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Estimating the Amount of Oil and Gas Accumulation from Top Seal and Trap Geometry

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ABSTRACT

Oil and gas volumes are controlled by top-seal capillary properties, spillpoints, and trap geometry. The top-seal capillary properties and seal capacity can be estimated from the equivalent grain size (EGS) method. The EGS method uses an experimentally derived relationship between pore-throat size, porosity, and grain size to evaluate seal capacity. A "pure spillpoint-limited trap" is one in which the hydrocarbon column height is determined solely by the spillpoints. The observed hydrocarbon column in this trap is less than that which can be held by top-seal capacity. This trap type will be dominated by gas. In a "capillary and spillpoint mixed trap," where both oil and gas can be filled down to the spillpoint, both top-seal capacity and spillpoint control relative oil and gas column heights. A "pure capillary-limited trap" is that where the oil and gas are not filled down to the spillpoint.

Top seal and spillpoint have been the focus of seal analyses; however, a case study for fields referred to as AN and YA in this chapter demonstrates an important relationship between trap geometry and top-seal capacity. These two fields have the same top-seal capacity, but the total column heights, as well as the relative oil and gas columns, are very different. This is explained by the different ratios of the base area to its relief in the two fields. The ratio of the area to its relief of the AN field is smaller, whereas that of the YA field is much larger. Given the same top-seal capacity, a trap with a higher area-to-relief ratio can hold a larger gas column because the oil pushed down by the migrated gas reduces its column height remarkably.

Thus, the EGS method can provide new insights into understanding hydrocarbon fill patterns in fields and prospects, including fault traps.

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INTRODUCTION

A seal analysis is important in order to understand the oil and gas accumulation in fields and prospects, including fault traps (e.g., Gussow, 1954; Downey, 1994; Sales, 1997). The seal capacity of a cap rock (the maximum hydrocarbon column height that a cap rock can hold) does not control the hydrocarbon column heights in all traps, even if sufficient amounts of hydrocarbons were supplied to saturate the trap. Hydrocarbons only leak through the top seal in traps where the height of the trap is larger than the maximum hydrocarbon column height that the top seal can hold (Figure 1). However, in traps where the maximum hydrocarbon column height is larger than the height of the trap, the overcharged hydrocarbons will migrate out from the trap through the spillpoint because these traps are fully filled with hydrocarbons before the seal failure occurs (Figure 1).

Sales (1997) suggested that traps are characterized as oil prone or gas prone by the relationship between the seal capacity and the height of the trap described as above. A practical method is required to evaluate the seal capacity for applying Sales' concept to petroleum exploration effectively. The authors modified and applied the equivalent grain size (EGS) method, which gives a macro view of the effective sealing of a trap (Nakayama and Sato, 2002). The aims of this chapter are (1) to introduce the concept and methodology of the EGS method and (2) to discuss the factors controlling oil and gas accumulation through a case study of a discovered field using the EGS method. It is also hoped that this newly developed method to evaluate the top-seal capacity should help the prediction of the oil and gas accumulation in fault traps.

OVERVIEW: TRAP CLASSIFICATION

Figure 2 shows three types of traps classified by the relationship between the height of a trap and the maximum hydrocarbon column height to be held by the top seal (Sales, 1997). According to Sales, traps are also characterized as oil prone or gas prone by this relationship. Gas with a lower density and higher mobility than oil preferentially fills a trap from the top. Even if a trap has been fully filled with oil, gas that migrated in a later stage would accumulate in the trap by replacing the preexisting oil.

In traps where the spillpoint is located above the level that is determined by the maximum gas column that the cap rock can hold (called "pure spillpoint-limited trap" in this chapter), the gas that migrated in the upper part of the trap pushes down the oil reserves, so that the oil tends to migrate out into the adjacent reservoirs in the updip direction through the spillpoint. The whole trap will eventually be occupied by gas. In traps where the spillpoint is located below the level that is determined by the maximum oil column that the cap rock can hold (called "pure capillary-limited trap" in this chapter), oil that is pushed down by migrated gas does not leak out through the spillpoint. The gas that is present above the oil may migrate upward by top-seal failure during the stage of gas migration. In traps where the spillpoint is located between the levels of the maximum possible oil and gas columns that the cap rock can hold (called "capillary and spillpoint mixed trap" in this chapter), overcharged gas migrates out from the trap through the top seal before the gas occupies the whole trap. Therefore, the upper part of the trap is filled with gas, but the oil still remains in the lower part of the trap, even if some oil may have migrated out through the spillpoint.

THE EQUIVALENT GRAIN SIZE METHOD

Concept of the EGS Method: Hydrostatic Trap-equilibrium Equation

Over the geological timescale of hydrocarbon migration, only capillary-pressure properties are needed to understand the static fluid-flow model. Recent geochemical research suggests that in most of the economical accumulations, hydrocarbons have migrated in a separate oil or gas phase (Barker, 1978; Hunt, 1979). Water, being the wetting phase, can migrate through any medium if there is a pore, whereas hydrocarbons can migrate through media only if the driving force exceeds the capillary entry pressure of that media.

