil through the interpretation of structural configurations. Many oil and gas fields were discovered by applying this method. However, the chances of success are not very high, and become slimmer with the passage of time, because most large and geologically simple oil fields have been already discovered and developed. The present method can lead directly to the location of oil and gas. It further enables us to estimate the total capacity of the reservoir by determining the porosity and the water line.

Since measurements of the reflectivity ratio are independent of the structural configuration they can be applied to any complicated type of geological feature, for instance, to stratigraphic traps.

They will also prevent errors due to misinterpretation of the nature of the structures: it is, for instance, possible that the fluids of lighter density do not migrate to their apparently logical location because of a small fault, which can not be detected, blocks the migration. It may also happen that the oil-water contact is tilted (Levorsen, 1967, p. 407 and p. 561-568); in such a case subsurface structural contour maps cannot yield the water line. Finally, if there is facies change between the structural high and low

points the concept of using structural contour maps to outline the production area will be wrong. None of these disadvantages occur when using the reflectivity ratio method.

For getting the best results for this kind of work the field operating techniques should be carefully designed. It is recommended that both long and short continuous split spreads be used and that charge size, geophone arrangement and instrumental settings be kept constant from shot to shot. In further studies of a partly developed field, controlled energy sources, such as vibro-seis or thumper, are preferable since they will not damage the nearby producing systems.

Sonic log and density log must be run, and a core analysis made after each well is drilled in order to check the relationships between velocities, densities and porosities.

Finally, attention is drawn to the fact that hundreds of thousands of old records can be re-examined by the present method. Those records obtained near producing fields may be especially valuable.

6. APPENDIX I

Computing program of average and interval velocities
for continuous split-spread records, Gurley oil field, Chey-
enne County, Nebraska.

B 5 5 0 0 F O R T R A N C O M P I L A T I O N

C COMPUTING THE AVERAGE VELOCITIES AND THE INTERVAL VELOCITIES
C FOR CONTINUOUS SPLIT-SPREAD SHOOTING RECORDS

DIMENSION TZROA(10),TZROB(10),TZROC(10),DELTT1(10),DELTT2(10),
1TXA(10),TXB1(10),TXB2(10),TXC(10),RADIN1(10),RADIN2(10),
2THETA1(10),THETA2(10),THETAM(10),DELTA(10),DELTB(10),DELTC(10),
3VBARA(10),VBARB1(10),VBARB2(10),VBARB(10),VBARC(10),VINTA(10),
4VINTB(10),VINTC(10),RTZROA(10),RTZROB(10),RTZROC(10),RTXA(10),
5RTXB1(10),RTXB2(10),RTXC(10)

READ 101, T CORR

33 L=1

J=1

C THE NUMBER OF RECORDS IS K

READ 22, K

22 FORMAT(I10)

READ 101, V DATUM

101 FORMAT(F10.5)

C THE NUMBER OF LAYERS IS M, M=N-1

READ 1, N, (RTZROA(I), RTXA(I), RTXB1(I), RTZROB(I), I=1, N)

1 FORMAT(I10/(4F10.4))

C THE SPREAD DISTANCES FROM SHOT HOLE A TO XA AND XB1 TO

C SHOT HOLE B ARE X1 AND X2

READ 2, X1, X2

2 FORMAT(2F10.5)

C THE DISTANCE BETWEEN SHOT HOLES A AND B IS XX1

READ 101, XX1

3 READ 4, (RTXB2(I), RTXC(I), RTZROC(I), I=1, N)

4 FURMAT (3F10.4)

C THE SPREAD DISTANCES FROM SHOT HOLE B TO XB2 AND XC TO

C SHOT HOLE C ARE X3 AND X4

READ 104, X3, X4

104 FORMAT(2F10.5)

C THE DISTANCE BETWEEN SHOT HOLES B AND C IS XX2

READ 101, XX2

C FIND THE DIPPING ANGLES

I=2

C THE TIE-IN-WELL TIME CORRECTION IS T CORR SECONDS

5 TZROA(I)=RTZROA(I)-T CORR

TZROB(I)=RTZROB(I)-T CORR

TZROC(I)=RTZROC(I)-T CORR

TXA(I)=RTXA(I)-T CORR

TXB1(I)=RTXB1(I)-T CORR

TXB2(I)=RTXB2(I)-T CORR

TXC(I)=RTXC(I)-T CORR

DELTA(I)=TZROA(I)-TZROA(I-1)

