Introduction to Reservoir Engineering

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Orientation: Reservoir Engineering

Reservoir Engineering Overview: (General)

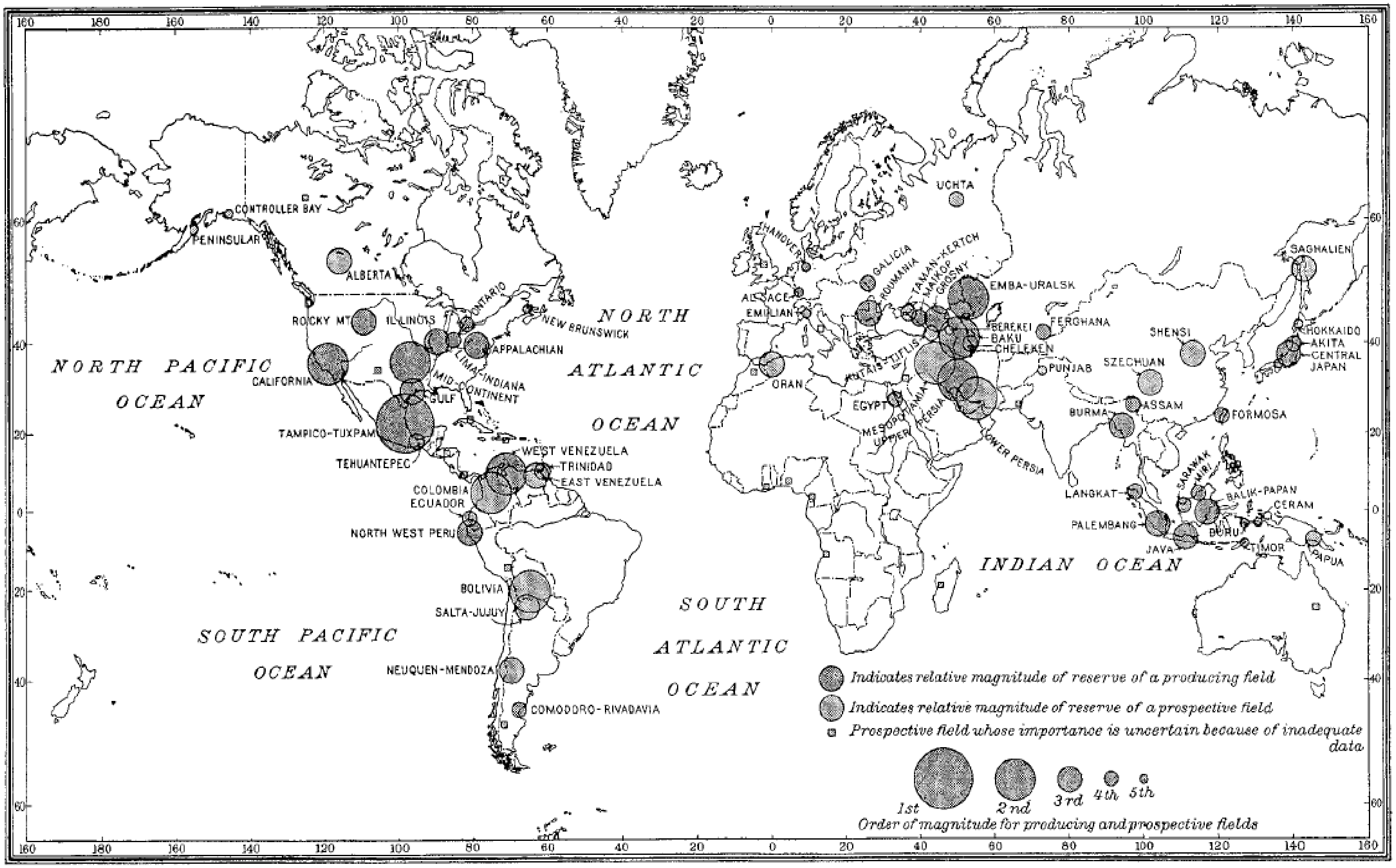
- Location of World Oil Resources
- Reservoir Structure/Depositional Sequences
- Petrophysics: Porosity, Permeability, and Correlations
- Rock Properties: Homogeneity/Heterogeneity
- Phase Behavior of Reservoir Fluids
- Formation Evaluation
- Pressure Transient Analysis
- Reservoir Modeling

History of Reservoir Engineering:

- History of Reservoir Engineering
- Tasks of the Reservoir Engineer
- Data Sources
- Fundamental Drive Mechanisms
- Trapping Mechanisms

Overview: World Oil Resources (Circa 1920)

From: Thom, W.T.: "Petroleum and Coal - The Keys to the Future," Oxford University Press, 1929.



Map showing distribution and relative size of world's oil resources, prepared under direction of U.S. Geological Survey in 1920. The general validity of this prophecy has been amply demonstrated in the past eight years-growth in the importance of the West Texas region balancing the shrinkage in the estimates of Mexican oil reserves.

Discussion:

- The known deposits of oil and gas in 1920.
- Offshore deposits would not have been discovered.
- Most deposits were discovered by seeps.

Overview: World Oil Resources (Circa 1920)

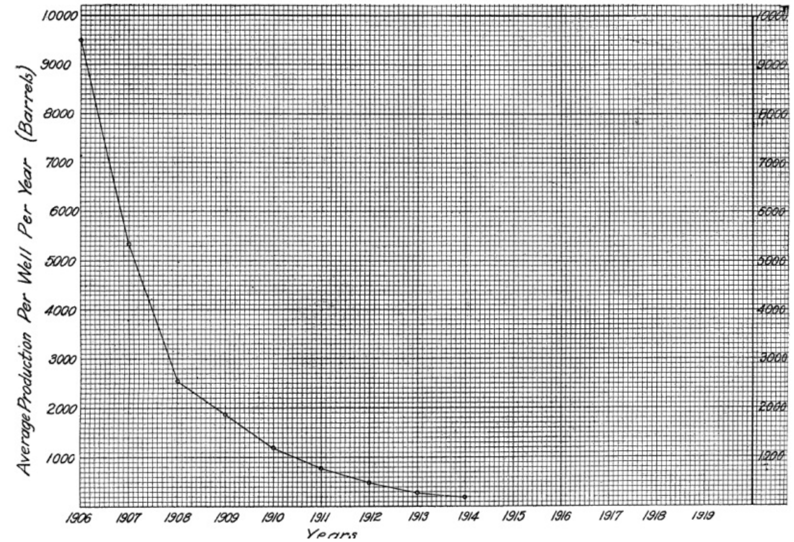
From: Thom, W.T.: "Petroleum and Coal - The Keys to the Future," Oxford University Press, 1929.

AUSTRALIA AND NEW ZEALAND

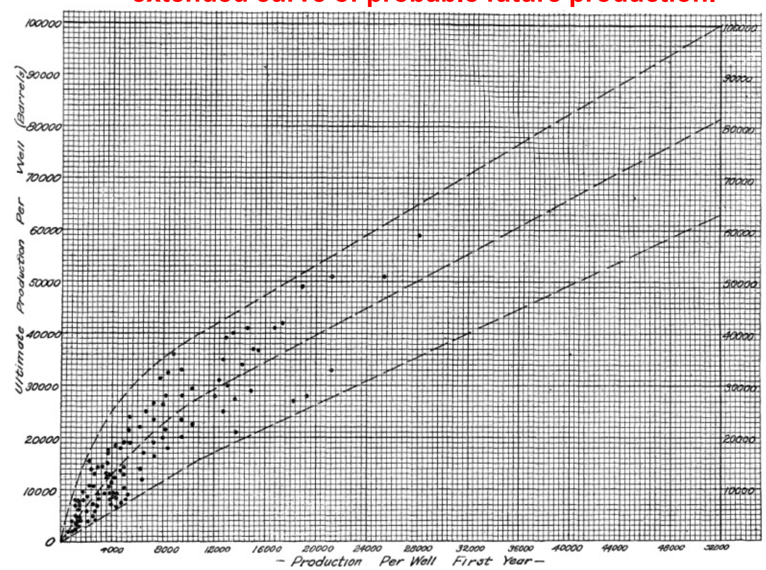
A moderate production of oil may ultimately be attained in New Zealand, but there is apparently only a remote chance that oil fields of more than local importance will be found in either Australia or New Zealand. Some 60,000 barrels of oil have been produced in New Zealand, and seepages have been noted in as yet untested localities. *Small quantities of oil and gas found at various localities in southeastern Australia appear to indicate that with further drilling and with more detailed structural mapping in Australian areas oil fields will be found. No major production is, however, probable.*

AFRICA

Africa is quite certainly devoid of major oil deposits, the surface of much of the continent being covered by rocks definitely barren of oil. Such oil production as is now obtained in Africa (1,100,000 barrels annually) comes almost entirely from the Egyptian fields on the Red Sea coast opposite the Sinai Peninsula, a tiny amount also being produced in Algeria. Some oil manifestations occur in British and Italian Somaliland, south of the Gulf of Aden; in Madagascar; doubtfully in Portuguese East Africa; in Natal; in Angola; and at various localities around the shore of the Gulf of Guinea; *but it appears unlikely that extensive or other than locally important development is probable in any of these regions*.



Production decline curve, showing the extended curve of probable future production.



Appraisal curve for an Oklahoma oil field.

From: Manual for the Oil and Gas Industry," US Internal Revenue Service — Treasury Department, 1919.

Discussion:

- **Note predictions in *red text* (all are wrong).**
- **Production analysis came about due to taxation.**
- **Early correlation of ultimate recovery given as "appraisal."**

Overview: Reservoir Structure/Depositional Environments

From: Berg, R.R., 1986, Reservoir Sandstones: Englewood Cliffs, NJ, Prentice-Hall.

