Chapter 5.
Isopach Mapping and Hydrocarbon Pore Volume

5.1 Objective

To estimate the hydrocarbon pore volume of a reservoir

5.2 Background

An isopach is a line representing equal stratigraphic thickness, and an isopach (or isopachous) map is one that shows bv means of isopachs the variations in true stratigraphic thickness of a stratum, formation, or group of formations. The subsurface isopach map is based primarily on formation thicknesses determined from well cuttings, cores or geophysical logs. Although isopachs must be drawn to agree with thicknesses plotted on the map, their spacing and the nature of thickening and thinning may be guided by other known facts concerning the source of sediments, their relative rates of deposition, truncation, and so forth. An isopach map drawn strictly to the numerical values and without regard to the geologic reasons for thickening and thinning of formations, is likely to present a picture difficult to integrate or reconcile with other geologic facts.

An example of an isopach map is shown in Figure 5.1. Close spacing of contours from zero to 200 feet on the west side of the map indicates the area of truncation where the formations are tilted along the granite mass. The conclusion is that the higher rate of thinning is caused by truncation of upturned edges of the strata, and the close spacing of contours is, therefore, maintained parallel to the granite area. Around the uplift on the east side of the map area, control points indicate a high rate of thickening, with the uplift being the source of these sediments.

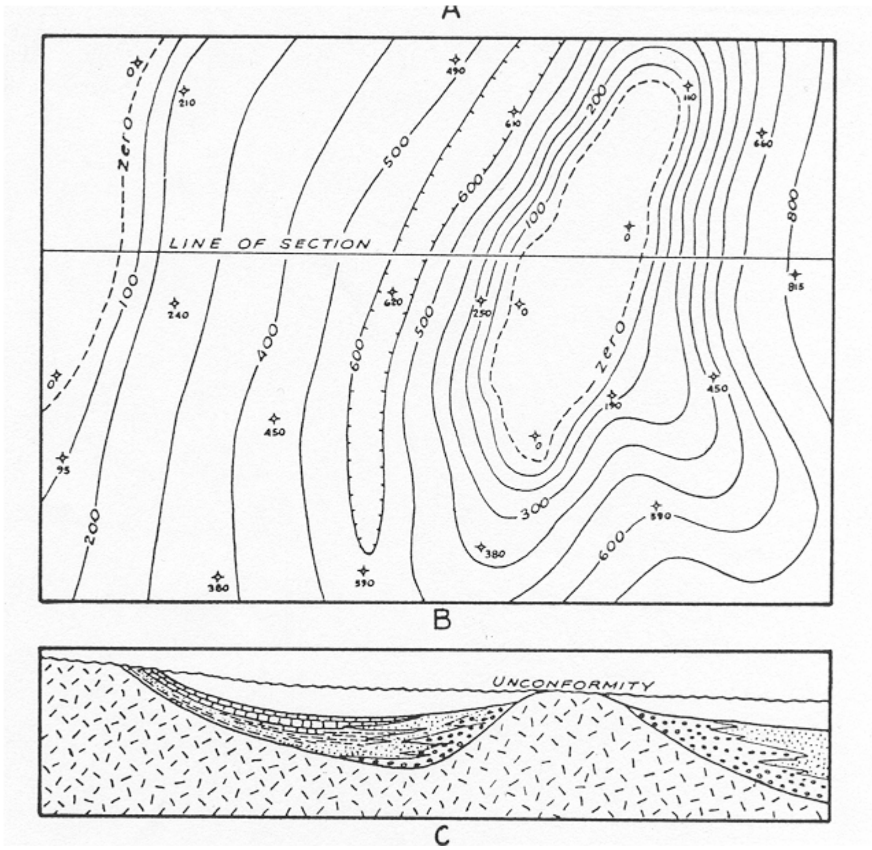


Figure 5.1 Top and cross-sectional views of an isopach map of the thickness of sediments between an unconformity and basement.

A common source of error in subsurface isopach maps is the too great apparent stratigraphic interval caused by steeply dipping strata at the point where the well is drilled. Obviously, a correct interval is obtained in a straight hole only where the strata are horizontal. Since most wells are drilled on structures, there are many opportunities for them to penetrate formations where appreciable dips exist; if dips are steep, the error in interval may be large enough to affect the regional aspects of the isopach map; there is little doubt that apparent thinning of section on the tops of some structures is the result of this condition. As an extreme case consider a deviated well in dipping beds as shown in Figure 5.2. The measured thickness (MT) greatly exceeds both the true vertical thickness (TVT) and the true stratigraphic thickness (TST) of the formation of interest. The result will impact the geologists ability to correlate from well-to-well and interpret the depositional history, and will impact the engineers ability to estimate the volume of hydrocarbons in place and flow capacity of a well.