Migrating hydrocarbons from the source rocks are trapped when a downward force resulting from the capillary pressure caused by the pore throat of the cap rock and interfacial tension of fluids restrains the upward buoyancy force of the hydrocarbon at the sealing surface (Figure 3). Hydrocarbons will be trapped until the buoyancy force reaches equilibrium with the capillary force at the top seal; the buoyancy force increases as the hydrocarbon column height increases. The situation where hydrocarbons have accumulated to the maximum possible column height is described by the hydrostatic trap-equilibrium equation (Nakayama and Van Siclen, 1981):

$$2\gamma \cos\theta / R = gH_c(\rho_w - \rho_h) \quad (1)$$

where γ is the interfacial tension; θ is the wettability (interfaced angle); R is the pore-throat radius; g is the

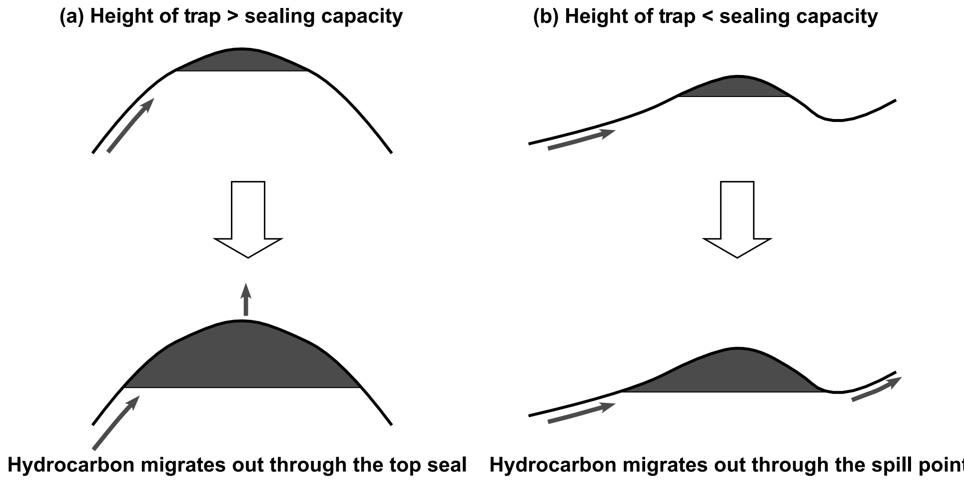

FIGURE 1. Schematic model showing different processes of hydrocarbon accumulation controlled by the relationship between the height of a trap and seal capacity. Overcharged hydrocarbons migrate out from a trap through either a top seal (a) or a spillpoint (b).

acceleration of gravity; ρ_w is the density of formation water; ρ_h is the density of hydrocarbons; and H_c is the maximum hydrocarbon column height.

In the traps where the buoyancy of hydrocarbon reaches a balance with the capillary forces, using the observed original hydrocarbon columns, it is possible to back-calculate an effective pore-throat radius assuming a proper consideration of interfacial tension, wettability, and fluid densities. This means that hydrocarbons cannot leak until a certain amount is trapped at the top of reservoirs, assuming a water-wet condition in cap rocks (Berg, 1975; Schowalter, 1979). Because water is the wetting phase, it can always go through permeable media.

Concept of the EGS Method: Conversion of Pore-throat Size to Grain Size

The ideal grain size, EGS, of the cap rock can be used as a parameter in the evaluation of seal capacity. The sealing capacity for a top seal can be quantified by the hydrostatic trap-equilibrium equation (equation 1); therefore, it can be related to the pore-throat size in the cap rock. If a cap rock consists of equal-size spherical grains, then the pore-throat size is a function of grain size and porosity. Figure 4 shows that the pore-throat sizes vary with the packing geometry even if the grain sizes are equal (Nakayama and Van Siclen, 1981). According to Nakayama and Van Siclen (1981), the ratio of pore throat to grain diameter (COEF) is estimated from the theoretical packing geometry as follows (Figure 5):

$$\mathrm{COEF} = 2R/D_m = 1.92\phi^2 + 0.0882\phi \qquad (2)$$

where R is the pore-throat radius; D_m is the grain diameter; and ϕ is the porosity.

To evaluate this theoretical relationship, physical experiments measured the maximum oil column in a sample of artificial glass beads with a known grain-size distribution (Figure 6) (Nakayama and Sato, 2002). The apparatus consisted of pipelines and a glass cylinder with an artificial seal disk that is made of artificial glass beads in the center. Two inlet tubes (one for oil and the other for water) were attached at the bottom of the cylinder (Figure 7).

At first, the whole system was filled with water; the oil line was then opened forming an oil accumulation under the seal disk. For the oil, dodecane was used as a measurable oil sample. Because the theoretical column height was too high for this apparatus, the water line was pressurized with a certain column height of water (water manometer), so that the pressure at the bottom of this artificial trap could be controlled (Figure 7). The water column above the seal disk (water capillary) was used to record the leakage of oil through the

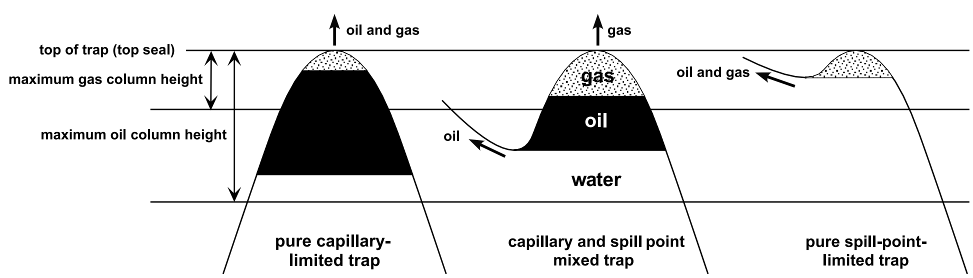

FIGURE 2. Schematic cross section showing three types of traps classified by the relation between the height of a trap and the maximum hydrocarbon column height to be held by the top seal (modified after Sales, 1997).