DELTB(I)=TZROB(I)-TZROB(I-1)

DELTC(I)=TZROC(I)-TZROC(I-1)

DELTT1(I)=TZROA(I)-TZROB(I)

DELTT2(I)=TZROB(I)-TZROC(I)

RADIN1(I)=ARSIN(V DATUM*DELTT1(I)/(2.*XX1))

RADIN2(I)=ARSIN(V DATUM*DELTT2(I)/(2.*XX2))

C THE DIPPING ANGLES ARE THETAS

THETA1(I)=RADIN1(I)*180./3.14159

THETA2(I)=RADIN2(I)*180./3.14159

```

      THETAM(I)=0.5*(THETA1(I)+THETA2(I))
      I=I+1
      IF(I-N)5,5,6
6     PRINT 7
7     FORMAT(/////1H061H  THETAM(1) THETAM(2) THETAM(3) THETAM(4) THETAM
      1(5) THETAM(6))
      PRINT 8,(THETAM(I),I=1,N)
8     FORMAT(1H06F10.2)
      IF(L.EQ.1) CALL VAVGA(TZROA,TXA,X1,RADIN1,VBARA,N)
      CALL VAVGB1(TZROB,TXB1,X2,RADIN1,VBARB1,N)
      CALL VAVGB2(TZROB,TXB2,X3,RADIN2,VBARB2,N)
      IF(J.EQ.(K-2)) CALL VAVGC(TZROC,TXC,X4,RADIN2,VBARC,N)
      DO 108 I=1,N
108  VBARB(I)=0.5*(VBARB1(I)+VBARB2(I))
      PRINT 9
9     FORMAT(1H061H  VBARB(1) VBARB(2) VBARB(3) VBARB(4) VBARB(5)
      1VBARB(6))
      PRINT 8,(VBARB(I),I=1,N)
      IF(L.EQ.1) CALL VMIDA(DELTA,VBARA,VINTA,N)
      CALL VMIDB(DELTB,VBARB,VINTB,N)
      IF(J.EQ.(K-2)) CALL VMIDC(DELTC,VBARC,VINTC,N)
      IF(L.EQ.1) PRINT 99,X1,X2,X3,X4,XX1,XX2
99  FORMAT(///6F10.2)
      IF(L.NE.1) PRINT 991, X3,X4,XX1,XX2
991 FORMAT(///4F10.2)
      IF(L.EQ.1) PRINT 100,(RTZROA(I),I=1,N)
      IF(L.EQ.1) PRINT 100,(RTXA(I),I=1,N)
      PRINT 100,(RTXB1(I),I=1,N)
      PRINT 100,(RTZROB(I),I=1,N)
      PRINT 100,(RTXB2(I),I=1,N)
      IF(J.EQ.(K-2)) PRINT 100,(RTXC(I),I=1,N)
      IF(J.EQ.(K-2)) PRINT 100,(RTZROC(I),I=1,N)
      PRINT 100,(THETA1(I),I=1,N)
      PRINT 100,(THETA2(I),I=1,N)
      IF(L.EQ.1) PRINT 100,(DELTA(I),I=1,N)
      PRINT 100,(DELTB(I),I=1,N)
      IF(J.EQ.(K-2)) PRINT 100,(DELTC(I),I=1,N)
      PRINT 100,(DELTT1(I),I=1,N)
      PRINT 100,(DELTT2(I),I=1,N)
100  FORMAT(1H06F10.5)
      L=0
      J=J+1
      IF(J.EQ.(K-1)) GO TO 33
      X1=X3
      X2=X4
      XX1=XX2
      DO 13 I=1,N
      RTZROA(I)=RTZROB(I)
      RTZROB(I)=RTZROC(I)
      DELTA(I)=DELTB(I)
      DELTB(I)=DELTC(I)
      RTXA(I)=RTXB2(I)
      RTXB1(I)=RTXC(I)
13  CONTINUE
      GO TO 3
      STOP
      END