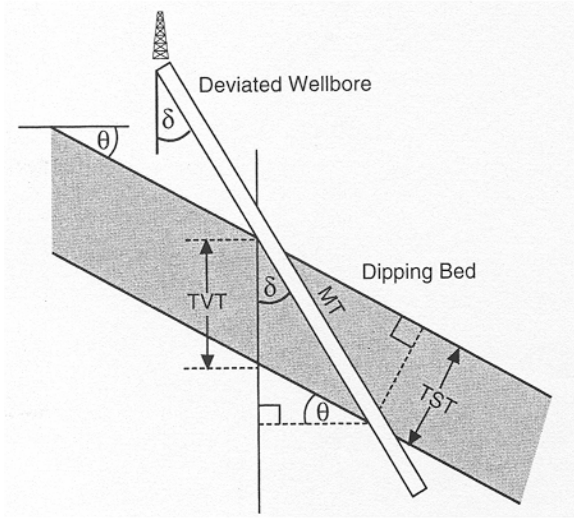


Figure 5.2 TVD principle for a deviated well and a dipping bed

Although subsurface maps representing drilled thicknesses are commonly called isopach maps, a more precise term is isochore. An isochore map is one that shows by contours drilled thicknesses of formations without regard to true stratigraphic thicknesses. The term is not ordinarily used but is mentioned because it appears occasionally in geologic literature.

Isopach and isochore maps are generally used:

a. for predetermining drilling depths to specific horizons in wildcat wells;
b. to locate buried structures in regions where formations habitually become thinner over structural crests.
c. In estimating the elevation of a datum bed below the total depth of a well that penetrated a higher known stratigraphic horizon.
d. To calculate the volume of oil in a formation

Figure 5.3 shows a structure contoured on the top of a producing formation. A few dry holes have been drilled on the flanks of the structure below the oil-saturated portion of the reservoir, and by means of these holes, the oil-water contact is established at a structural elevation of 660 feet. This contact is shown by the heavy dashed line on the map and also in the cross section. Since the thickness of the oil column is less than the thickness of the reservoir rock, the computation of the volume of saturated sandstone is simple, because the isopach map of the saturated rock is exactly the same as the structure map, with only the contour values being changed. It is evident in the cross section that the extra structural contour (oil-water line) of 660-foot elevation is the same as the zero isopach contour for the saturated zone. Likewise, the 700-foot structural contour becomes the 40-foot isopach line, the 800 becomes the 140, and so forth. The thickest part of the zone is on the top of the structure at an elevation of 1,050 feet, here the thickness is 390 feet.

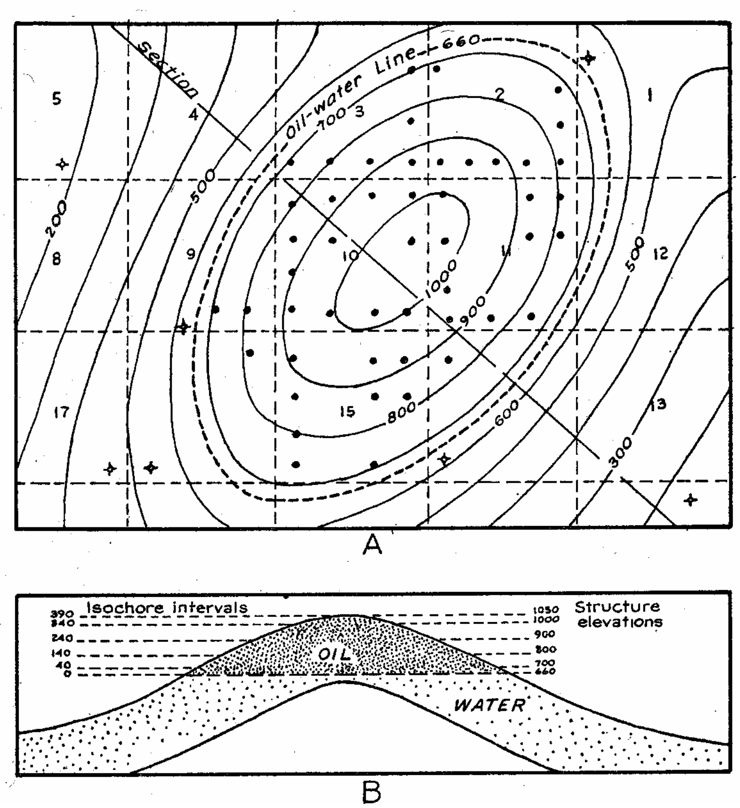


Figure 5.3 Structure map and corresponding isopach of the producing interval.