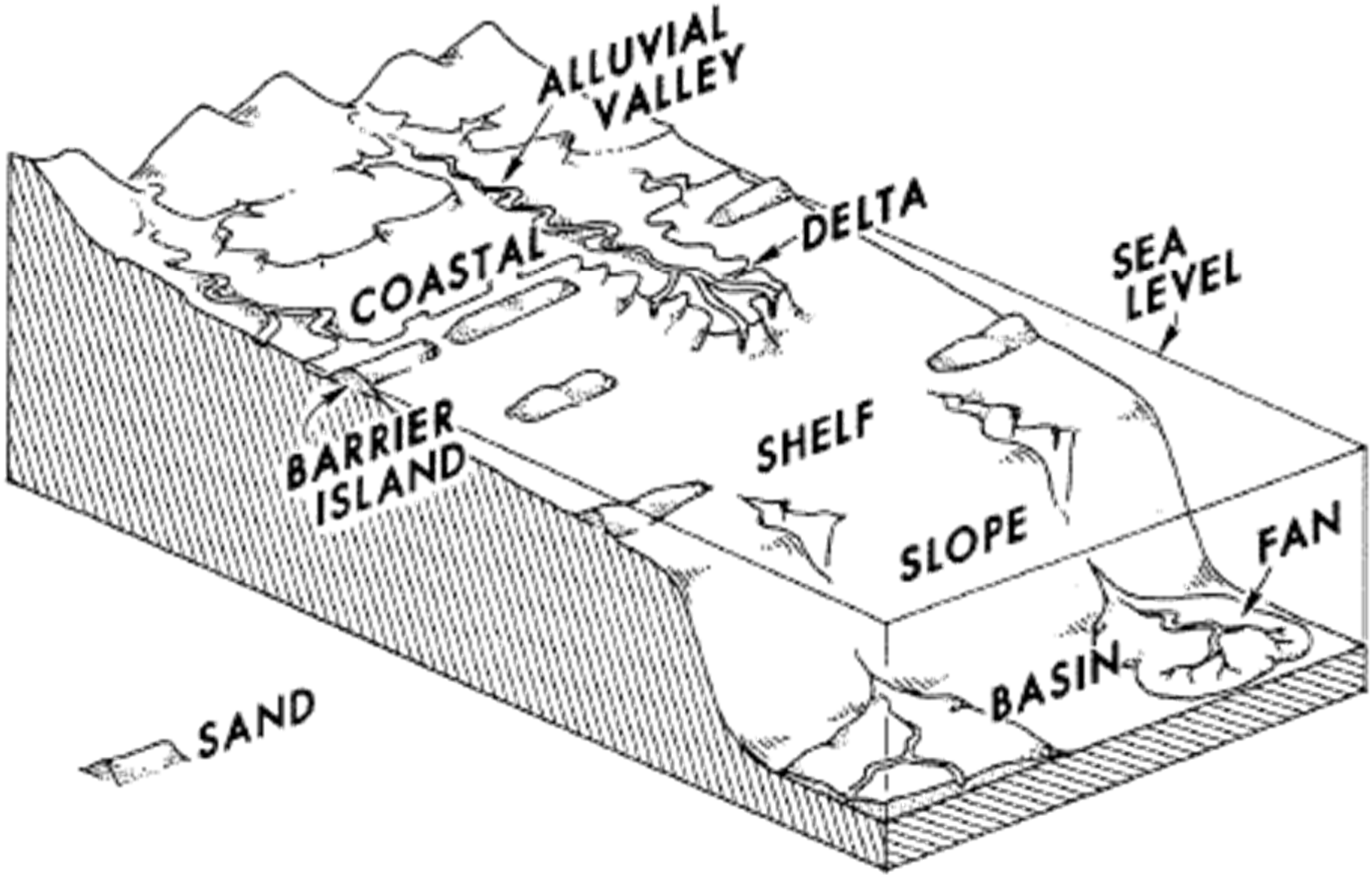


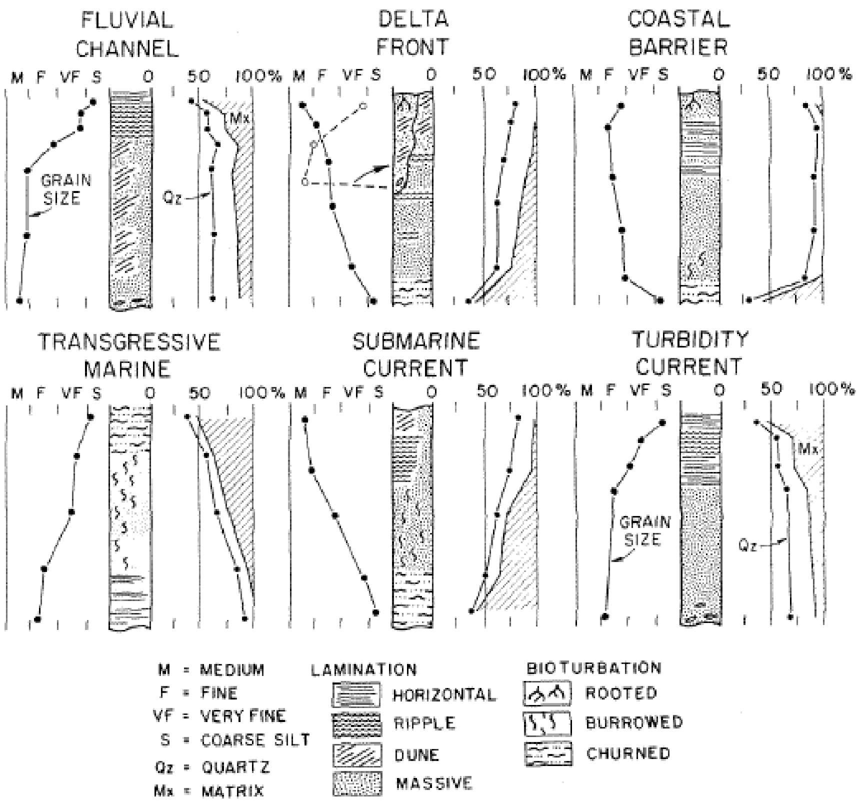
Diagram of major depositional environments for sandstones.

Discussion:

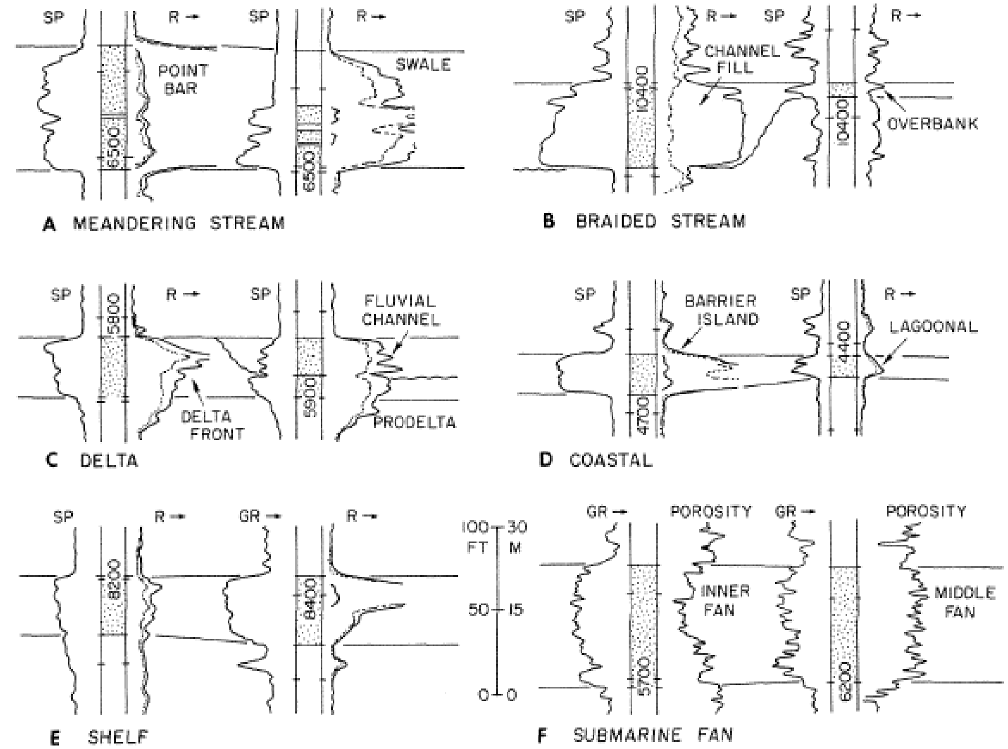
- Schematic for sandstone (clastic) reservoirs.
- Transport mechanism is water.
- Extremely large deposits of basin sandstones can exist.

Overview: Common Depositional Structures

From: Berg, R.R., 1986, Reservoir Sandstones: Englewood Cliffs, NJ, Prentice-Hall.



Common sequences of sedimentary structures, texture, and composition observed in reservoir sandstones of different origins. Diagrams have no vertical scale because thickness is not a criterion.



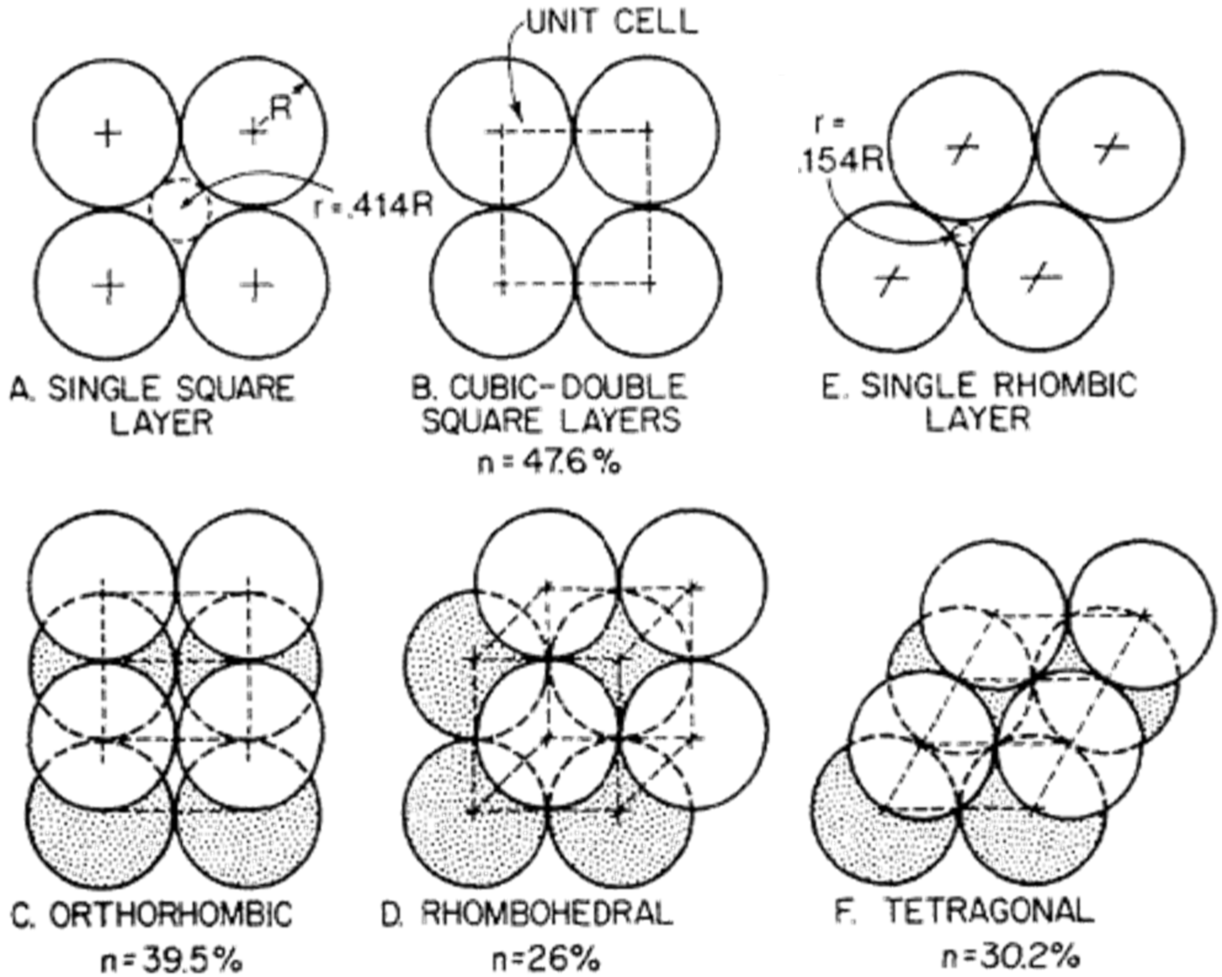
Typical response of spontaneous potential (SP) and gamma-ray (GR) log in sandstone sequences. Log patterns are similar to textural changes. Dotted patterns indicate dominant sandstone as interpreted from the logs. Resistivity (R) or porosity logs are also shown.

Discussion:

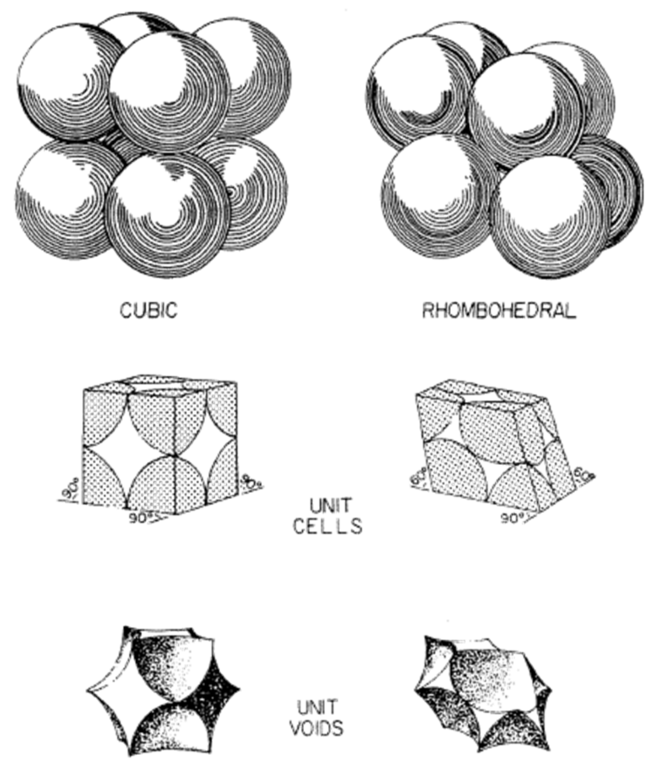
- Diagrams of sedimentary structures. (*on left*)
- Important to observe/describe core (rock) samples.
- Well log responses indicate similar profiles. (*on right*)

Overview: Concept of Porosity (packings of spheres)

From: Berg, R.R., 1986, Reservoir Sandstones: Englewood Cliffs, NJ, Prentice-Hall.



Diagrams of systematic packings of uniform spheres as described by Graton and Fraser (1935). Porosity (n) is given for the principal packings.



Diagrams of unit cells and unit voids for cubic and rhombohedral packings of uniform spheres.

Discussion:

- Idealized configurations help to establish limits.
- Orthorhombic (cubic) is highest (39.5 percent).
- Rhombohedral is lowest (26 percent).