```

```
SUBROUTINE VAVGA(TZROA, TXA, X1, RADIN1, VBARA, N)
DIMENSION TZROA(10), TXA(10), RADIN1(10), VBARA(10)
```

```
I=2
```

```
14 A=TZROA(I)*X1*SIN(ABS(RADIN1(I)))
```

```
B=TXA(I)**2-TZROA(I)**2
```

```
IF(RADIN1(I).LE.0.) VBARA(I)=(A+SQRT(A**2+B*X1**2))/B
```

```
IF(RADIN1(I).GT.0..AND.TXA(I).GT.TZROA(I)) VBARA(I)=(-A+SQRT
1(A**2+B*X1**2))/B
```

```
IF(RADIN1(I).GT.0..AND.TXA(I).LT.TZROA(I)) VBARA(I)=(-A-SQRT
1(A**2+B*X1**2))/B
```

```
I=I+1
```

```
IF(I=N)14,14,15
```

```
15 PRINT 16
```

```
16 FORMAT(1H061H VBARA(1) VBARA(2) VBARA(3) VBARA(4) VBARA(5)
1VBARA(6))
```

```
PRINT 17,(VBARA(I),I=1,N)
```

```
17 FORMAT(1H06F10,2)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VAVGB1(TZROB, TXB1, X2, RADIN1, VBARB1, N)
DIMENSION TZROB(10), TXB1(10), RADIN1(10), VBARB1(10)
```

```
I=2
```

```
14 A=TZROB(I)*X2*SIN(ABS(RADIN1(I)))
```

```
B=TXB1(I)**2-TZROB(I)**2
```

```
IF(RADIN1(I).GE.0.) VBARB1(I)=(A+SQRT(A**2+B*X2**2))/B
```

```
IF(RADIN1(I).LT.0..AND.TXB1(I).GT.TZROB(I)) VBARB1(I)=(-A+SQRT
1(A**2+B*X2**2))/B
```

```
IF(RADIN1(I).LT.0..AND.TXB1(I).LT.TZROB(I)) VBARB1(I)=(-A-SQRT
1(A**2+B*X2**2))/B
```

```
I=I+1
```

```
IF(I=N)14,14,15
```

```
15 PRINT 16
```

```
16 FORMAT(1H061H VBARB1(1) VBARB1(2) VBARB1(3) VBARB1(4) VBARB1(5)
1VBARB1(6))
```

```
PRINT 17,(VBARB1(I),I=1,N)
```

```
17 FORMAT(1H06F10,2)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VAVGB2(TZROB, TXB2, X3, RADIN2, VBARB2, N)
DIMENSION TZROB(10), TXB2(10), RADIN2(10), VBARB2(10)
```

```
I=2
```

```
14 A=TZROB(I)*X3*SIN(ABS(RADIN2(I)))
```

```
B=TXB2(I)**2-TZROB(I)**2
```

```
IF(RADIN2(I).LE.0.) VBARB2(I)=(A+SQRT(A**2+B*X3**2))/B
```

```
IF(RADIN2(I).GT.0..AND.TXB2(I).GT.TZROB(I)) VBARB2(I)=(-A+SQRT
1(A**2+B*X3**2))/B
```

```
IF(RADIN2(I).GT.0..AND.TXB2(I).LT.TZROB(I)) VBARB2(I)=(-A-SQRT
1(A**2+B*X3**2))/B
```

```
I=I+1
```

```
IF(I=N)14,14,15
```

```
15 PRINT 16
```

```
16 FORMAT(1H061H VBARB2(1) VBARB2(2) VBARB2(3) VBARB2(4) VBARB2(5)
1VBARB2(6))
```

```
PRINT 17,(VBARB2(I),I=1,N)
```

```
17 FORMAT(1H06F10,2)
```

```
RETURN
```

```
END
```



```