Two methods will be applied in this lab to estimate volumes from an isopach map. The first will be to use a planimeter to estimate the average thickness within the isopach area. The second method utilizes a software package that includes digitizing the isopach map and applying geostatistics to determine the volumetrics.

5.3 Planimeter

5.3.1 Planimeter Architecture

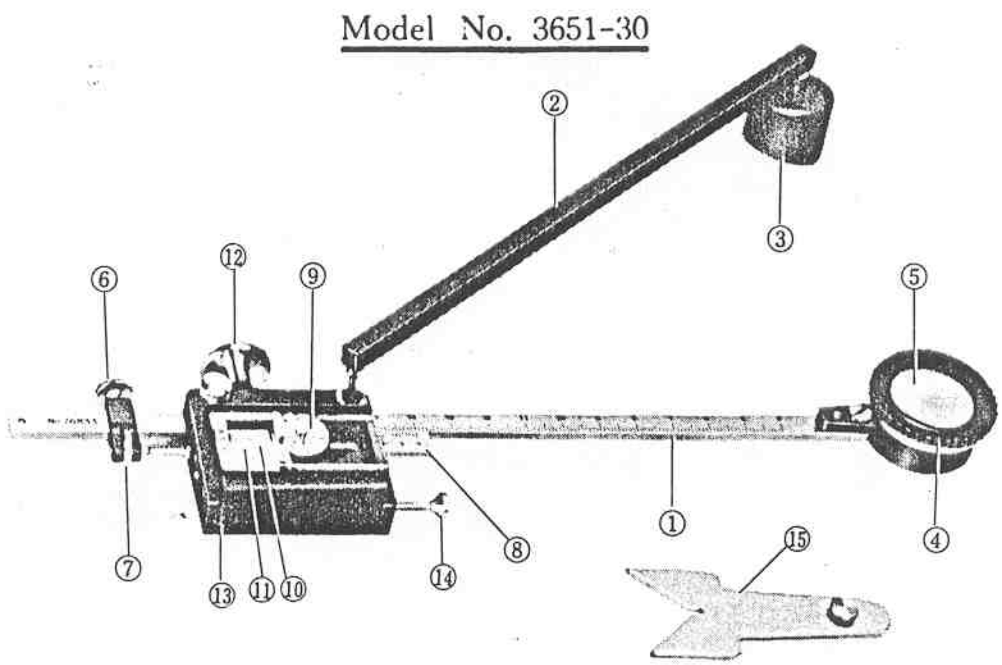


Figure 5.4 Planimeter components.

Part #	Name	Part #	Name
1	Tracer Arm	9	Revolution Recording Dial
2	Pole Arm	10	Measuring Wheel
3	Pole Weight	11	Measuring Wheel Vernier
4	Hand Grip	12	Idler Wheel
5	Tracing Magnifier (Tracing Pin)	13	Carriage
6	Clamp Screw	14	Zero Setting Slide Bar
7	Fine Movement Screw	15	Checking Bar
8	Tracer Arm Vernier		

5.3.2 Planimeter Reading

The reading is shown by a drum and dial on a planimeter as illustrated in Figure 5.5.

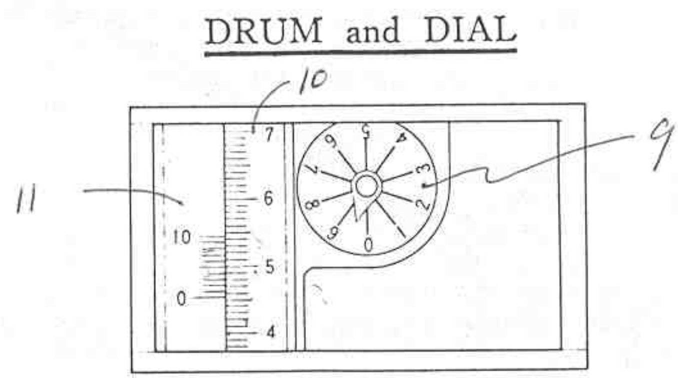


Figure 5.5 Drum and dial of planimeter.