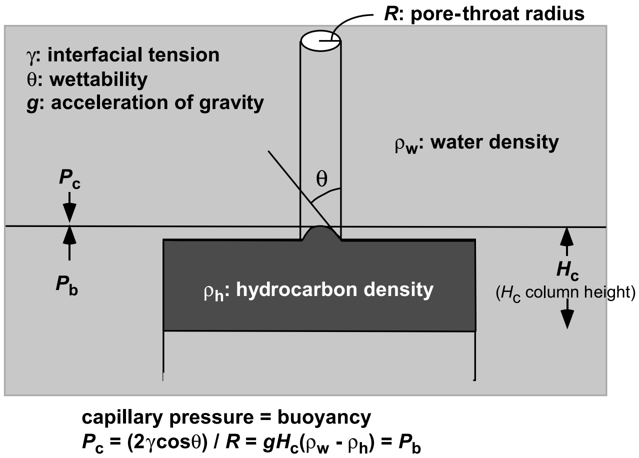

FIGURE 3. Schematic diagram showing hydrostatic equilibrium condition. Assuming that hydrocarbons have migrated in a separate hydrocarbon phase, the upward buoyancy must be smaller than the downward capillary pressure for the hydrocarbon accumulation in a trap. At the maximum hydrocarbon height, the buoyancy should be equal to the capillary pressure (hydrostatic trap-equilibrium equation).

top of the seal. Figure 8 is a plot of the column height measurements. The initial increase of pressure is caused by the oil invading the pore space in the artificial seal. The next phase of the experiment (pressure plateau) corresponds to hydrocarbon sealing. The phase with overpressure corresponds to seal leakage. The measured pressure of leakage is then converted into an equivalent oil column height.

The experiment used four artificial seal disks representing different grain sizes. From the hydrostatic trap-equilibrium equation (equation 1), the observed capillary-pressure values that were measured by the physical experiments were converted to the pore-throat size (Table 1). Using these results and the measured porosities of the artificial seals, the corrected relation between porosity and COEF (the ratio of pore-throat diameter to grain diameter) shown in Figure 5 was modified as

$$\mathrm{COEF} = 2R/D_\mathrm{m} = 3.085\phi^2 + 0.2087\phi \qquad (2a)$$

where R is the pore-throat radius; D_m is the grain diameter; and ϕ is the porosity.

The change in the values of constants in equation 2a from equation 2 can be explained by the drag effect at the grain surface for the case of the experiment. It is suggested to be closer to nature than to the theoretical case.

Assuming the relation between porosity and COEF that is derived from the experiment described above, the authors developed a spreadsheet to easily calculate the maximum oil and gas column height (Figure 9). In this spreadsheet, physical conditions, such as temperature, density, and interfacial tension, are automatically determined as a function of depth. After the observed oil and gas column height is obtained, the EGS is calculated on this sheet using an iterative technique of trial and error. The EGS is expressed in the phi scale (phi = $-\log_2 d$, where d is the grain size in millimeters); a higher grain size value in the phi scale corresponds to finer grain size and indicates higher sealing capacity.

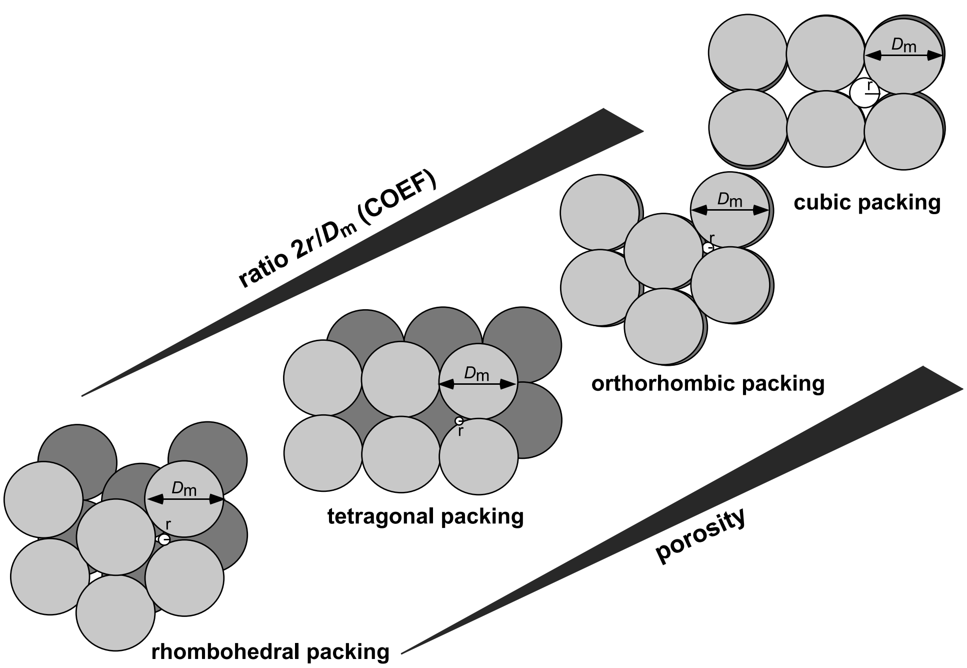

FIGURE 4. The theoretical relation of pore throat and porosity according to the packing types. COEF indicates the ratio of pore-throat diameter ($2r$) to grain size (D_m). COEF is a function of the porosity according to the geometrical calculation if the grains consist of equally-sized spheres.

Methodology

The advantages of the EGS method are that (1) it requires no rock samples; (2) it gives a macro view of the effective sealing of a trap; and

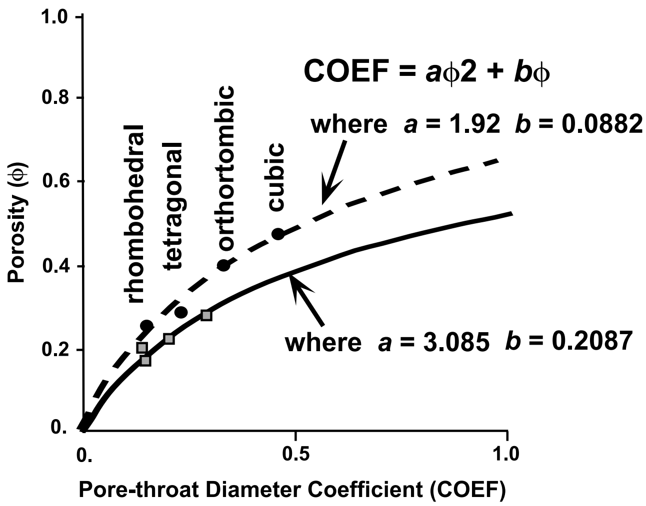

FIGURE 5. Approximations of the relationship between COEF and porosity obtained from the theoretical case using the different packing types (a = 1.92, b = 0.0882; after Nakayama and Van Siclen, 1981) and from the case that resulted from the physical experiment (a = 3.085, b = 0.2087).