SUBROUTINE VAVGC(TZROC, TXC, X4, RADIN2, VBARC, N)
DIMENSION TZROC(10), TXC(10), RADIN2(10), VBARC(10)
```

```
I=2
```

```
14 A=TZROC(I)*X4*SIN(ABS(RADIN2(I)))
```

```
B=TXC(I)**2-TZROC(I)**2
```

```
IF(RADIN2(I).GE.0.) VBARC(I)=(A+SQRT(A**2+B*X4**2))/B
```

```
IF(RADIN2(I).LT.0..AND.TXC(I).GT.TZROC(I)) VBARC(I)=(-A+SQRT
```

```
1(A**2+B*X4**2))/B
```

```
IF(RADIN2(I).LT.0..AND.TXC(I).LT.TZROC(I)) VBARC(I)=(-A-SQRT
```

```
1(A**2+B*X4**2))/B
```

```
I=I+1
```

```
IF(I=N)14,14,15
```

```
15 PRINT 16
```

```
16 FORMAT(1H061H VBARC(1) VBARC(2) VBARC(3) VBARC(4) VBARC(5)
```

```
1VBARC(6))
```

```
PRINT 17,(VBARC(I),I=1,N)
```

```
17 FORMAT(1H06F10.2)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VMIDA(DELTA, VBARA, VINTA, N)
```

```
DIMENSION DELTA(10), VBARA(10), VINTA(10)
```

```
I=2
```

```
DLTA=0.
```

```
18 DLTA=DLTA+DELTA(I)
```

```
D=VBARA(I-1)**2*(DLTA-DELTA(I))
```

```
VINTA(I)=SQRT(ABS((VBARA(I)**2*DLTA-D)/DELTA(I)))
```

```
I=I+1
```

```
IF(I.LE.N) GO TO 18
```

```
PRINT 19
```

```
19 FORMAT(1H061H VINTA(1) VINTA(2) VINTA(3) VINTA(4) VINTA(5)
```

```
1VINTA(6))
```

```
PRINT 20,(VINTA(I),I=1,N)
```

```
20 FORMAT(1H06F10.2)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VMIDB(DELTB, VBARB, VINTB, N)
```

```
DIMENSION DELTB(10), VBARB(10), VINTB(10)
```

```
I=2
```

```
DLTB=0.
```

```
18 DLTB=DLTB+DELTB(I)
```

```
D=VBARB(I-1)**2*(DLTB-DELTB(I))
```

```
VINTB(I)=SQRT(ABS((VBARB(I)**2*DLTB-D)/DELTB(I)))
```

```
I=I+1
```

```
IF(I.LE.N) GO TO 18
```

```
PRINT 19
```

```
19 FORMAT(1H061H VINTB(1) VINTB(2) VINTB(3) VINTB(4) VINTB(5)
```

```
1VINTB(6))
```

```
PRINT 20,(VINTB(I),I=1,N)
```

```
20 FORMAT(1H06F10.2)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VMIDC(DE LTC,VBARC,VINTC,N)
DIMENSION DELTC(10),VBARC(10),VINTC(10)
I=2
DLTC=0.
18 DLTC=DLTC+DE LTC(I)
D=VBARC(I-1)**2*(DLTC-DE LTC(I))
VINTC(I)=SQRT(ABS((VBARC(I)**2*DLTC-D)/DE LTC(I)))
I=I+1
IF(I,LE,N) GO TO 18
PRINT 19
19 FORMAT(1H061H VINTC(1) VINTC(2) VINTC(3) VINTC(4) VINTC(5)
1VINTC(6))
PRINT 20,(VINTC(I),I=1,N)
20 FORMAT(1H06F10.2)
RETURN
END
```