Guidelines for reading the planimeter are:

1. The dial (Part 9) numbered 1 to 0 (10) indicates the number of revolutions of the measuring wheel (Part 10).
2. The Measuring Wheel (Part 10) is numbered 1 to 0 (10) and each number represents 1/10 of a revolution of the Measuring Wheel.
3. Each of the 10 numbered parts of the Measuring Wheel is further divided into 10 parts be graduations so each graduation represents 1/100 of a revolution of the Measuring Wheel.
4. The vernier (Part 11) represents 1/10 of each Measuring Wheel graduation (1/100 revolutions) or 1/1000 of a revolution of the Measuring Wheel.

5.3.3 Hydrocarbon in Place by the Volumetric Method

The standard cubic feet of gas in a reservoir which has a gas pore volume of V_g cubic feet is simply B_g V_g, where B_g is expressed in units of standard cubic feet per cubic foot. As the gas volume factor B_g changes with pressure, the gas in place also changes as the pressure declines. The gas pore volume V_g may also be changing owing to water influx into the reservoir. The gas pore volume is related to the bulk or total reservoir volume by the average porosity ϕ and the average connate water S_w.. The bulk reservoir volume V_b is commonly expressed in acre-feet, and the standard cubic feet of gas in place, G, is given by

$$G = 43{,}560 \times V_b \times \phi \times (1 - S_w) \times B_g \qquad (5.1)$$

Similarly for an oil well, the standard barrel of oil in place N is given by

$$N = 7758 \times V_b \times \phi \times (1 - S_w) \times B_o \qquad (5.2)$$

The volumetric method makes use of subsurface and isopachous maps based on the data from electric logs, cores, and drill-stem and production tests. A *subsurface contour* map is a map showing lines connecting points of equal elevations on the top of a marker bed, and is therefore a map showing geologic structure. A net *isopachous* map is a map showing lines connecting points of equal net formation thickness, and the individual lines connecting points of equal thickness are called *isopach* lines. The reservoir engineer uses these maps to determine the bulk productive volume of the reservoir. The contour map is used in preparing the isopachous maps where there is an oil-water, gas-water, or gas-oil contact. The contact line is the zero isopach line. The volume is obtained by planimetering the areas between the isopach lines of the entire reservoir or of the individual units under consideration. The principal problems in preparing a map of this type are the proper interpretation of net sand thickness from the well logs, and the outlining of the productive area of the field as defined by the fluid contacts, faults, or permeability barriers on the subsurface contour map.

Two methods are commonly used to determine the approximate volume of the productive zone from the planimeter readings.

1) Pyramidal Method.

The volume of the frustum of a pyramid is given by

$$\Delta V_b = \frac{h}{3}(A_n + A_{n+1} + \sqrt{A_n A_{n+1}}), \tag{5.3}$$

where ΔV_b is the bulk volume in acre-feet, A_n is the area enclosed by the lower isopach line in acres, A_{n+1} is the area enclosed by the upper isopach line in acres, and *h* is the interval between the isopach lines in feet. This equation is used to determine the volume between successive isopach lines and the total volume is the sum of these separate volumes.

2) Trapezoidal Method

The volume of a trapezoid is

$$\Delta V_b = \frac{h}{2}(A_n + A_{n+1}), \tag{5.4}$$

so, for a series of successive trapezoids

$$\Delta V_b = \frac{h}{2}(A_0 + 2A_1 + 2A_2 ... 2A_{n-1} + 2A_n) + t_{avg} A_n, \tag{5.5}$$

where A_0 is the area enclosed by the zero isopach line in acres; A_1, A_2, . . . A_n are the areas enclosed by successive isopach lines in acres; t_{avg} is the average thickness above the top or maximum thickness isopach line in feet; and h is the isopach interval.

For best accuracy the pyramidal formula should be used; however because of its simpler form, the trapezoidal formula is commonly used which introduces an error of 2 per cent when the ratio of successive areas is 0.50. Therefore, a commonly adopted rule in utilization programs is wherever the ratio of the areas of any two successive isopach lines is smaller than five tenths, the pyramidal formula is applied. Whenever the ratio of the areas of any two successive isopach lines is found to be larger than five tenths, the trapezoidal formula is applied.