Overview: Concept of Porosity (unconsolidated sands)

From: Beard, D. C. and Weyl, P. K.: "Influence of Texture on Porosity and Permeability of Unconsolidated Sand," AAPG Bull., Vol. 57, No. 2, (1973), 349-369.

Data of Beard and Weyl: (unconsolidated sands) (porosity is given in *fraction*)

	Size							
	Coarse		Medium		Fine		Very Fine	
Sorting	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Extremely well sorted	0.431	0.428	0.417	0.413	0.413	0.435	0.423	0.430
Very well sorted	0.408	0.415	0.402	0.402	0.398	0.408	0.412	0.418
Well sorted	0.380	0.384	0.381	0.388	0.391	0.397	0.402	0.398
Moderately sorted	0.324	0.333	0.342	0.349	0.339	0.343	0.356	0.331
Poorly sorted	0.271	0.298	0.315	0.313	0.304	0.310	0.305	0.342
Very poorly sorted	0.286	0.252	0.258	0.234	0.285	0.290	0.301	0.326

Porosity = f(Grain size,
Sorting,
Texture,
Angularity,
Composition (lithology),
digenetic processes, and
in-situ stress)

For packings of uniform spheres:
— Cubic (orthorhombic) = 40% (or 0.40)
— Rhombohedral = 26% (or 0.26)

Discussion:

- Porosity has many control factors.
- Most controls on porosity are from primary deposition.
- Secondary (digenetic) processes can also dominate.

Overview: Concept of Permeability (Darcy's Experiment)

From: Hubbert, M. King: Entrapment of Petroleum under Hydrodynamic Conditions, Bull. Am. Assoc. Petrol. Geologists, August, 1953, p. 1954.

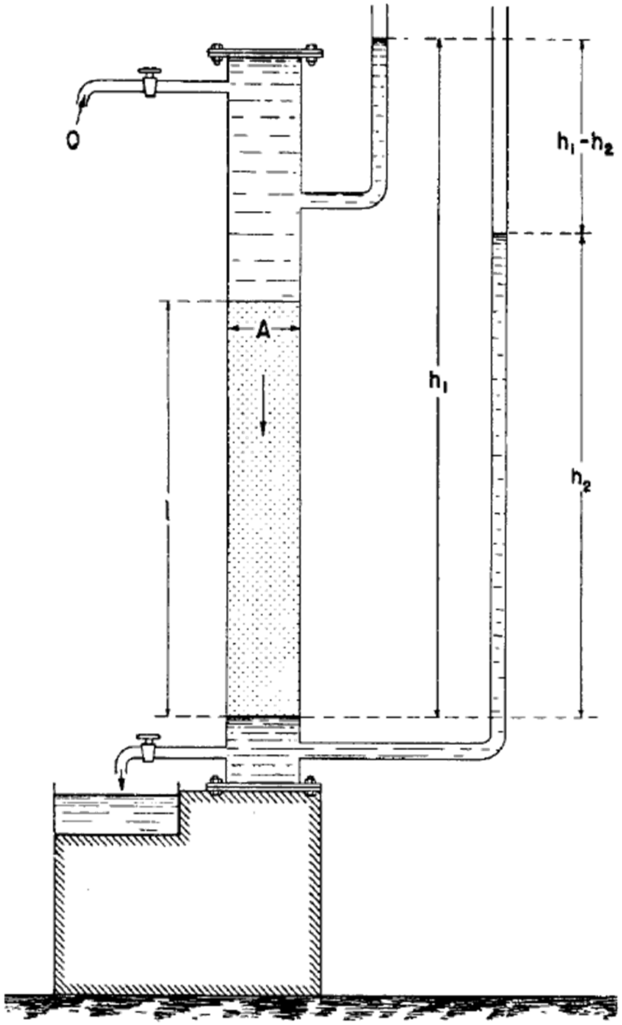


Diagram of Darcy's experiment.

Governing Relation:

$$q = kA\frac{\Delta h}{L}$$

$q \quad = \text{Flowrate}$

$A \quad = \text{Flow Area}$

$\Delta h = \text{Head Change}$

$L \quad = \text{Distance}$

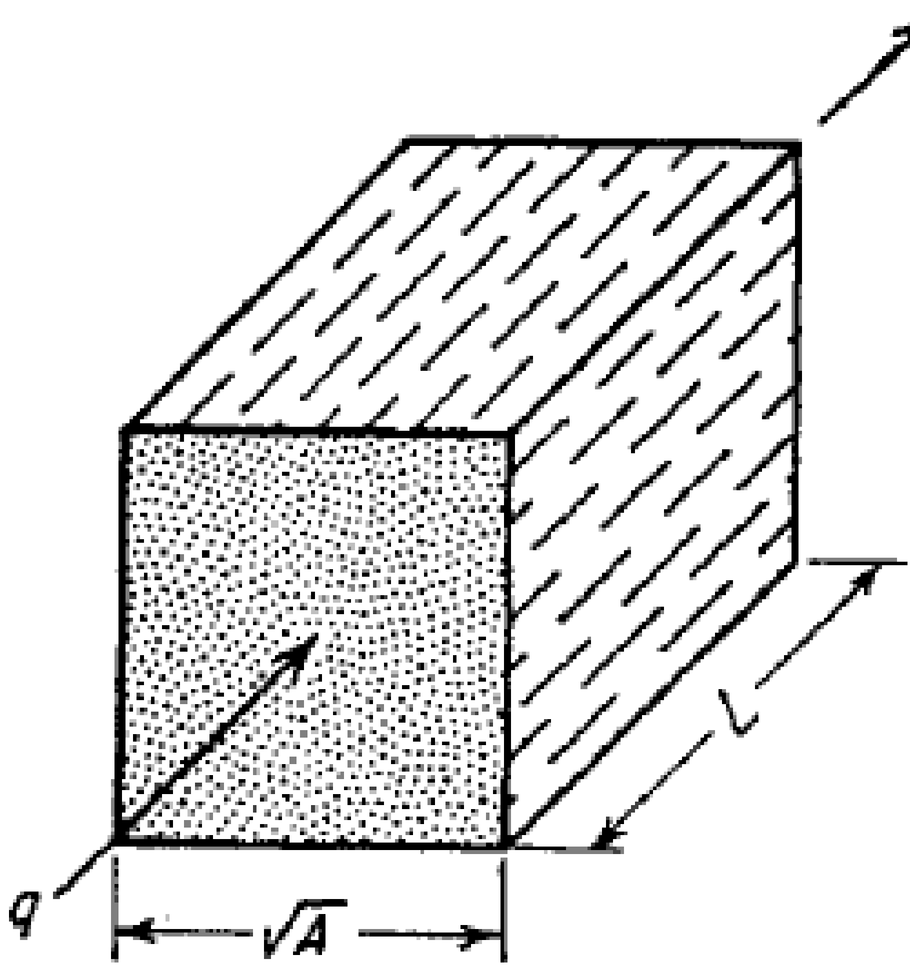
Image of Henry Darcy.

Discussion:

- Darcy's experimental apparatus.
- Darcy's flow relation.
- Image of Henry Darcy.

Overview: Concept of Permeability — Definition of a "Darcy"

From: Katz, D. L., Cornell, R., Kobayashi, R., Poettmann, F. H., Vary, J. A., Elenblass, J. R., & Weinaug, C. G.: Handbook of Natural Gas Engineering (McGraw–Hill, New York) (1959).



$$K = \frac{q\mu}{A}\left(\frac{-dL}{dP}\right)$$

$$= \frac{1\ \text{cc (rate)}}{1\ \text{sec}} \cdot \frac{1\ \text{cp (vis)}}{1\ \text{cm}^{2}\ \text{(area)}} \cdot \frac{1\ \text{cm (length)}}{1\ \text{atm (pressure drop)}}$$

$$K = \text{darcy}$$

The unit of permeability — a Darcy.

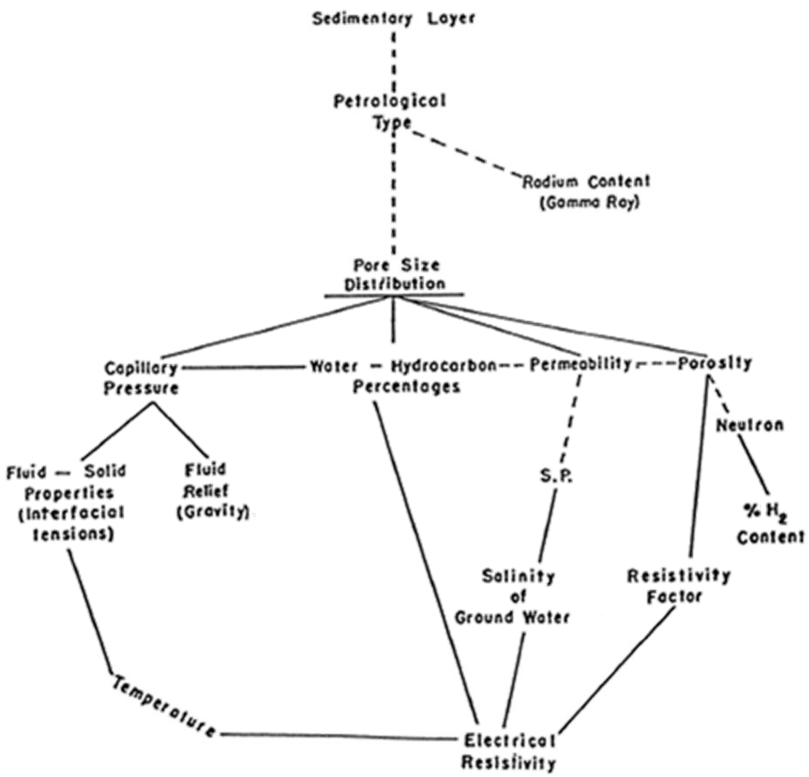
Discussion:

- (*Important*) The "Darcy" is a defined unit.
- Image shows square cross-section (can be generalized).
- The dimension of permeability is L^2 (*i.e.*, area).

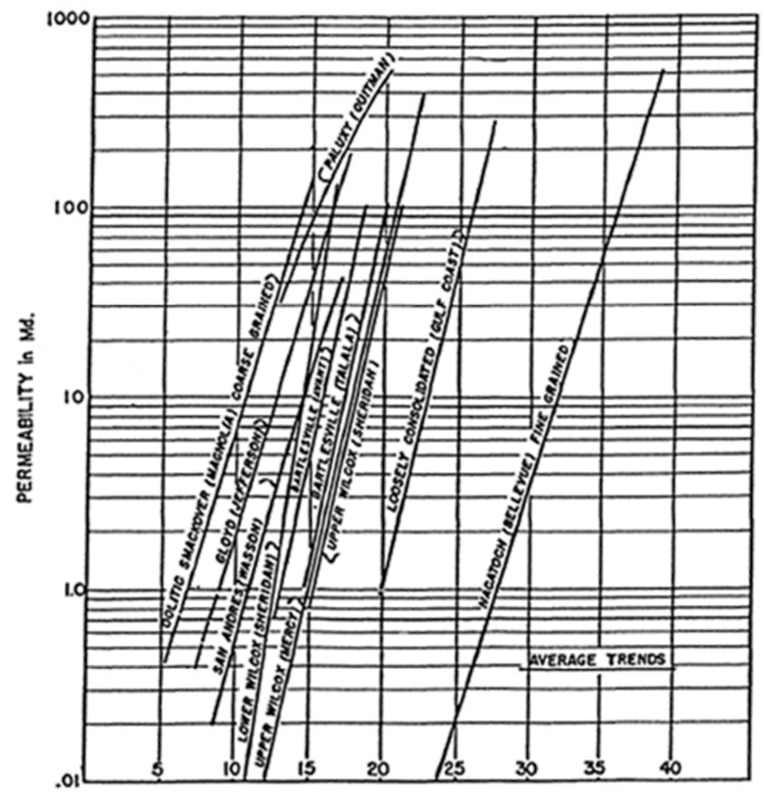
Overview: Petrophysics Map — Archie (1950)

From: Archie, G. E. "Introduction to Petrophysics of Reservoir Rocks," Am. Assoc. Pet. Geol. Bul., Vol. 34, No. 5, May 1950, pp. 943–961.

Archie "Map" of Inter-relations of Petrophysical Properties (1950!)



a. Systematic "mapping" of the inter-relation of petrophysical properties. Note that Archie observed that permeability was "connected" to saturation, porosity, and electrical properties — but the relationship was vague, as it remains today.



b. Crossplot of permeability to porosity (average trends) — used to imply that porosity and permeability have some type of functional relationship. Obviously, this remains a topic of considerable discussion.