7. APPENDIX II

Computing program of the velocities of the fluids contained in the reservoir rocks, Gurley oil field, Cheyenne County, Nebraska.

B 5 5 0 0 F O R T R A N C O M P I L A T I O N

```

C      COMPUTATION OF THE VELOCITIES OF THE FLUIDS CONTAINED
C      IN THE RESERVOIR ROCKS, GURLEY OIL FIELD, NEBRASKA
C      THE DEFINITIONS OF THE SYMBOLS ARE AS FOLLOWS
C      VSHM=VELOCITY OF SHALE MATRIX
C      VSSM=VELOCITY OF SANDSTONE MATRIX
C      VSHA=VELOCITY OF SHALE AT A
C      VSHB=VELOCITY OF SHALE AT B
C      VSSA=VELOCITY OF SANDSTONE AT A
C      VSSB=VELOCITY OF SANDSTONE AT B
C      PHISHA=POROSITY OF SHALE AT A
C      PHISHB=POROSITY OF SHALE AT B
C      PHISSA=POROSITY OF SANDSTONE AT A
C      PHISSB=POROSITY OF SANDSTONE AT B
C      RHOSHA=DENSITY OF SHALE AT A
C      RHOSHB=DENSITY OF SHALE AT B
C      RHOSSA=DENSITY OF SANDSTONE AT A
C      RHOSB=DENSITY OF SANDSTONE AT B
C      REFLA=REFLECTIVITY AT A
C      RHOVSB=(DENSITY OF SANDSTONE AT B)
C           X (VELOCITY OF SANDSTONE AT B)
C      VGSSB=VELOCITY OF SANDSTONE IF CONTAINING OIL AT B
C      VWSSB=VELOCITY OF SANDSTONE IF CONTAINING SALT WATER AT B
C      VGAS=VELOCITY OF FLUID IN SANDSTONE IF IT IS OIL
C      VWATER=VELOCITY OF FLUID IN SANDSTONE IF IT IS SALT WATER

      READ 1,VSHM,VSSM,PHISSA,PHISSB
1  FORMAT(4F10.3)
      READ 2,VSHA,VSSA
2  FORMAT(2F10.2)
3  READ 4,VSHB
      READ 4,VSSB
      READ4,REFLR
4  FORMAT(F10.3)
      PHISHA=(VSHM-VSHA)/(VSHA*(VSHM/5000.-1.))
      PHISHB=(VSHM-VSHB)/(VSHB*(VSHM/5000.-1.))
      RHOSHA=PHISHA+2.68*(1.-PHISHA)
      RHOSHB=PHISHB+2.68*(1.-PHISHB)
      RHOSSA=0.82*PHISSA+2.68*(1.-PHISSA)
      REFLA=(RHUSSA*VSSA-RHOSHA*VSHA)/(RHOSSA*VSSA+RHOSHA*VSHA)
      RHOVSB=RHOSHB*VSHB*(1.+REFLR*REFLA)/(1.-REFLR*REFLA)
      VOSSB=RHOVSB/(0.81*PHISSB+2.68*(1.-PHISSB))
      VWSSB=RHOVSB/(PHISSB+2.68*(1.-PHISSB))
      VOIL=(VOSSB*VSSM*PHISSB)/(VSSM-VOSSB*(1.-PHISSB))
      VWATER=(VWSSB*VSSM*PHISSB)/(VSSM-VWSSB*(1.-PHISSB))
      PRINT 5
5  FORMAT(/IX,"THE VELOCITY OF THE FLUID IN THE SANDSTONE AT SHOT POI
1NT")
      IF(VOIL.LT.4400.) GO TO 6
      IF(VWATER.GT.4400.) GO TO 8