(3) it indicates the primary seal property of the cap rock that is related to the lithological facies.

Conventionally, the seal property of the cap rock is estimated by measuring the pore-throat size of shale samples. Two conditions are required for this method. First, a seal sample must be available, and second, the sample must be representative of the entire trap (Downey, 1994). If the cap rock is not uniform over the entire trap, then the hydrocarbon accumulation should be affected by this situation. In other words, the observed hydrocarbon column height results from the effective seal capacity of the entire trap. The EGS determined from the observed hydrocarbon column height does not correspond to the actual grain size, but it indicates this effective seal capacity.

The EGS is more useful for the discussion of the primary seal property of the cap rock than for the discussion of the pore-throat size varying with the burial depth, because the grain size is independent of the porosity. The seal capacity is related to the grain size (not the pore size), which relates to lithological facies controlled by depositional environments in the EGS method. Advancing this concept, the EGSs that are calculated from the observed hydrocarbon column heights, where overlying cap rocks are the same in horizon and lithology, should be identical to other accumulations in the area. Consequently, when the suitable grain size holding the observed oil and gas column height in a field is determined, the maximum possible column height for the other traps within or near this field can be estimated using that grain size.

The EGS method also enables a quantitative evaluation or prediction of the relationship between the maximum oil and gas column heights and the heights of traps. Figure 10 shows the relations between the heights and top-seal depths of the assumed traps A and B, and the maximum oil and gas column heights derived from modeled EGS (8.0 phi), temperature, density, and porosity. Trap A plots between the lines of the maximum gas column height and the maximum oil column height, indicating that it is a capillary and spillpoint mixed trap, whereas trap B plots below the line showing the maximum gas column height, indicating that trap B is a gas-prone, pure spillpoint-limited trap. This technique indicates that trap A has more oil potential than trap B.

Two factors must be clarified for the prediction of the seal capacity using the EGS method. The first is the type of the trap that is used for the determination of the grain size, and the second is the spillpoint.

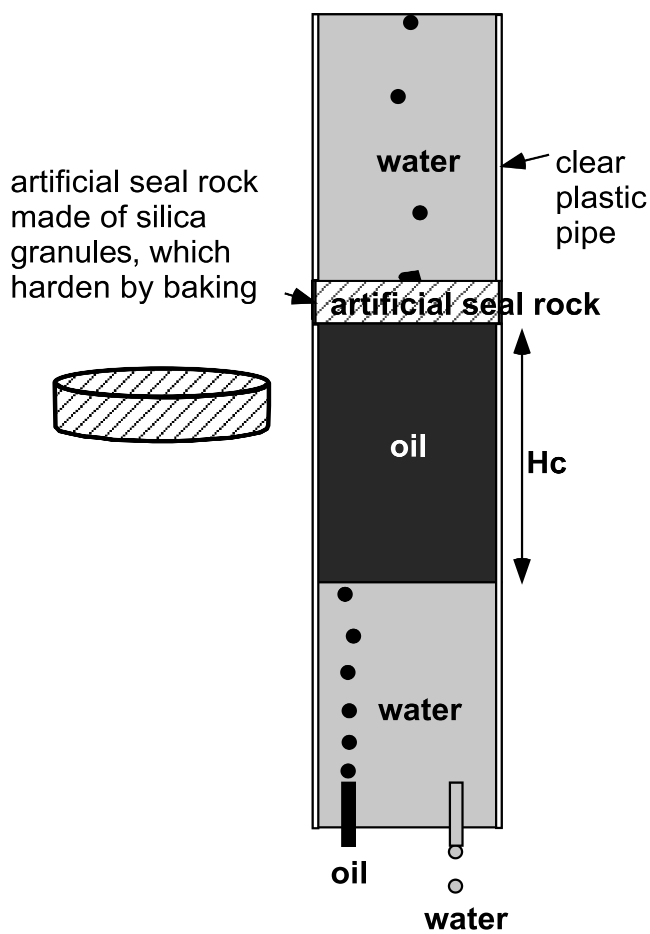

FIGURE 6. Schematic diagram showing the main cylinder of the physical experimental apparatus used to measure maximum oil column (H_C) with the artificially created seal. The artificial seals are made of silica beads with a known grain size.