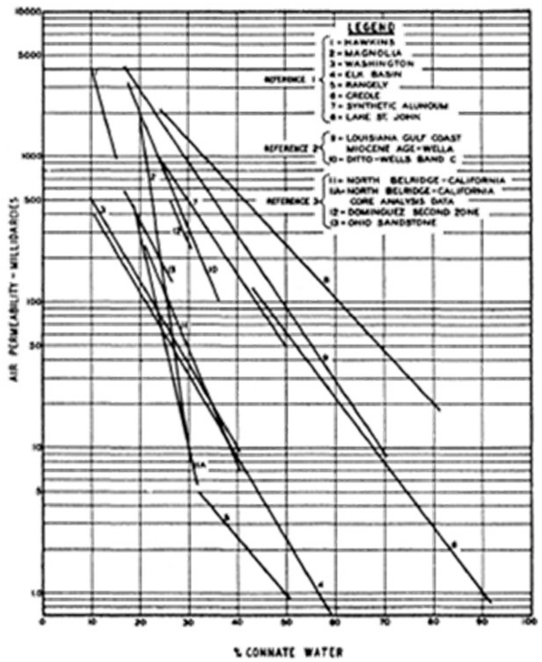
Discussion: Archie Petrophysics Proposals

- "Petrophysics map" was put forth in 1950 (*left*).
- Proposed the log(permeability) vs. porosity plot (*right*).
- These were the earliest "petrophysics" tools.

Overview: Petrophysics — Early Correlation Concepts

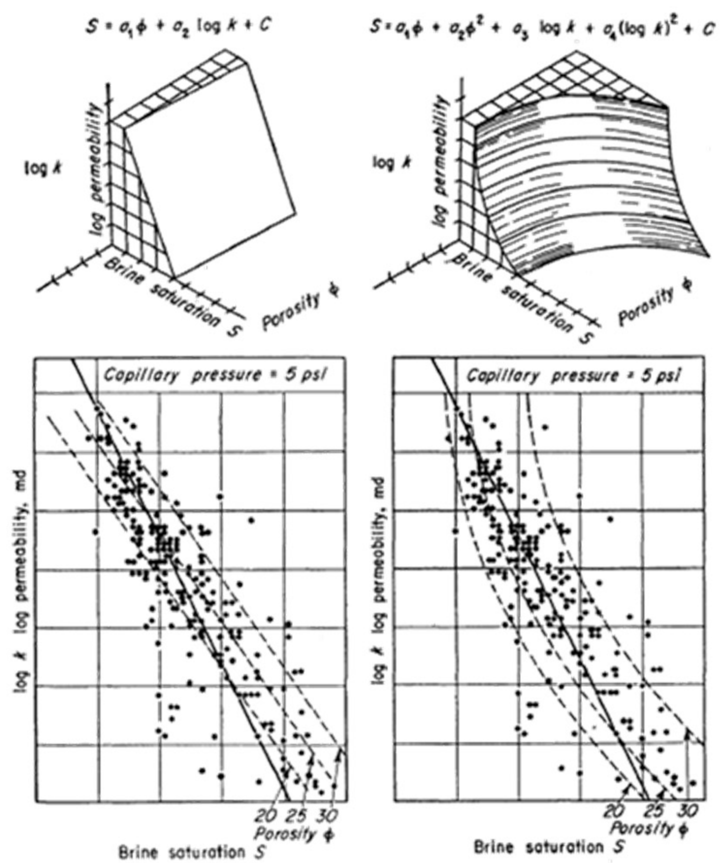
k-S_{wi} Model (Bruce and Welge): $k = \hat{\alpha}\exp[-\hat{\beta}S_{wi}]$

[From: Calhoun, J.C.: *Fundamentals of Reservoir Engineering*, University of Oklahoma Press (1960).]



[1] Bruce and Welge, "The Restored State Method for Determination of Oil in Place and Connate Water," A.P.I. Division of Production; Mid-Continent Section spring meeting, 1947; *The Oil and Gas Journal* (July 26, 1947), p. 223.
[2] Thornton and Marshall, "Estimating Interstitial Water by the Capillary Pressure Method," A.I.M.E. *Transactions* (1947), p. 170; (Abs.) *The Oil and Gas Journal* (October 5, 1946), p. 97.
[3] McCullough, Albaugh, and Jones, "Determination of the Interstitial Water Content of Oil and Gas Sand by Laboratory Tests of Core Samples," A.P.I. *Drilling and Production Practice* (1944).

a. Bruce and Welge correlation modified by Calhoun (average trend constructed as exponential decay).



b. Generalized (linear) relations for permeability, water saturation, and porosity. Using the most simple expression, and ignoring porosity, yields the Bruce and Welge model.

[From: Guthrie, R.K., and Greenberger, M.K.: "The Use of Multiple Correlation Analyses for Interpreting Petroleum-Engineering Data," *Drilling and Production Practice*, API (1955), 130-137.]

Discussion:

- log(permeability) vs. irreducible water saturation (*left*).
- Univariate correlations may not be sufficient.
- Multivariate correlations relied on simple relations (*right*).

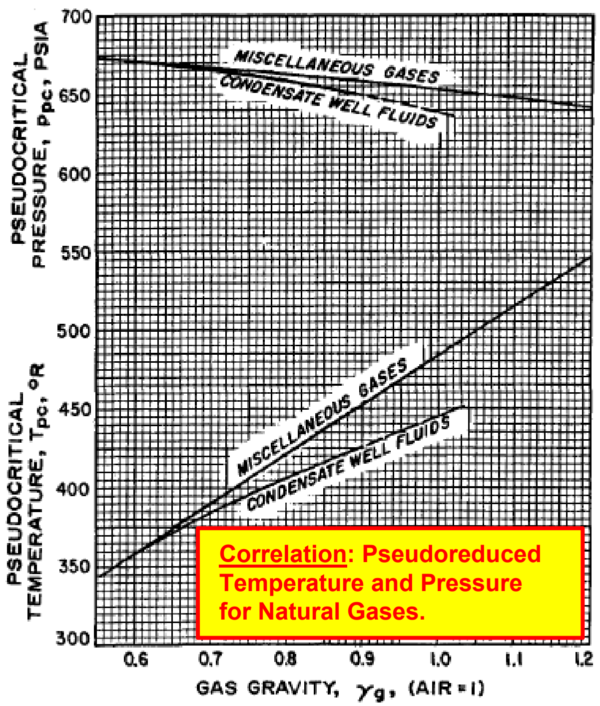
Overview: Phase Behavior (Example Gas Data/Correlations)

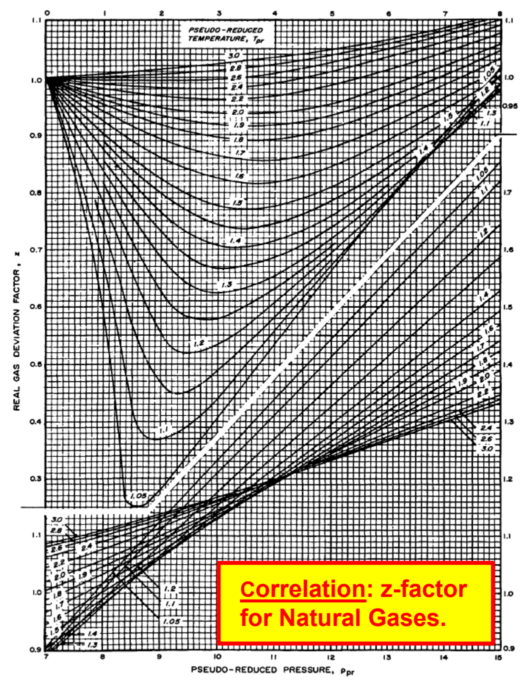
From: SPE Monograph Series 5 — Earlougher Jar, R. C. *Advances in Well Test Analysis*: Society of Petroleum Engineers 1977.

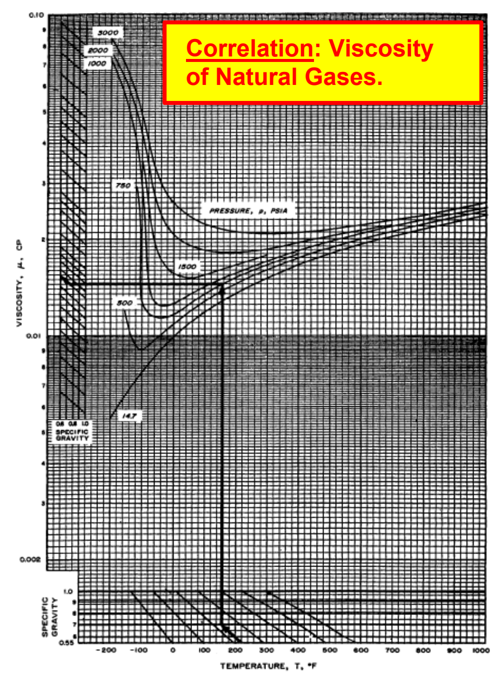
Constituent	Molecular Weight	Normal Boiling Point °F	Normal Boiling Point °R	Liquid Density (lb_m/cu ft)	Gas Density at 60 °F, 1 atm (lb_m/cu ft)	Critical Temperature (°R)	Critical Pressure (psia)
Methane, CH_4	16.04	−258.7	201	18.72*	0.04235	344	673
Ethane, C_2H_6	30.07	−127.5	332	23.34*	0.07986	550	712
Propane, C_3H_8	44.09	−43.8	416	31.68**	0.1180	666	617
iso-butane, C_4H_{10}	58.12	10.9	471	35.14**	0.1577	735	528
n-butane, C_4H_{10}	58.12	31.1	491	36.47**	0.1581	766	551
iso-pentane, C_5H_{12}	72.15	82.1	542	38.99	—	830	483
n-pentane, C_5H_{12}	72.15	96.9	557	39.39	—	847	485
n-hexane, C_6H_{14}	86.17	155.7	615	41.43	—	914	435
n-heptane, C_7H_{16}	100.20	209.2	669	42.94	—	972	397
n-octane, C_8H_{18}	114.22	258.1	718	44.10	—	1,025	362
n-nonane, C_9H_{20}	128.25	303.3	763	45.03	—	1,073	335
n-decane, $C_{10}H_{22}$	142.28	345.2	805	45.81	—	1,115	313
Nitrogen, N_2	28.02	−320.4	140	—	0.0739	227	492
Air (O_2 + N_2)	29	−317.7	142	—	0.0764	239	547
Carbon dioxide, CO_2	44.01	−109.3	351	68.70	0.117	548	1,073
Hydrogen sulfide, H_2S	34.08	−76.5	383	87.73	0.0904	673	1,306
Water	18.02	212	672	62.40	—	1,365	3,206

*Apparent density in liquid phase.
**Density at saturation pressure.

Physical properties of hydrocarbons and associated compounds.