```

```
6 PRINT 7,VOIL
7 FORMAT(/F30.2,5X,"FEET/SEC.",5X,"THIS IS A PRODUCING LOCATION")
  GO TO 10
8 PRINT 9,VWATER
9 FORMAT(/F30.2,5X,"FEET/SEC.",5X,"THIS IS A NON-PRODUCING ZONE")
10 PRINT 11
11 FORMAT(/4X,"VSHM",6X,"VSSM",6X,"VSHA",6X,"VSSA",6X,"VSHB",6X,
1"VOSSB",5X,"VWSSB",5X,"PHISSA",4X,"PHISSB",4X,"RHOSHA",4X,"RHOSHB"
2,5X,"REFLR")
  PRINT 12, VSHM,VSSM,VSHA,VSSA,VSHB,VOSSB,VWSSB,PHISSA,PHISSB,
1RHOSHA,RHOSHB,REFLR
12 FORMAT(12F10.3)
  PRINT 13
13 FORMAT(/5X,"VOIL",5X,"VWATER",4X,"VSSB (FOR CHECKING USE)")
  PRINT 14,VOIL,VWATER,VSSB
14 FORMAT(/3F10.2)
  GO TO 3
  STOP
  END
```

8. APPENDIX III

Computing program of average and interval velocities
for single split-spread records, Tiehchenshan gas field,
Taiwan.

B 5 5 0 0 F O R T R A N C O M P I L A T I O N

C COMPUTING THE AVERAGE VELOCITIES AND THE INTERNAL VELOCITIES
C FOR SINGLE SPLIT-SPREAD SHOOTING RECORDS

DIMENSION TZRO(20),TX1(20),TX2(20),DELT(20),DELTAT(20),
1 RADIAN(20),THETA(20),VAVG1(20),VAVG2(20),VBAR1(20),
2 VBAR2(20),VBAR(20),VMID(20),VINT(20),
3 RTZRO(20),RTX1(20),RTX2(20)

READ 1, N, VDATUM

1 FORMAT(I10/F10.2)

READ 3, FCORR

2 READ 3, X

3 FORMAT(F10.4)

READ 4, (RTZRO(I), I=2, N)

READ 4, (RTX1(I), I=2, N)

READ 4, (RTX2(I), I=2, N)

4 FORMAT(3F10.5)

I=2

C THE FILTER CORRECTION TIME IS FCORR SECONDS

5 TZRO(I)=RTZRO(I)-FCORR

TX1(I)=RTX1(I)-FCORR

TX2(I)=RTX2(I)-FCORR

DELT(I)=TZRO(I)-TZRO(I-1)

DELTAT(I)=TX1(I)-TX2(I)

RADIAN(I)=ARSIN(VDATUM*DELTAT(I)/(2,*X))

THETA(I)=RADIAN(I)*180./3.14159

I=I+1

IF(I,LE,N) GO TO 5

PRINT 6

6 FORMAT(///22X,"THETA(1)",12X,"THETA(2)",13X,"THETA(3)")

PRINT 7, (THETA(I), I=2, N)

7 FORMAT(/10X,3F20.4/)

CALL VAVG1(TZRO,TX1,X,RADIAN,VBAR1,N)

CALL VAVG2(TZRO,TX2,X,RADIAN,VBAR2,N)

DO 8 I=1,N

8 VBAR(I)=0.5*(VBAR1(I)+VBAR2(I))

PRINT 9

9 FORMAT(1H0,22X,"VBAR(1)",13X,"VBAR(2)",14X,"VBAR(3)")

PRINT 10, (VBAR(I), I=2, N)

10 FORMAT(/10X,3F20.2/)

CALL VMID(DELT,VBAR,VINT,N)

PRINT 11, X

11 FORMAT(///F10.2)

PRINT 12, (RTX1(I), I=2, N)

PRINT 12, (RTZRO(I), I=2, N)

PRINT 12, (RTX2(I), I=2, N)