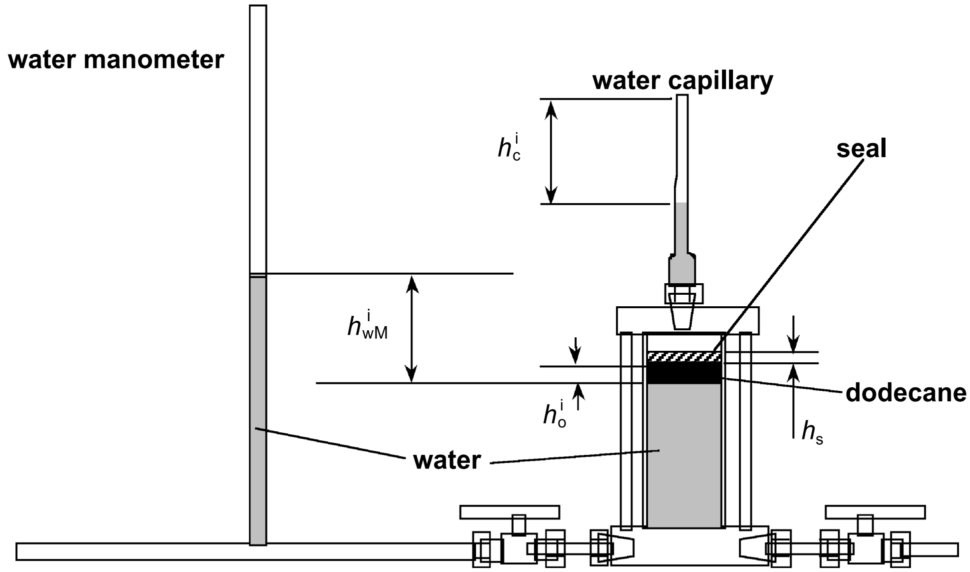

FIGURE 7. Schematic diagram showing the concept of the experiment for artificial seal measurement. For the actual measurement, the hydrodynamic force separately pushes the oil column as necessary. Setting up the seal-oil (dodecane)-water sequence (from the upper position) in the cylinder, the water column (h_{WM}) increases gradually in the water manometer. To detect the leaking, the water column in the water capillary (h_c) above seal is measured.

An EGS must be determined from the observed column heights of hydrocarbons. As described in the previous section, the total buoyancy of oil and gas reaches a balance with the capillary forces in a pure capillary-limited trap and a capillary and spillpoint mixed trap. In such cases, the estimated EGS can be used as an effective parameter to indicate the seal capacity. However, the hydrocarbon column height in a pure spillpoint-limited trap is commonly much shorter than the maximum column height that the top seal can hold. Therefore, the back-calculated EGS from the observed hydrocarbon column shows only the minimum value for the actual seal capacity.

The spillpoint may not correspond to the bottom of the maximum closure in all traps, because hydrocarbons can migrate out across a fault through sand-to-sand juxtaposition (Allan, 1989) or the point of smear-gauge failure. The crest and bottom of the maximum closure is available from seismic data; however, an across-fault sealing assessment (e.g., Skerlec, 1999; Sorkhabi et al., 2002) is also required for the estimation of the across-fault spillpoint in a trap bounded by faults.

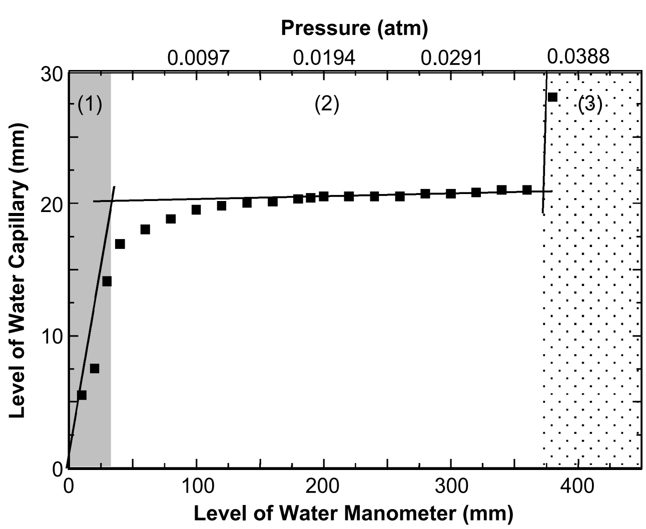

FIGURE 8. Graph showing a typical response of the experiment. As h_{WM} increases gradually, h_c increases correspondingly: Area 1 = the oil migrating into the pore space of the seal; area 2 = oil accumulating; and area 3 = oil leaking.

CASE STUDY: FACTORS CONTROLLING OIL AND GAS ACCUMULATION

This chapter concerns a study of seals in actual discovered oil and gas fields in Russia, based on the concept of the EGS method. This case study indicates that the geometry of a trap is also an important factor in controlling the oil and gas column height in a pure capillary-limited trap. This is in addition to the functions of the seal capacity and the height of the trap emphasized by Sales (1997).

In the fields referred to as YA, AN, and DU in this chapter, oil and gas have accumulated in the reservoir, which dips southward in a homoclinal feature. Reservoir facies in these fields are very variable. If the reservoir is near low-permeable facies, then the lateral change in reservoir facies acts as a seal, forming a stratigraphic trap in those fields (Figures 11, 12). All three traps are not filled with the hydrocarbons to the synclinal spillpoints. Consequently, the traps in those fields

Table 1. Result of pore-throat estimation with four kinds of artificial seal material consisting of different-sized glass beads. Two kinds of pore-throat radiuses are shown: estimated from the capillary failure in the experiment and from the theoretical relation of pore throat and porosity according to the packing types (after Nakayama and Van Siclen, 1981).

Sample	*Porosity (%)*	*Average Grain Size (μm)*	*Standard Deviation (μm)*	*Experimental Capillary Pressure (atm)*	*Calculated Pore-throat Radius from Sealing Pressure (μm)*	*Theoretical Pore-throat Radius (μm)*
A (100)	28.0	79.33	10.78	0.0674	12.204	8.008
B (200)	22.4	185.90	16.28	0.0431	18.985	11.818
C (300)	17.2	280.88	28.71	0.0379	21.601	11.587
D (400)	20.3	357.12	22.94	0.0327	24.991	19.056

are pure capillary-limited traps, assuming sufficient amounts of hydrocarbon have migrated into the traps.