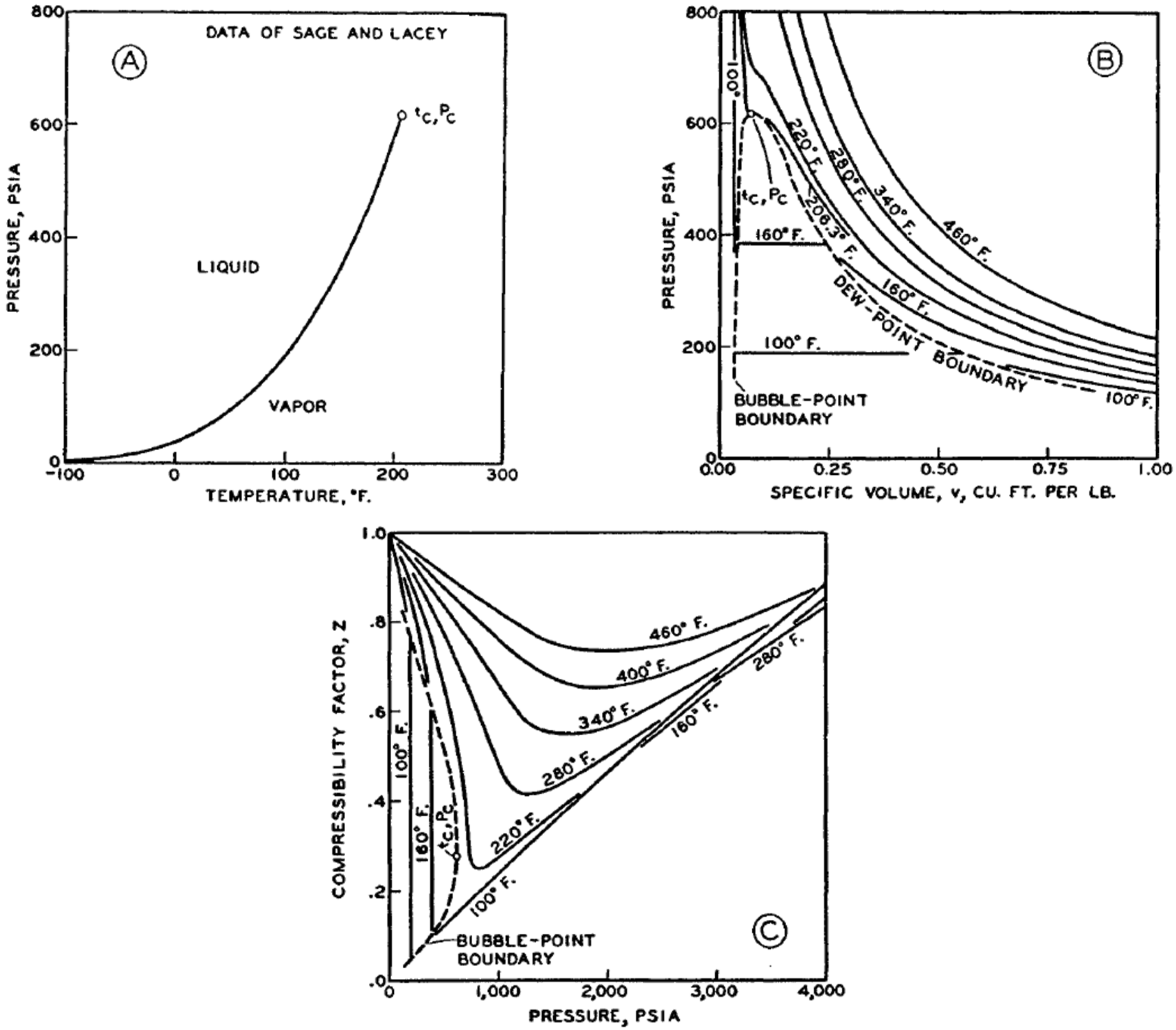






<u>Overview</u>: Phase Behavior (Vapor-Liquid Equilibria)

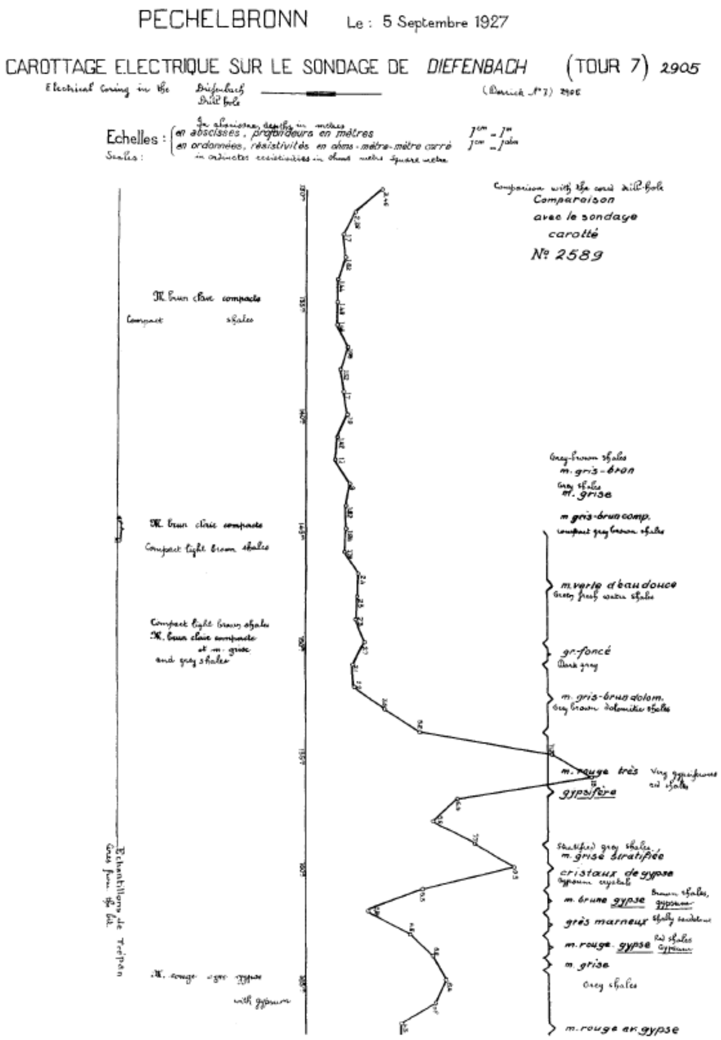
From: Eilerts, C.K.: Phase Relations of Gas Condensate Fluids, Vol. I, Monograph 10, Bureau of Mines, American Gas Association (1959) 763-764.



Phase relationships and compressibility of a single component — propane.

Overview: Formation Evaluation (Types and Uses of Well Logs)

- **Resistivity Logs:**
  - Measures resistance of flow of electric current.
  - Response is a function of porosity & pore fluid in rock.
  - Frequently used to identify lithology.
- **Spontaneous Potential (SP) Logs:**
  - Measures electrical current in well.
  - Due to salinity contrast (formation water/borehole mud).
  - Indicates bed boundaries of sands & shales.
- **Gamma Ray Logs:**
  - Records radioactivity of a formation.
  - Shales have high levels of radioactive minerals.
  - Gamma ray logs infer grain size/sedimentary structure.
- **Neutron Logs:**
  - Counts quantity of hydrogen present.
  - Used to estimate porosity.
  - Lithology indicator when used with the density log.
- **Density Logs:**
  - Measures bulk density of the formation.
  - Used to estimate porosity.
  - Used with sonic log to yield synthetic seismic traces.
- **Sonic (acoustic) Logs:**
  - Measures of speed of sound in formation.
  - Used to estimate porosity.
  - Used with density log to yield synthetic seismic traces.

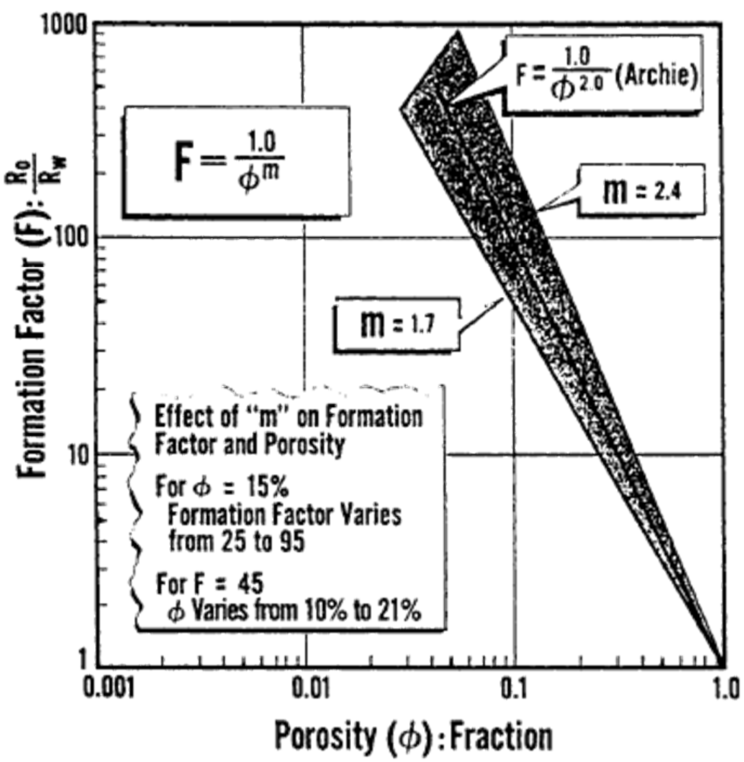


First well log — run by Schlumberger brothers (1927).

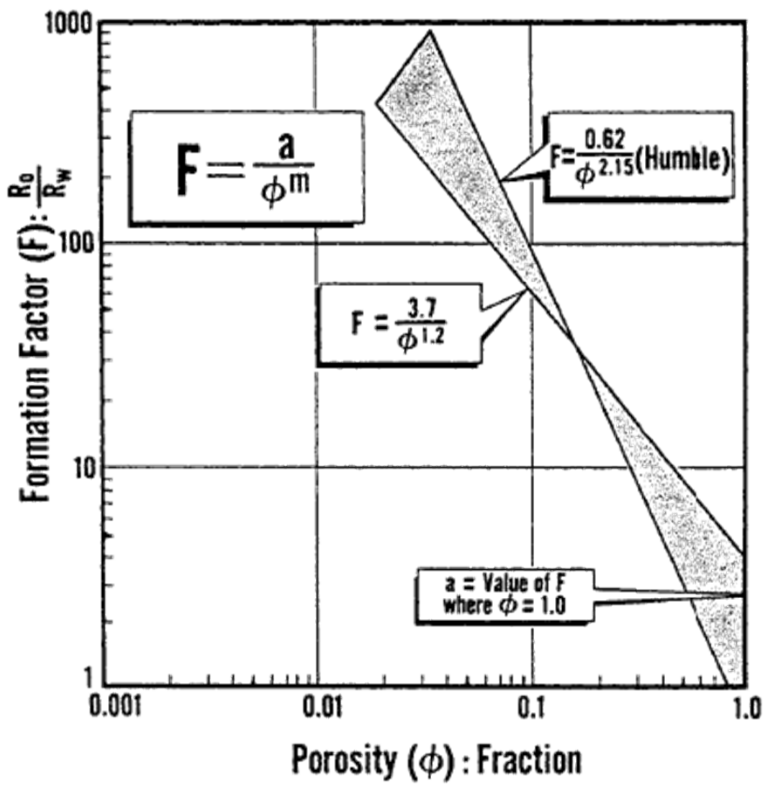
Overview: Formation Evaluation — Formation Factor (ϕ)

$$F = \frac{R_o}{R_w} = \frac{a}{\phi^m}$$

From: Keelan, D.: "Special Core Analysis," Core Laboratories Report (1982).



Formation Factor vs Porosity
for Range of Measured Cementation Factor



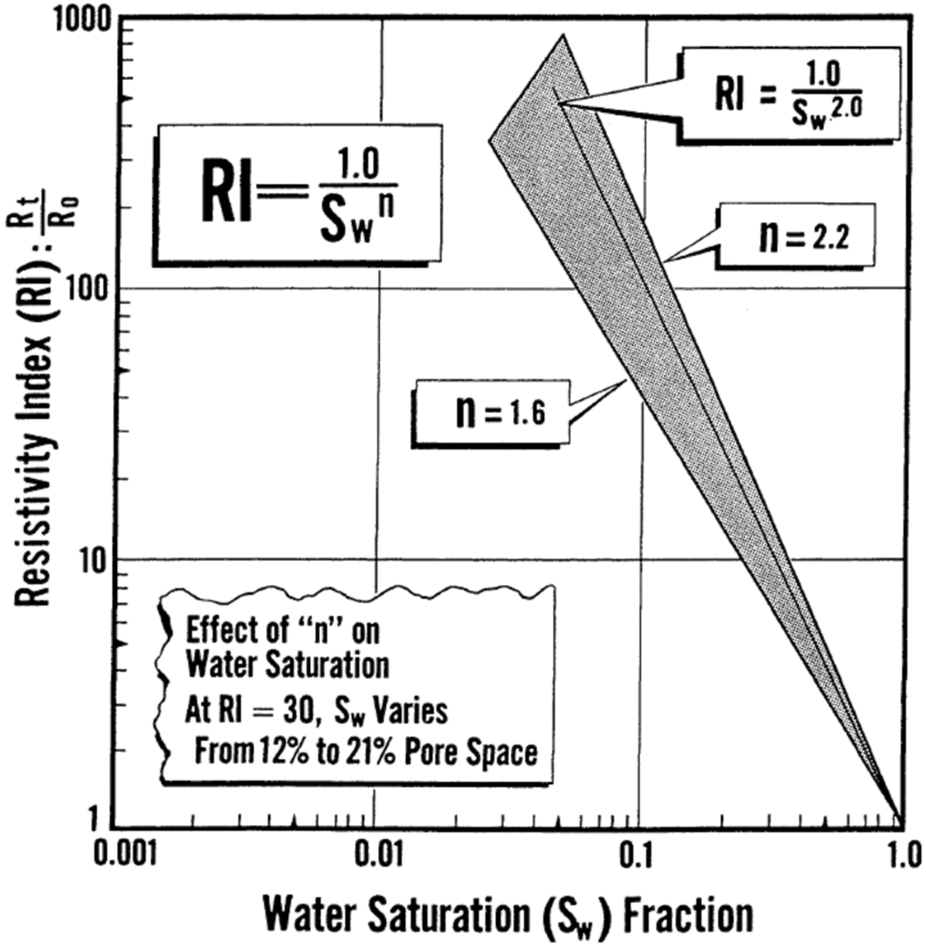
Formation Factor vs Porosity
Illustrating Variation in Intercept "a"

Discussion:

- Archie's First Law [Formation Factor = f(Porosity)].
- The "cementation factor" (m) is the correlating parameter.
- Typical range: $1.7 \leq m \leq 2.4$.