5.4 Procedures to Calculate Hydrocarbon Pore Volume from Planimeter Measurements

Example 5.1 shows the method of calculating the volume of a gas reservoir from an isopachous map, Figure 5.6. The volume between areas A_4 and A_5, by the trapezoidal equation is 570 ac-ft, compared with the more accurate figure of 558 ac-ft by the pyramidal equation. Where the formation is rather uniformly developed and there is good well control, the error in the net bulk reservoir volume should not exceed a few per cent.

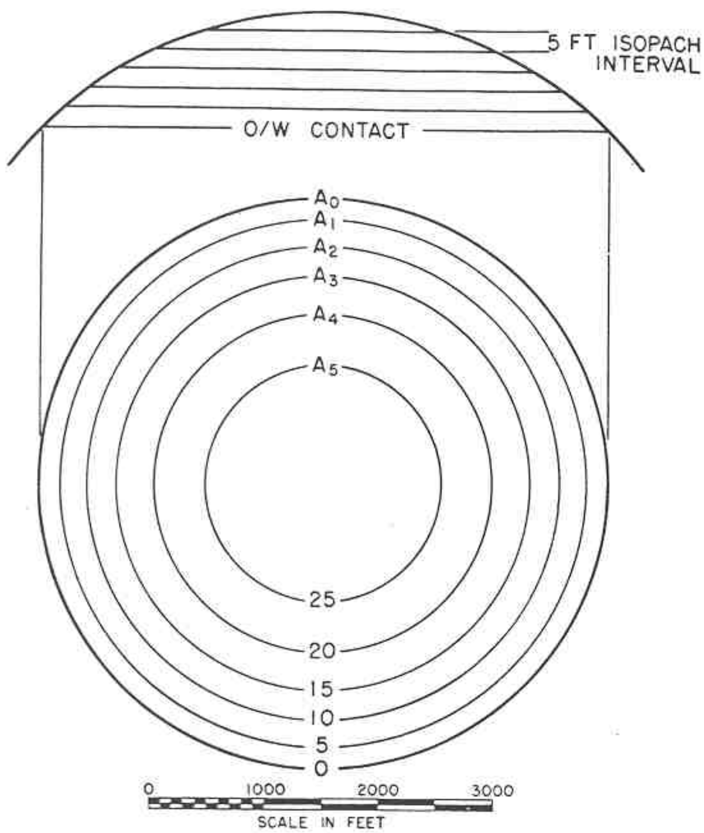


Figure 5.6 Cross section and isopachous map of an idealized reservoir. (from Craft & Hawkins)

Example 5.1. Calculating the net volume of an idealized reservoir from the iopachous map shown in Figure 5.6.

Given: The planimetered areas in Figure 5.6 within each isopach line, A_0, A_1, A_2, etc. and the planimeter constant.

Solution:

Table 5.1 Calculation Procedures for Total Pore Volume

Productive Area	Planimeter Area Sq in.	Area Acres	Ratio of Areas	Interval h, ft	Equation	ΔV ac-ft
A_0	19.64	450				
A_1	16.34	375	0.83	5	Trap.	2063
A_2	13.19	303	0.80	5	Trap.	1695
A_3	10.05	231	0.76	5	Trap.	1335
A_4	6.69	154	0.67	5	Trap.	963[a]
A_5	3.22	74	0.48	5	Pyr.	558[b]
A_6	0.00	0	0.00	4	Pyr.	99[c]
Total						6713

For a map scale of one inch = 1000 ft; one square inch = 22.96 acres.

[a] $\Delta V = \frac{5}{2}(231 + 154) = 963 ac - ft$

[b] $\Delta V = \frac{5}{3}(154 + 74 + \sqrt{154 \times 74}) = 558 ac - ft$

[c] $\Delta V = \frac{4}{3}(74) = 99 ac - ft$

5.5 Data Analysis

1) Per Well

Determination of hydrocarbons-in-place can be calculated from either of the following equations.

$$HIP = c\frac{A}{B_{oi}}\sum_{i=1}^{n} h_i\phi_i(1-S_{w_i}) \\ = c\frac{Ah_p\bar{\phi}(1-\overline{Sw})}{B_i} \tag{5.6}$$

where c is a constant equal to 7358 for oil and 43560 for gas, respectively and B is B_o for oil and B_g for gas. The steps to evaluate the potential of a well are:

a. apply cutoffs to determine intervals which meet criteria.
b. Apply the appropriate averaging technique
c. apply a recovery factor to remaining intervals to account for displacement efficiency.