The EGS of the cap rock for the YA field is estimated as 8.06 phi. The oil and gas distribution map shows that the top seal is 2085 m (6841 ft) below sea level, and gas and oil column heights are 51 and 21 m (167 and 69 ft), respectively, in the YA field (Figure 11). Fluid densities at the depth of the top seal that are determined from production tests are 1.23 g/cm^3 for the formation water, 0.76 g/cm^3 for the oil, and 0.30 g/cm^3 for the gas. Gas interfacial tension contact with the top seal is also calculated as 46.84 mN/m. Because total buoyancy (P_b) balances the capillary pressure (P_c) in pure capillary-limited traps, the pore throat is estimated as 0.000333 mm (1 $\times$ 10^{-5} in.) in diameter (2R) from the hydrostatic trap-equilibrium equation (equation 1).

$$P_b = \{21\ \text{m} \times 9.81\ \text{m/s}^2 \times (1.23\ \text{g/cm}^3 - 0.76\ \text{g/cm}^3)\} + \{51\ \text{m} \times 9.81\ \text{m/s}^2 \times (1.23\ \text{g/cm}^3 - 0.30\ \text{g/cm}^3)\}$$

$$P_c = \frac{2 \times 46.84\ \text{mN/m}}{R\ (\text{in mm})/1000}$$

The pore-throat size is converted into the EGS using the relationship between porosity and COEF in equation 2a. The porosity of the top seal is calculated from

Seal Capacity Estimation (Quick Version)								Field name:	Trap A	
Density of Fm water	ρ_0	1.260	(g/cm^3)	subsurface		1.23				
Density of oil	ρ_1	0.830	(g/cm^3)	subsurface		0.75	R_s	1022.5	Bo	1.1011
Gas specific gravity	ρ_2	0.680	(frac)	subsurface		0.32				
Z-factor	Z	0.90		acceleration of gravity	γ	981	(cm/s^2)	AMW	19.56	
Oil interfacial tension	γ_1	37.06	(mN/m)	subsurface		37.06	$\Delta\rho$	0.48		
Gas interfacial tension	γ_2	44.61	(mN/m)	subsurface		44.61	$\Delta\rho$	0.91	Tr	1.66
Contact angle	θ	0.00	(degree)	0 : water wet					A	3.327643
						5.00	surface temperature [ºC]			
Grain size of rock	d_m	8.00	(phi)			1.50	geothermal gradient [ºC/100 m]			
	d_m	0.00391	(mm)	Porosity-surface	60	0.000700	compaction factor			
Porosity	ϕ	10.43	(%)			2500.00	depth (m)			
			Gas Eff x 0.7			42.50	Temperature [ºC]			
Pore-throat diameter	PTD	0.000216	(mm)	COEF		0.055	(-)			
Oil column height	H_{co}	147.25	(m)	C for Effective PTD	C	1.00	(-)			
Gas column height	H_{cg}	92.55	(m)					Cinv		
				Observed oil column	H_o	-	(m)	#VALUE!		
				Observed gas column	H_g	-	(m)	#VALUE!		

FIGURE 9. Spreadsheet (Excel®) for calculating oil and gas column height from equivalent grain size. The given fluid densities at the surface are converted into the subsurface condition, which is calculated from the depth, geothermal gradient, surface temperature, etc. The porosity is calculated from the exponential function of depth provided the compaction factor is given. The other parameters (interfacial tensions, contact angle, and Z-factor) are also estimated in the subsurface condition. The sheet calculates the oil and gas column height corresponding to the given equivalent grain size. If the observed maximum column height is known, we can find a suitable equivalent grain size using this sheet by trial and error.

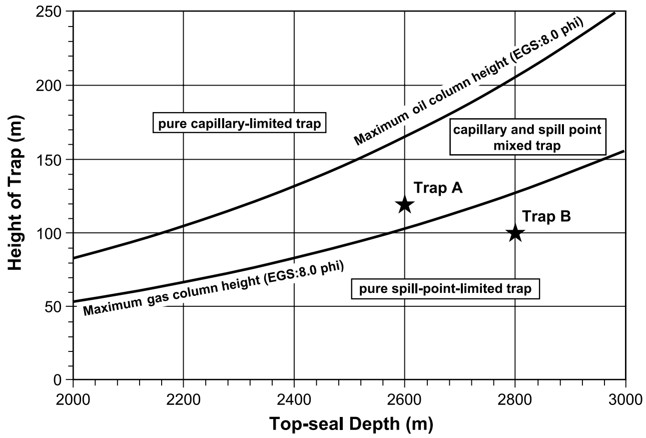

Figure 10. Crossplot of heights and top-seal depths of the virtual traps (A and B) overlying the maximum oil and gas column heights that the top seal can hold assuming the equivalent grain size of 8.0 phi. Trap B, plotted below the line showing the maximum gas column height, is classified as a gas-prone, spillpoint-limited trap. Trap A, plotted between the lines showing the maximum oil and gas column height, is classified as a mixed trap.

the compaction factor that is derived from the core analyses. The EGSs of cap rocks, which is estimated by same sequence as above, are 8.00 phi for the AN field and 8.61 phi for the DU field, respectively (Figure 11).

Although EGSs and top-seal depths of the YA and AN fields are similar, oil and gas column heights are different from each other. The oil column height is 21 m (69 ft), and the gas column height is 51 m (167 ft) in the YA field. In the AN field, the oil column height is 45 m (148 ft), and the gas column height is 35 m (115 ft). Figure 13 shows the estimated hydrocarbon-accumulating processes in the YA and AN fields. It is generally suggested that oil accumulated first; then gas migrated in from the deeper part of basin center. If this scenario is correct, then the traps were filled with oil until the maximum column height that the top seal could hold (phase I in Figure 13). Overcharged oil leaked upward through the top seal during this first phase. Because seal capacities of two fields are nearly equal, oil column heights should also be nearly equal; however, the oil volume was controlled by the trap geometry.