Overview: Formation Evaluation — Formation Factor (S_w)

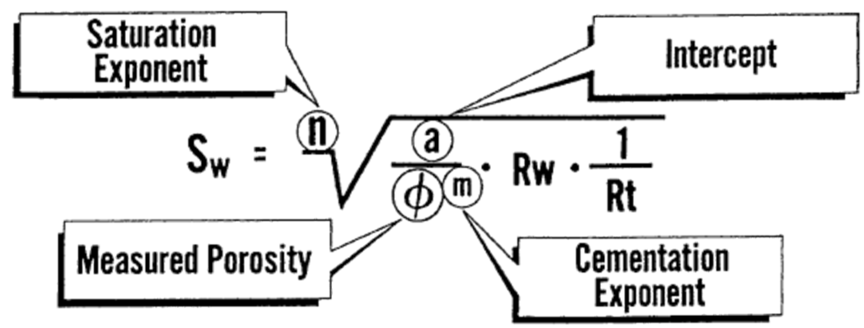
From: Keelan, D.: "Special Core Analysis," Core Laboratories Report (1982).



Resistivity Index vs Water Saturation
for Range of Measured Saturation Exponents

$$I = \frac{R_t}{R_o} = {S_w}^{-n}$$

$$S_w = \sqrt[n]{\frac{F \cdot R_w}{R_t}} = \sqrt[n]{\frac{R_o}{R_t}}$$



Discussion:

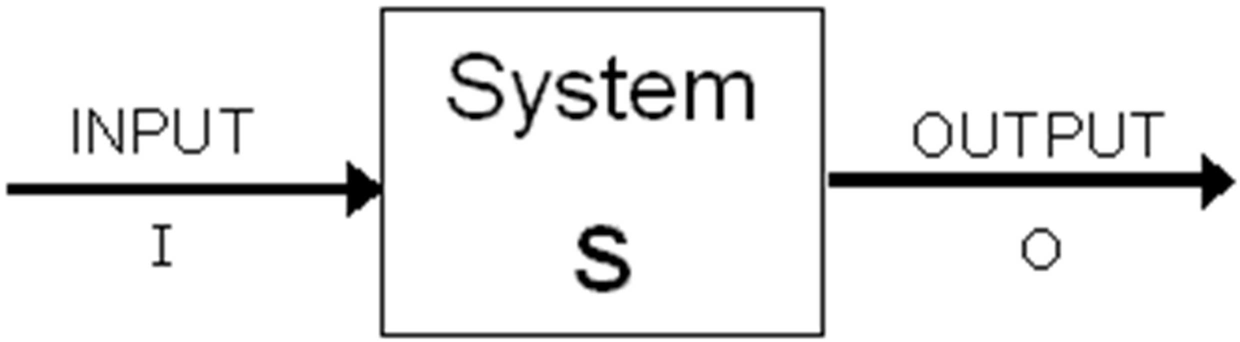
- Archie's Second Law [Resistivity Index = *f*(Saturation)].
- The "saturation exponent" (*n*) is the correlating parameter.
- Typical range: $1.6 \leq m \leq 2.2$.

Overview: Introduction — Pressure Transient Analysis (PTA)

What is Pressure Transient Analysis? (or "Well Test Analysis")

- The goal of well testing is to collect information about flow conditions in the well, around the immediate vicinity of the well, as well as in the virgin portions of the reservoir not influenced by the drilling operations and simulation treatments, and to obtain informa-tion about the boundaries of the reservoir. The well flowrate is varied and the resulting pressure transients are measured. The measurement of variation of pressure with time provides a pressure transient data which then can be analyzed to determine the forma-tion parameters that characterize the flow conditions that exist in the system.

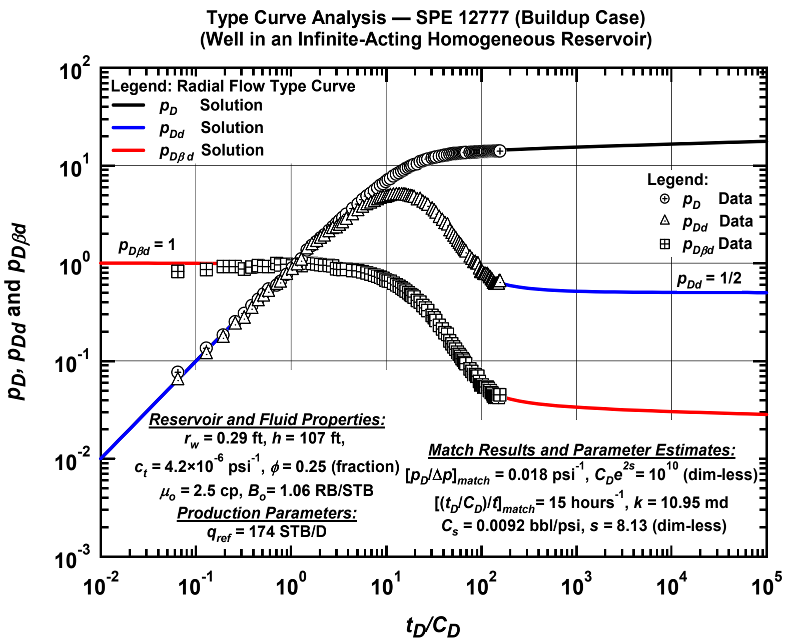
- Well test analysis can be considered as a systems analysis technique:



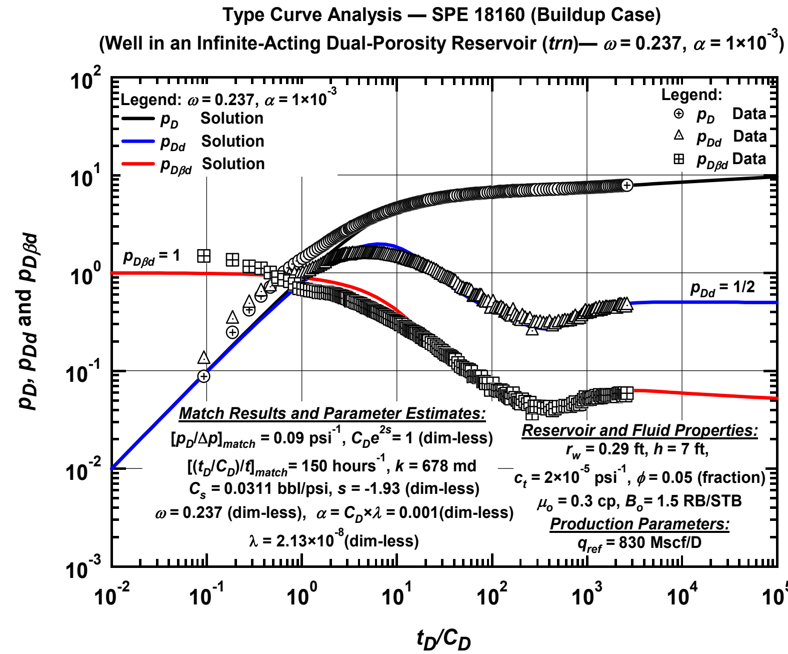
- The system "S" represents the wellbore and the formation that it is in communication with. The input "I" represents the constant withdrawal of the reservoir fluid and it can be considered as a forcing function applied to the system "S". The response of the system, "O" which represents the change in reservoir pressure is measured during the test.

From: Ertekin,T. (Penn State U.)

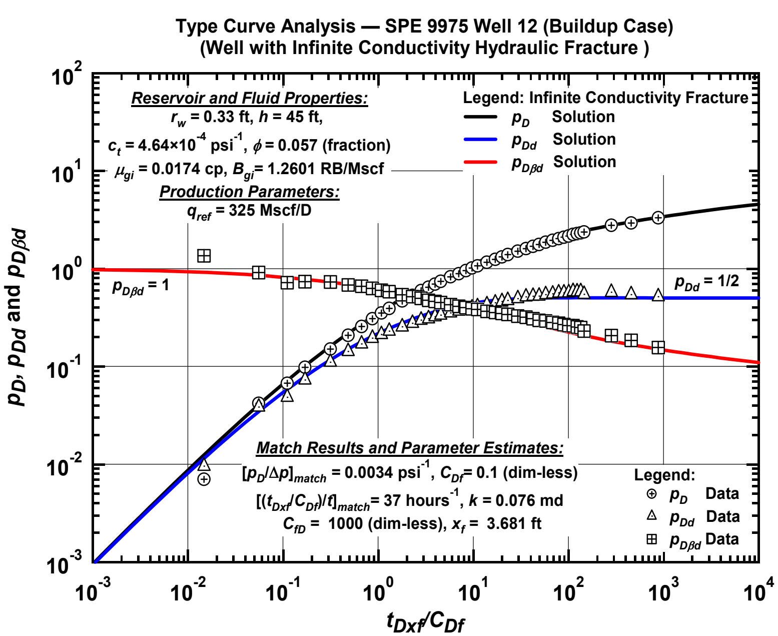
Overview: PTA — Example Pressure Transient Tests



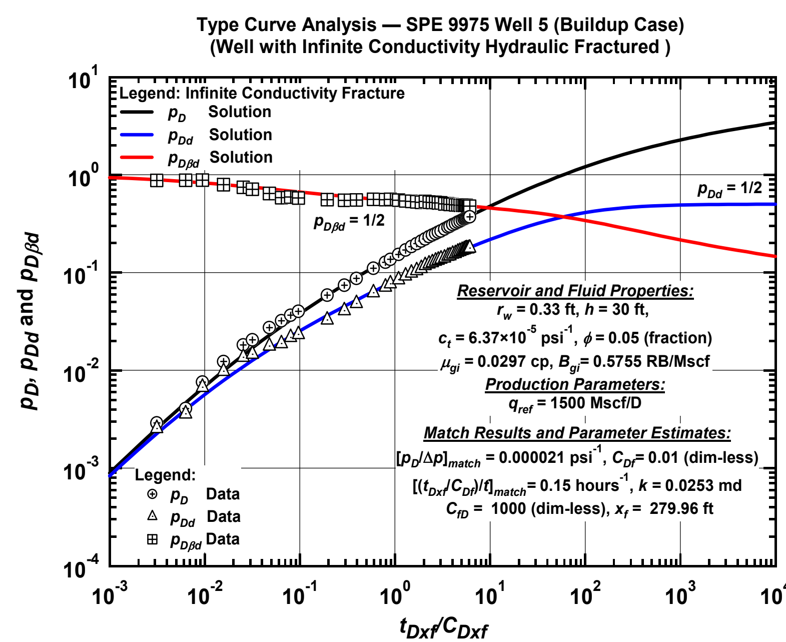
a. Case 1 — Unfractured well, homogeneous reservoir.



b. Case 2 — Unfractured well, dual porosity reservoir.



c. Case 3 — Fractured gas well, *low* fracture conductivity.



d. Case 4 — Fractured gas well, *high* fracture conductivity.

Overview: Reservoir Modeling — Introduction

What Questions can a Reservoir Model Answer?

***Basic Simulation Approaches*:**

- ***Analytical approach*** **— providing an exact solution to an approximate problem. This approach is utilized in classical well test analysis.**
- ***Numerical approach*** **— providing the approximate solution to an exact problem. This approach attempts to solve the more realistic problem with very limited assumptions.**

***Reservoir Characterization*:**

- **A reservoir simulator can be used to characterize the reservoir under study using a process called history-matching in which the reservoir parameters are adjusted or tuned to match the past performance of the reservoir.**

***Forecasting*:**

- **After the simulation model has been adjusted and validated through the history matching process, the model can then be used to forecast future reservoir performance.**
- **The history-matched model allows an engineer to investigate reservoir performance under various production and operation strategies in order to develop a well-designed strategy for field development and field operation practices.**

***Feasibility Analysis*:**

- **Results from the simulation study can then be used to perform cost and revenue calculations in order to select a feasible production and operation strategy for the field.**

From: Ertekin, T. (Penn State U.)