12 FORMAT(1H04F10.5)

GO TO 2

STOP

END

```
SUBROUTINE VAVG1(TZRO, TX1, X, RADIAN, VBAR1, N)
DIMENSION TZRO(20), TX1(20), RADIAN(20), VBAR1(20)
```

```
I=2
```

```
11 AA=TZRO(I)*X*SIN(ABS(RADIAN(I)))
```

```
BB=TX1(I)**2-TZRO(I)**2
```

```
IF(RADIAN(I).GE.0.) VBAR1(I)=(AA+SQRT(ABS(AA**2+BB*X**2)))/BB
```

```
IF(RADIAN(I).LT.0..AND.TX1(I).GT.TZRO(I)) VBAR1(I)=(-AA+SQRT(
1ABS(AA**2+BB*X**2)))/BB
```

```
IF(RADIAN(I).LT.0..AND.TX1(I).LT.TZRO(I)) VBAR1(I)=(-AA-SQRT(
2ABS(AA**2+BB*X**2)))/BB
```

```
I=I+1
```

```
IF(I=N)11,11,12
```

```
12 PRINT 13
```

```
13 FORMAT(1H0,21X,"VBAR1(1)",12X,"VBAR1(2)",13X,"VBAR1(3)")
```

```
PRINT 14,(VBAR1(I),I=2,N)
```

```
14 FORMAT(/10X,3F20.2/)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VAVG2(TZRO, TX2, X, RADIAN, VBAR2, N)
DIMENSION TZRO(20), TX2(20), RADIAN(20), VBAR2(20)
```

```
I=2
```

```
11 AA=TZRO(I)*X*SIN(ABS(RADIAN(I)))
```

```
BB=TX2(I)**2-TZRO(I)**2
```

```
IF(RADIAN(I).LE.0.) VBAR2(I)=(AA+SQRT(ABS(AA**2+BB*X**2)))/BB
```

```
IF(RADIAN(I).GT.0..AND.TX2(I).GT.TZRO(I)) VBAR2(I)=(-AA+SQRT(
1ABS(AA**2+BB*X**2)))/BB
```

```
IF(RADIAN(I).GT.0..AND.TX2(I).LT.TZRO(I)) VBAR2(I)=(-AA-SQRT(
2ABS(AA**2+BB*X**2)))/BB
```

```
I=I+1
```

```
IF(I=N)11,11,12
```

```
12 PRINT 13
```

```
13 FORMAT(1H0,21X,"VBAR2(1)",12X,"VBAR2(2)",13X,"VBAR2(3)")
```

```
PRINT 14,(VBAR2(I),I=2,N)
```

```
14 FORMAT(/10X,3F20.2/)
```

```
RETURN
```

```
END
```

```
SUBROUTINE VMID(DELT, VBAR, VINT, N)
DIMENSION DELT(20), VBAR(20), VINT(20)
```

```
I=2
```

```
DLT=0.
```

```
15 DLT=DLT+DELT(I)
```

```
DD=VBAR(I-1)**2*(DLT-DELT(I))
```

```
VINT(I)=SQRT(ABS((VBAR(I)**2+DLT-DD)/DELT(I)))
```

```
I=I+1
```

```
IF(I.LE.N) GO TO 15
```

```
PRINT 16
```

```
16 FORMAT(1H0,22X,"VINT(1)",13X,"VINT(2)",14X,"VINT(3)")
```

```
PRINT 17,(VINT(I),I=2,N)
```

```
17 FORMAT(/10X,3F20.2)
```

```
RETURN
```

```
END
```


9. APPENDIX IV

Computing program of the velocities of the fluids
contained in the reservoir rocks, Tiehchenshan gas field,
Taiwan.