In the second phase (phase II in Figure 13), oil generation ceased, and gas was generated and migrated into the traps, replacing oil from the top of the trap, pushing down the oil column. During this phase, gas made contact with the top seal, which held the total buoyancy of oil and gas. Although the volume of oil did not change during the accumulation of gas, the oil column height decreased because of the geometry of the trap. In the AN field, the area of the reservoir does not

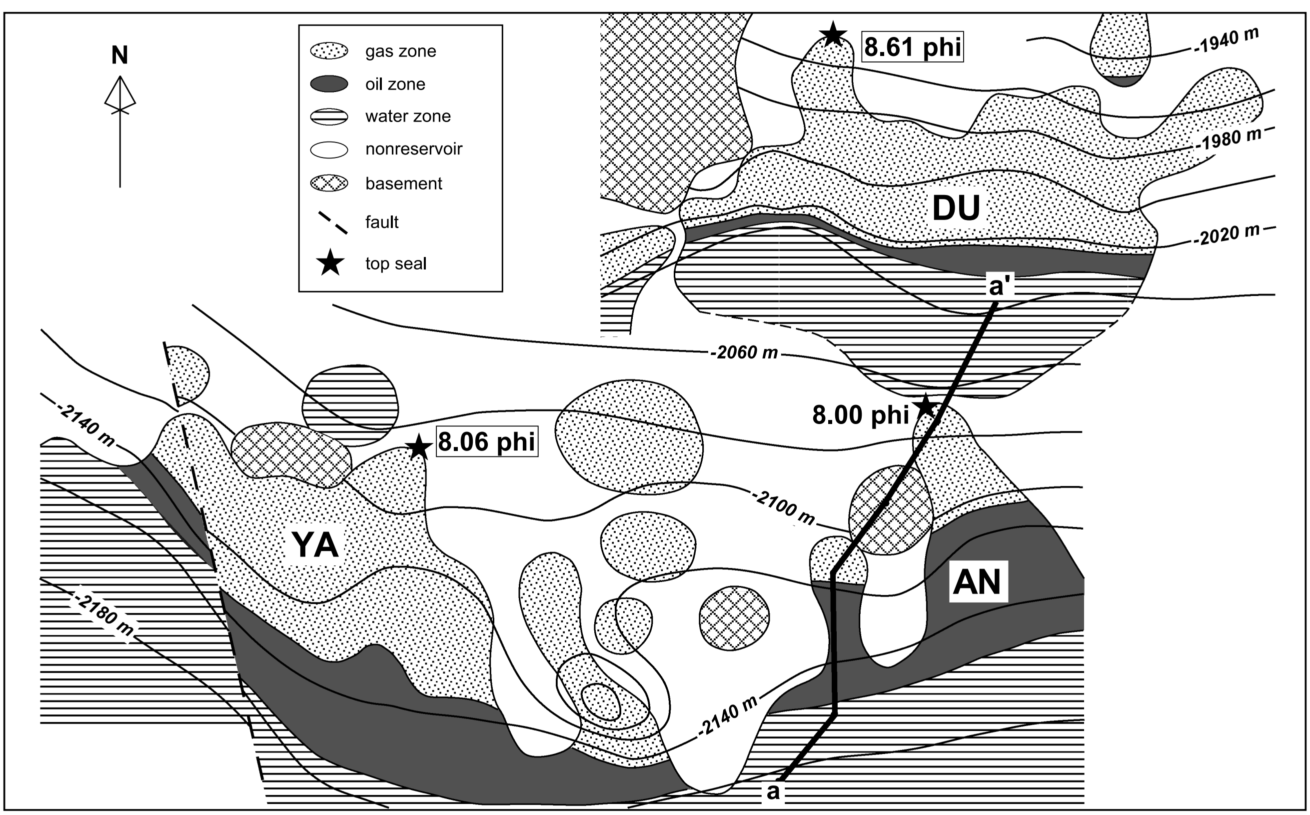

Figure 11. Depth contour map of the top reservoir horizon, showing the distribution of the oil and gas pools in the AN, YA, and DU fields.

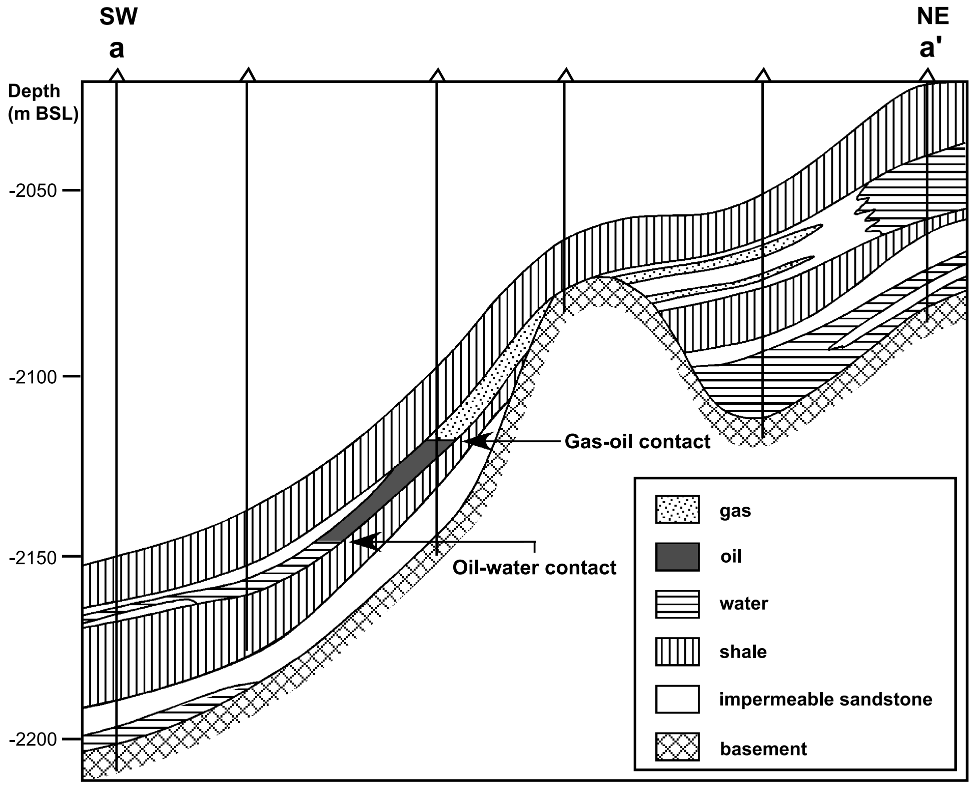

FIGURE 12. Geologic cross section across the AN–DU fields (vertical scale is exaggerated). Cross section aa′ corresponds to that in Figure 11.

change much with depth; therefore, the oil column height did not change much before and after the accumulation of gas. In the YA field, where the area of the reservoir remarkably increased with depth, the oil column height decreased dramatically despite the fact that no change occurred in oil volume.