<u>Overview</u>: Reservoir Modeling — Preliminary Work

***Establishing the Objectives of the Study*:**

- **The basic information required to establish a reservoir study includes:**
  - **— Amount and quality of data available (*i.e.*, seismic, logs, well tests, etc.).**
  - **— Recovery stage of the reservoir.**
  - **— Additional data that would be needed in order to perform the study.**
  - **— The time to perform the project.**

***Checking the Inventory of Data*:**

- **The information required to perform a field study comes from different sources (different in levels and disciplines), it is important to perform an exhaustive organization of the data.**

***Data Analysis*:**

- **In order to define whether a data set is appropriate for inclusion in a reservoir model, the engi-neer must be aware of not only the way the data was measured, but also the physics and the conditions of the measurement itself.**

***Resolution of Data Conflicts*:**

- **When there are two or more sets of data representing the same property, the simulation engineer must define which measurement represents the actual mechanism in the reservoir more closely. To achieve this resolution, these data are input into the model and, by means of history matching and sound engineering judgment, a "most likely" case is established.**

***Availability of The Computational Resources*:**

- **When defining the objectives of a reservoir study, one must be aware that the degree of complexity of the description for a given problem must match the available computing power.**

From: Ertekin, T. (Penn State U.)

Overview: Reservoir Modeling — History Matching

***Parameters to be Specified and Parameters to be Matched*:**

- **In general, the data to be specified are the flowrates of the reservoir fluids (*e.g.,* oil flowrate for oil reservoirs and gas flowrate for gas reservoirs).**
- **The parameters to be matched during the history-match process depend on the availability of the historical production data. However, there are two broad categories — the pressure history and the fluid performance data (*e.g.,* flowrates, water/oil ratio (WOR), gas/oil ratio (GOR), and water/gas ratio (WGR)).**

***Additional Tools*:**

- **Material balance studies and aquifer influx studies.**
- **Pressure transient analysis, which provides permeability and (*kh*).**
- **Single-well models, which can be used to study coning (and other phenomena).**

***Quality of a History Match*:**

- **The important issue is that the history-match must be consistent with the objectives of the study. The purpose of the adjusted model obtained from a history match will dictate whether the match is good enough and can be used to perform the desired task with a good level of confidence.**

***Rules of Thumb for History Matching Studies*:**

- **Adjustment parameters should be the data which are least accurately known.**
- **Adjustments within acceptable ranges defined by the engineers and geologists.**
- **Permeability is the most common parameter used in history-matching.**

From: Ertekin, T. (Penn State U.)

Overview: Reservoir Modeling — Forecasting

Process Selection:

- The feasibility of different production processes can be investigated through simulation by making a forecast of future reservoir performance under different production schemes.

Operational Parameters:

- The purpose of specifying operational parameters is to predict the important events which may be associated with a given production scheme.
- Such parameters include: flowrate, well spacing, operating conditions, etc.

Process Optimization:

- The focal point of any study is "how fast" and "how much" can we recover?
- The optimal flowrate and ultimate recovery are to be investigated/established.

Validating and Analyzing Results of the Forecasting Study:

- The validation process is required to ensure that the results are realistic.
- Results should be compared to results obtained/estimated by other means.
- A good check is to compare the predicted results to the performance of analog fields which have comparable rock and fluid properties, similar well patterns and spacing, and similar field operations.

Rules of Thumb for Forecasting Studies:

- A base case is required for the comparisons of impact of various development plans and production strategies.
- Once the base case is established, any variety of sensitivity cases can be designed/performed.

From: Ertekin, T. (Penn State U.)

Overview: Reservoir Modeling — Perspectives

***There are Five Basic Steps in the Process of a Simulation Study*:**

- **Setting concrete objectives for the study.**
- **Selecting the proper simulation approach.**
- **Preparing the input data.**
- **Planning the computer simulations.**
- **Analyzing the results.**

***Factors that help Us to Define Appropriate Objectives*:**

- **Available data.**
- **The required level of detail.**
- **Available technical support.**
- **Available resources.**

***Two Types of Objectives*:**

- **Fact-finding.**
- **Optimization strategy.**

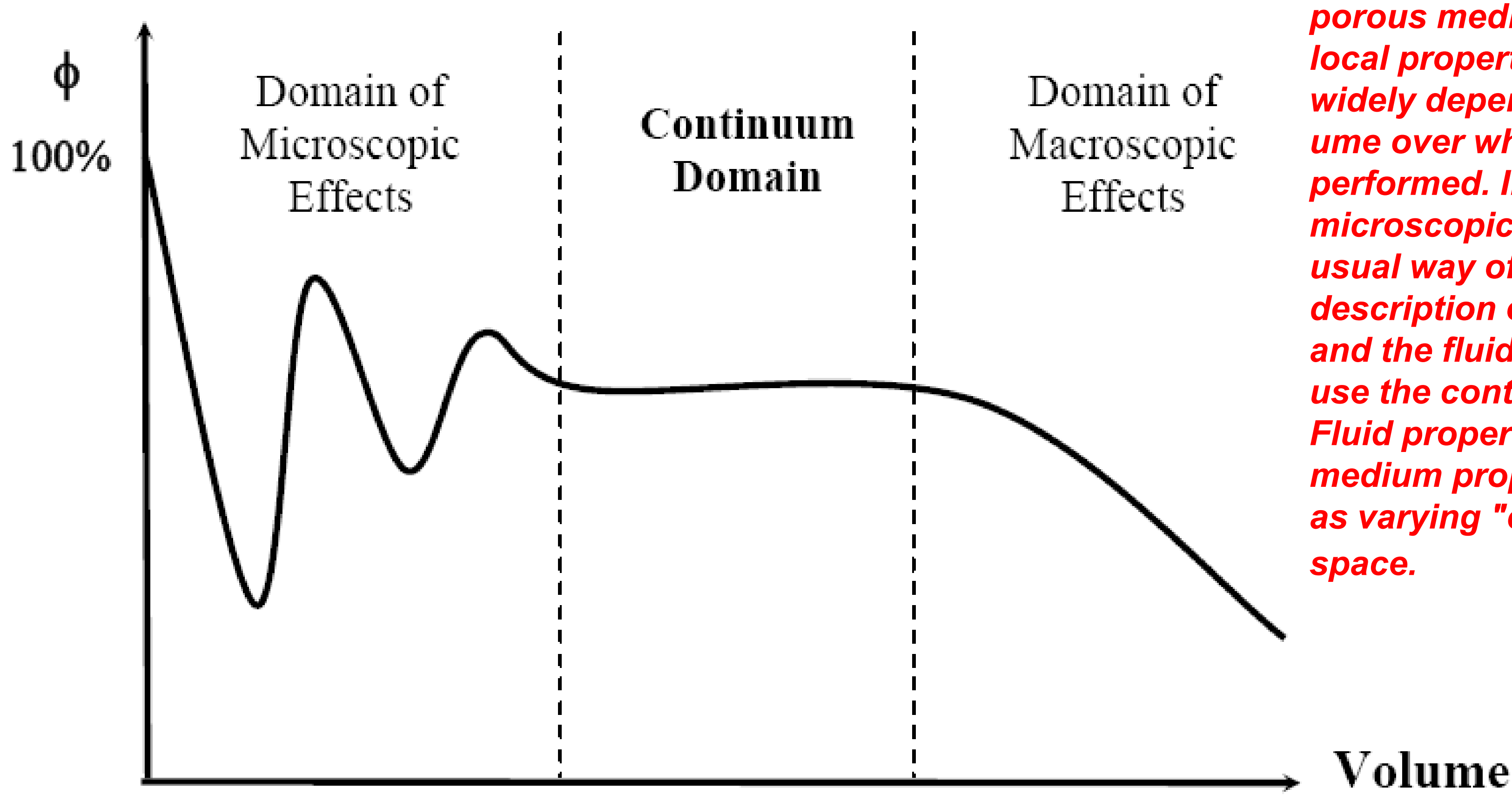
***Choosing the Simulation Approach*:**

- **Reservoir complexity.**
- **Fluid type.**
- **Scope of the study.**

From: Ertekin, T. (Penn State U.)

Overview: Reservoir Modeling — General Concepts

The Porous Medium as a Continuum:



The microscopic scrutiny of a porous medium reveals that its local properties may vary widely depending on the volume over which the scrutiny is performed. Instead of a microscopic description, the usual way of approaching a description of a porous media and the fluids within it is to use the continuum approach. Fluid properties and porous medium properties are treated as varying "continually" in space.

From: Ertekin,T. (Penn State U.)

The Fundamental Equations:

1. The *Continuity Equation* describes mass accumulation/transfer in the system.
2. The *Equation of State* describes density as a function of pressure and temperature.
3. The *Energy Equation* describes energy accumulation/transfer in the system.
4. The *Momentum Equation* describes momentum accumulation/transfer in the system.
5. The *Constitutive Equation* describes deformation of the fluid as a result of motion.

Overview: Reservoir Modeling — Potential Areas of Conflict

Porosity:		
● Core:	Core Scale	(High Confidence)
● Open-Hole Logs:	Reservoir Scale	(High Confidence)
Permeability:		
● Core:	Core Scale	(High Confidence)
● Open-Hole Logs:	Reservoir Scale	(Low Confidence)
● Pressure Transient Analysis:	Reservoir Scale	(High Confidence)
Reservoir Pressure:		
● Formation Wireline Tester:	Reservoir Scale	(High Confidence)
● Pressure Transient Analysis:	Reservoir Scale	(Medium Confidence)
Initial Saturations:		
● Core:	Core Scale	(Medium Confidence)
● Open-Hole Logs:	Reservoir Scale	(High Confidence)
● Cased-Hole Logs:	Reservoir Scale	(Medium Confidence)
End-Point Saturations:		
● Core:	Core Scale	(High/Medium Confidence)
● Open-Hole Logs:	S_{wir} — Reservoir Scale	(High Confidence)
● Open-Hole Logs:	S_{or} — Reservoir Scale	(Medium/Low Confidence)
● Cased-Log Logs:	S_{or} — Reservoir Scale	(High/Medium Confidence)

From: Ertekin, T. (Penn State U.)

Overview: Reservoir Modeling — Resolution of Conflicts

Always give more Weight to Data which:

- **Contain a High Degree of Confidence:**
  - ***Pressure Transient Permeability versus Well Log Derived Permeability***
  - ***Unsteady-State versus Steady-State Relative Permeability***
  - ***Bottom-Hole PVT Samples versus Recombined Separator Samples***
- **Are Measured at the Appropriate Scale for the Reservoir Model:**
  - ***Well Log versus Core Data***
  - ***Pressure Transient Data versus Core Data***
- **Are Representative of the Processes Occurring in the Reservoir:**
  - ***Differential*** (***Variable Composition***) ***PVT Data***
  - ***Flash*** (***Constant Composition***) ***PVT Data***
  - ***Imbibition*** (***Increasing Wetting Phase Saturation***) p_c ***and*** k_r.
  - ***Drainage*** (***Decreasing Wetting Phase Saturation***) p_c ***and*** k_r.

Best Advice:

- **Use preliminary versions of the simulation model can be used to screen conflicting data to determine further course(s) of action.**

From: Ertekin, T. (Penn State U.)

History of Reservoir Engineering: Orientation

Topics:

- History of Reservoir Engineering
- Tasks of the Reservoir Engineer
- Data Sources
- Fundamental Drive Mechanisms
- Trapping Mechanisms

From: Towler, Brian F. Fundamental Principles of Reservoir Engineering. (2002) Society of Petroleum Engineers, Richardson Texas.

History: History of Reservoir Engineering — Timelines

History of Reservoir Engineering: (Towler Ch. 1)

- **1930's:**
  - Fancher (Petrophysics)
  - Muskat (Fluid Flow Solutions)
  - Schilthuis (Material Balance)
- **1940's:**
  - Buckley-Leverett (Fractional Flow)
  - Tarner (Solution-Gas-Drive)
  - Purcell-Burdine (p_c-k-k_r)
- **1950's:**
  - Early reservoir simulation
  - Deliverability testing
  - Advances in phase behavior
  - Formation evaluation (well logs)
- **1960's:**
  - Reservoir simulation
  - Pressure transient testing
  - Fractured reservoirs
- **1970's:**
  - Fetkovich (Decline Type Curve Analysis)
  - Advanced pressure transient testing
- **1980's:**
  - Fractured wells (1970s/1980s)
  - Geostatistics
  - Production-driven economics
- **1990's:**
  - Very intensive reservoir simulation
  - Integrated reservoir management
  - Blasingame (Production Analysis)
  - Heterogeneity (k-distributions)
- **2000's:**
  - Software-driven reservoir engineering
  - Distributed temperature and pressure
  - Deconvolution of well test data
- **2010's:**
  - Very large-scale reservoir simulation
  - Nanoscale petrophysics
  - Nanoscale phase behavior
  - Nanoscale fluid flow

From: Towler, Brian F. Fundamental Principles of Reservoir Engineering. (2002)
Society of Petroleum Engineers, Richardson Texas.