B 5 5 0 0 F O R T R A N C O M P I L A T I O N

```

C      COMPUTATION OF THE VELOCITIES OF THE FLUIDS CONTAINED
C      IN THE RESERVOIR ROCKS, TIEHCHENSHAN GAS FIELD, TAIWAN
C      THE DEFINITIONS OF THE SYMBOLS ARE AS FOLLOWS
C      VSHM=VELOCITY OF SHALE MATRIX
C      VSSM=VELOCITY OF SANDSTONE MATRIX
C      VSHA=VELOCITY OF SHALE AT A
C      VSHB=VELOCITY OF SHALE AT B
C      VSSA=VELOCITY OF SANDSTONE AT A
C      VSSB=VELOCITY OF SANDSTONE AT B
C      PHISHA=POROSITY OF SHALE AT A
C      PHISHB=POROSITY OF SHALE AT B
C      PHISSA=POROSITY OF SANDSTONE AT A
C      PHISSB=POROSITY OF SANDSTONE AT B
C      RHOSHA=DENSITY OF SHALE AT A
C      RHOSHB=DENSITY OF SHALE AT B
C      RHOSSA=DENSITY OF SANDSTONE AT A
C      RHOSSB=DENSITY OF SANDSTONE AT B
C      REFLA=REFLECTIVITY AT A
C      RHOVSB=(DENSITY OF SANDSTONE AT B)
C      X (VELOCITY OF SANDSTONE AT B)
C      VGSSB=VELOCITY OF SANDSTONE IF CONTAINING GAS AT B
C      VWSSB=VELOCITY OF SANDSTONE IF CONTAINING SALT WATER AT B
C      VGAS=VELOCITY OF FLUID IN SANDSTONE IF IT IS GAS
C      VWATER=VELOCITY OF FLUID IN SANDSTONE IF IT IS SALT WATER

      READ 1,VSHM,VSSM,PHISSA
1  FORMAT(3F10.3)
      READ 2,VSHA,VSSA
2  FORMAT(2F10.2)
3  READ 2,VSHB,VSSB
      READ 4,PHISSB
      READ 4,REFLR
4  FORMAT(F10.3)
      PHISHA=(VSHM-VSHA)/(VSHA*(VSHM/1524,-1.))
      PHISHB=(VSHM-VSHB)/(VSHB*(VSHM/1524,-1.))
      RHOSHA=PHISHA+2.68*(1.-PHISHA)
      RHOSHB=PHISHB+2.68*(1.-PHISHB)
      RHOSSA=0.0007168*PHISSA+2.68*(1.-PHISSA)
      REFLA=(RHOSSA*VSSA-RHOSHA*VSHA)/(RHOSSA*VSSA+RHOSHA*VSHA)
      RHOVSB=RHOSHB*VSHB*(1.+REFLR*REFLA)/(1.-REFLR*REFLA)
      VGSSB=RHOVSB/(0.0007168*PHISSB+2.68*(1.-PHISSB))
      VWSSB=RHOVSB/(PHISSB+2.68*(1.-PHISSB))
      VGAS=(VGSSB*VSSM*PHISSB)/(VSSM-VGSSB*(1.-PHISSB))
      VWATER=(VWSSB*VSSM*PHISSB)/(VSSM-VWSSB*(1.-PHISSB))
      PRINT 5
5  FORMAT(/1X,"THE VELOCITY OF THE FLUID IN THE SANDSTONE AT SHOT POI
      INT")
      IF(VGAS.GT.300..AND.VGAS.LT.900.) GO TO 6
      IF(VWATER.GT.1300..AND.VWATER.LT.1900.) GO TO 8

```

```
6 PRINT 7,VGAS
7 FORMAT(/F30.2,5X,"METERS/SEC.",5X,"THIS IS A PRODUCING LOCATION")
GO TO 10
8 PRINT 9,VWATER
9 FORMAT(/F30.2,5X,"METERS/SEC.",5X,"THIS IS A NON-PRODUCING ZONE")
10 PRINT 11
11 FORMAT(/4X,"VSHM",6X,"VSSM",6X,"VSHA",6X,"VSSA",6X,"VSHB",6X,
1"VGSSB",5X,"VWSSB",5X,"PHISSA",4X,"PHISSB",4X,"RHOSHA",4X,"RHOSHB"
2,5X,"REFLR")
PRINT 12, VSHM,VSSM,VSHA,VSSA,VSHB,VGSSB,VWSSB,PHISSA,PHISSB,
1RHOSHA,RHOSHB,REFLR
12 FORMAT(12F10,3)
PRINT 13
13 FORMAT(/5X,"VGAS",5X,"VWATER",4X,"VSSB (FOR CHECKING USE)")
PRINT 14,VGAS,VWATER,VSSB
14 FORMAT(/3F10,2)
GO TO 3
STOP
END
```

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