Consider the following hypothetical example.

Depth, ft	h_i	ϕ_i	ϕ_i h_i	S_{wi}	ϕ_i h_i S_{wi}	Remarks
1600-02	2	0.02				Tight
1602-04	2	0.10	0.2	0.20	0.04	Pay
1604-06	2	0.20	0.4	0.30	0.12	Pay
1606-08	2	0.15	0.3	0.60	-	Water

Since log and core data is acquired on a depth basis, the parallel model is applicable.

$$h_p = \sum_{i=1}^{2} h_i = 4'$$

$$\bar{\phi}h_p = \sum_{i=1}^{2} \phi_i h_i = 0.6'$$

$$\left(\bar{\phi}h_p\right)\overline{S_w} = \sum_{i=1}^{2} \phi_i h_i S_{wi} = 0.16'$$

Recovery factor can be calculated by:

(i) material balance (requires history)
(ii) core tests (requires special core analysis)
(iii) log analysis (easy but not precise)

$$(RF)_{wd} = \frac{S_{xo} - S_w}{1 - S_w} \tag{5.7}$$

$$(RF)_{dcp} = \frac{1}{2}(RF)_{wd} \tag{5.8}$$

correlations, which are a function of drive mechanism, lithology, and GOR.

2) Per Field or Area

Equation 5.6 can be used to determine hydrocarbons-in-place on a fieldwide or area basis, but with a slight difference. Consider the following cases.

(i) Constant properties

The simpliest case is to assume constant properties (net pay, porosity, etc) throughout the reservoir. This relies on performing appropriate averaging techniques, such as the following,

$$\bar{h} = \frac{\sum_{i=1}^{N} h_i}{N}, \tag{5.9}$$

where h_i is the thickness for well i, N is the number of the wells, and $\bar{h}$ is the average thickness.

(ii) Variable properties

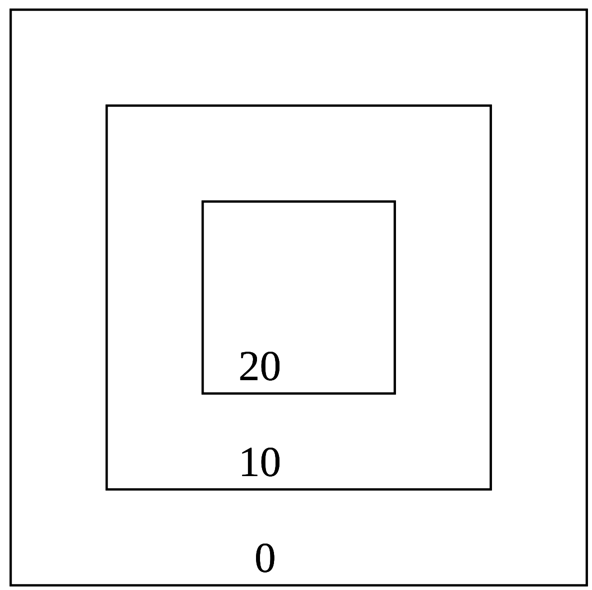
In this case each well has a value of the property, which is mappable (isopach) within the areal plane. Planimetering and digitizing are examples of this mapping. Three types of isopach maps can be constructed:

a. net pay isopach reveals the distribution and areal extent of the net pay only. For estimating hydrocarbons-in-place, both average porosity and saturation are necessary.
b. Pore volume map (ϕh) provides the distribution relative the storage capacity of the formation. In this case, an average water saturation is needed.
c. Hydrocarbon pore volume map ($\phi h S_o$) exhibits the extent of the hydrocarbons within the porous rock.

5.5 Exercise in Class

Calculate the oil-in-place for the hypothetical reservoir shown in the figure on the next page.

Isopach mapping



ϕ = 10%
S_w = 50%
B_{oi} = 1.0 rbbl/stb

OOIP = ________Bo

Net pay map
Contour Interval = 10 ft.
Map scale: 1” = 1000 ft.

Planimeter #___________
Conversion factor = _______________acres/unit