As mentioned above, the total buoyancy of the oil and gas that the top seal can hold in the AN field is almost equal to that in the YA field, but oil column heights are

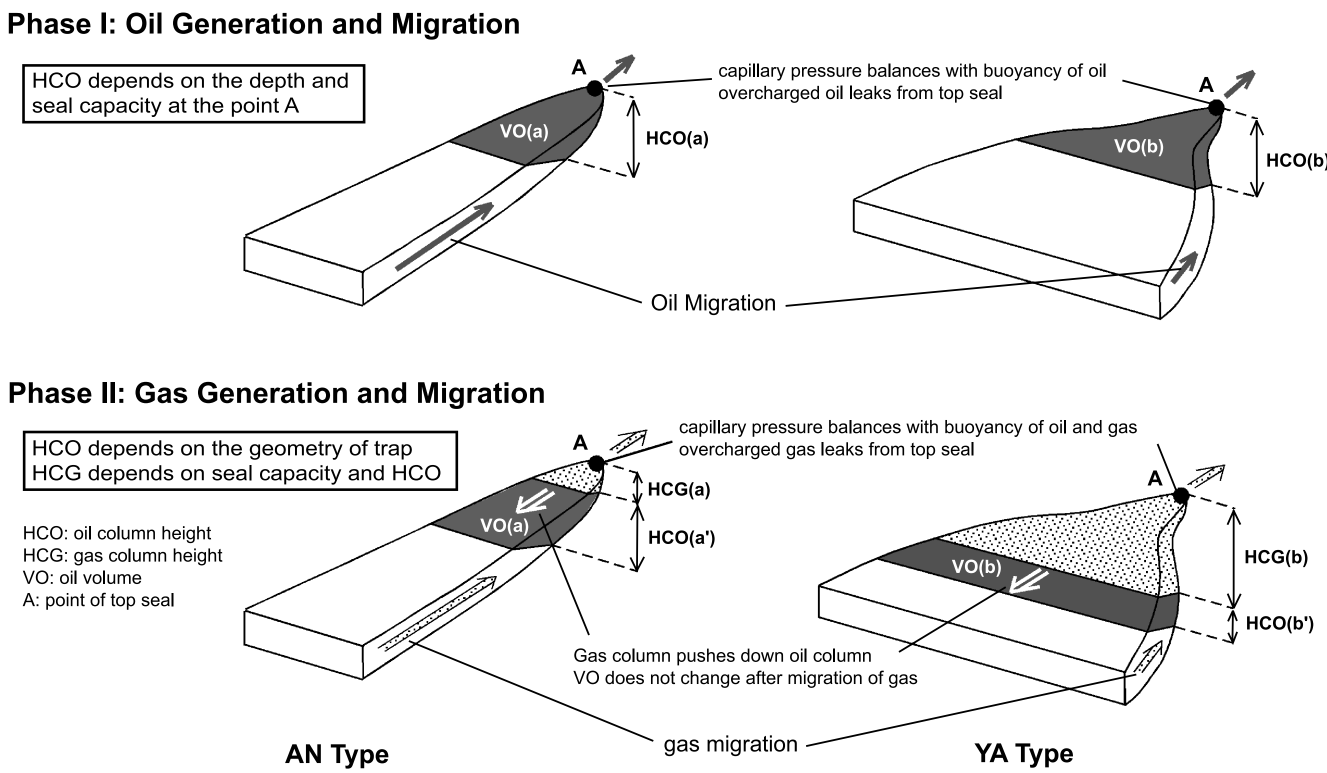

FIGURE 13. Schematic model explaining the differences of the oil and gas distributions in the AN and YA fields. Note that the geometries of the traps can affect the oil and gas distributions, even if the sealing capacities are equal, assuming that oil has accumulated in the traps before the inflow of gas.

different after the accumulation of gas. As a result, the accumulated volume and column height of the gas in the AN field are different from that in the YA field. The final gas column height in the AN field is relatively small because of the small decrease in oil column after the inflow of gas. In contrast, the final gas column height is much larger in the YA field, because the oil column height decreases remarkably after the inflow of gas caused by the trap geometry. Once the hydrostatic equilibrium is established, the overcharged gas leaks upward through the top seal.

CONCLUSIONS

The height of trap, the maximum oil and gas column height to be held by a cap rock, and the trap geometry are essential factors in predicting or interpreting oil and gas accumulations. A pure spillpoint-limited trap is one in which the hydrocarbon column height is determined solely by the spillpoints. The hydrocarbon column is less than that determined solely by the top-seal capacity. This trap will be dominated by gas. Pure capillary-limited trap is that not filled down to the spillpoint. A case study of the AN and YA fields demonstrates that both the trap geometry and the top-seal capacity control hydrocarbon column heights in these traps. In capillary and spillpoint mixed trap, both the top-seal capacity and the height of the trap control hydrocarbon column heights.

The EGS method quantifies seal capacity in terms of the ideal grain size of a cap rock. If the EGS can be inferred to the depositional environment, the calculated grain size holding the observed oil and gas column height in a given field can be used in the estimation of the possible maximum column height in the traps nearby. In combination with the determination of the spillpoint from seismic data and across-fault sealing assessment, this method helps to understand how the trap characteristics would control the oil and gas accumulation in fields and prospects, including fault traps. Furthermore, the concept of the EGS method may be applied not only to the top seal but also to the clay-rich fault gauge in the light of further studies in the future.

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