History: Tasks of the Reservoir Engineer

Tasks of the Reservoir Engineer:

- How much oil and gas is originally in place?
- What are the drive mechanisms for the reservoir?
- What are the trapping mechanisms for the reservoir?
- What is the recovery factor by primary depletion?
- What will future production rates from the reservoir be?
- How can the recovery be increased economically?
- What data are needed to answer these questions?

Example Activities:

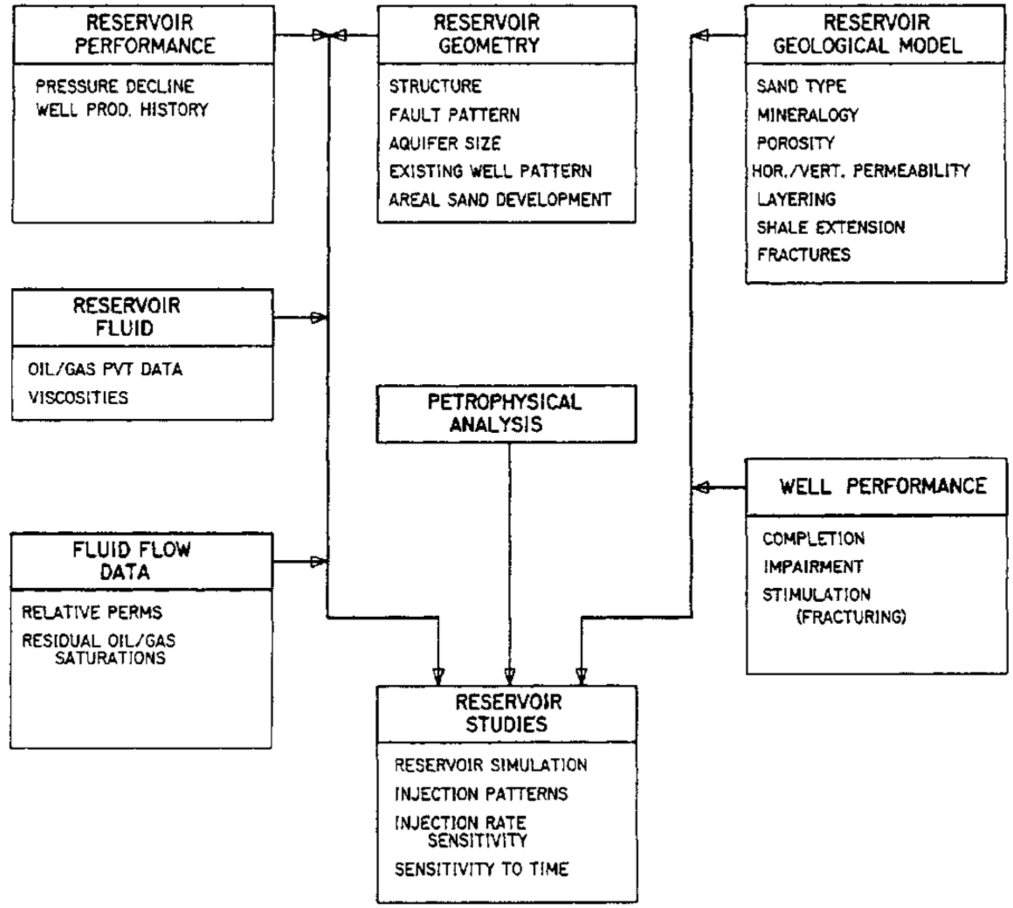
- Estimation of reservoir volume by material-balance.
- Evaluation of reservoir drive indices.
- Fluid displacement theory for recovery.
- Decline-curve models — future production/ultimate recoveries.
- Improved/enhanced reservoir recovery (IOR/EOR)
- Economic evaluation for primary recovery/IOR/EOR?

From: Towler, Brian F. Fundamental Principles of Reservoir Engineering. (2002)
Society of Petroleum Engineers, Richardson Texas.

History: Data Sources/Reservoir Engineering Workflows

***Data Sources*:**

- **Reservoir Properties:**
  - **Reservoir porosity**
  - **Reservoir thickness**
  - **Reservoir permeability**
  - **Fluid saturations**
- **Phase Behavior:**
  - **Formation volume factors**
  - **Gas-to-oil ratios**
  - **Fluid viscosities**
- **Saturation-Dependent Data:**
  - **Capillary pressures**
  - **Relative permeability**
- **Production Data:**
  - **Production rates**
  - **Surface and bottomhole pressure data**
  - **Gas and oil gravities measured as a function of time.**



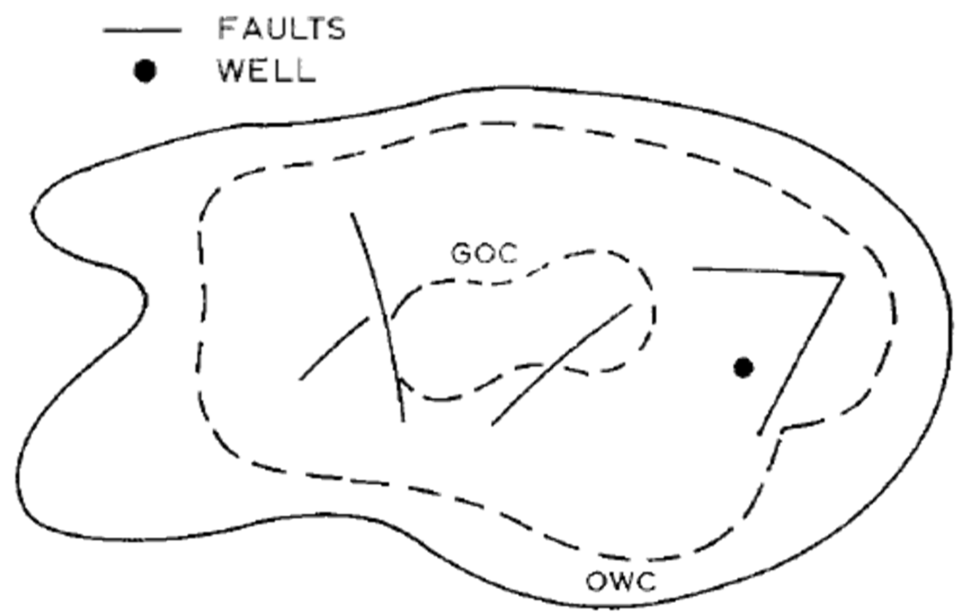
From: Towler, Brian F. Fundamental Principles of Reservoir Engineering. (2002)
Society of Petroleum Engineers, Richardson Texas.

From: How Heterogeneity Affects Oil Recovery — Weber (1986).

History: Fundamental Drive Mechanisms

Fundamental Drive Mechanisms:

- **Solution-Gas Drive:**
  - Oil expansion for $p > p_b$.
  - Oil and gas expansion for $p < p_b$.
- **Gas-Cap Drive:**
  - $p = p_b$ at the gas-oil-contact (GOC)
  - Gas cap expansion drives oil.
- **Waterdrive:**
  - Aquifer under or aside oil column.
  - Aquifer movement drives oil.
- **Gravity Drive:**
  - Gravity drives segregation of phases.
  - Efficient/effective, but very slow.
- **Compaction Drive:**
  - Weak/deformable rock drives fluid.
  - "Abnormally pressured gas" reservoirs.
- **Imbibition Drive:**
  - Capillary imbibition.
  - Often requires a cyclic process.

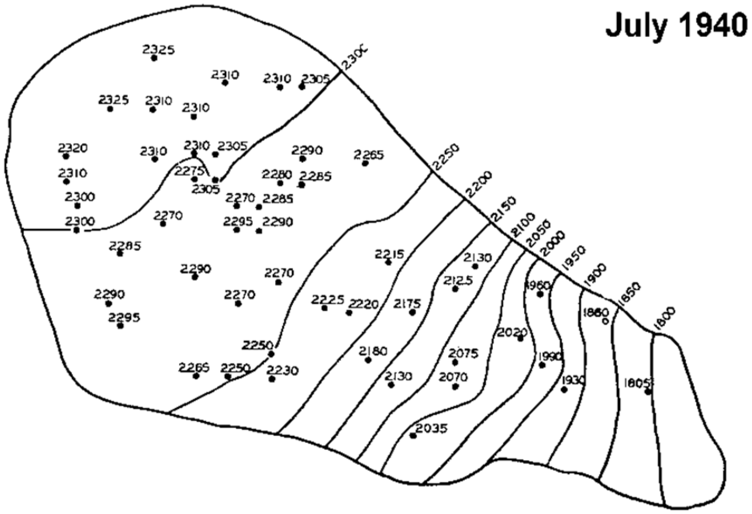


(conceptual) *Geological model including faults/fluid contacts.*

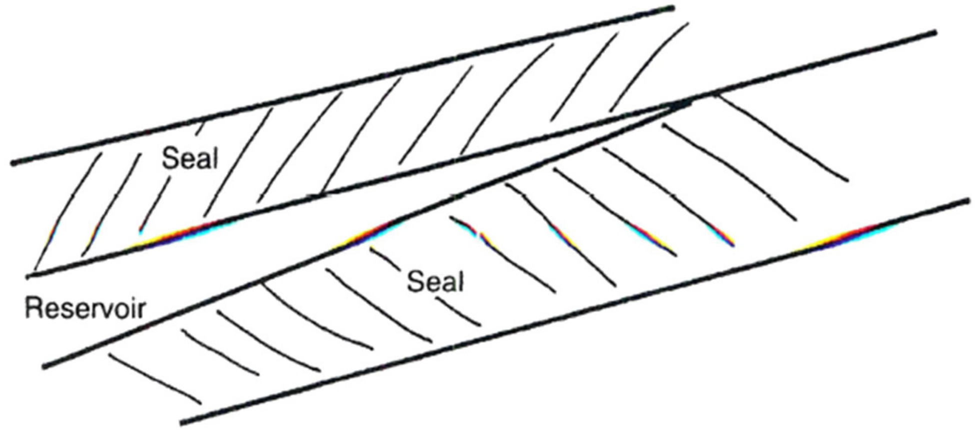
From: Dake, L. P.: The Practice of Reservoir Engineering, Elsevier (1994).

From: Towler, Brian F. Fundamental Principles of Reservoir Engineering. (2002) Society of Petroleum Engineers, Richardson Texas.

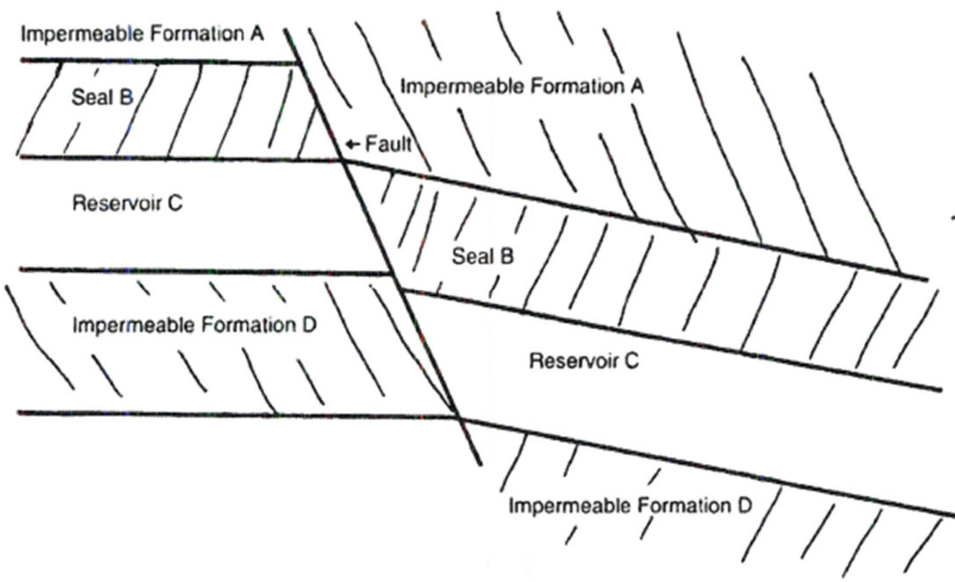
History: Trapping Mechanisms



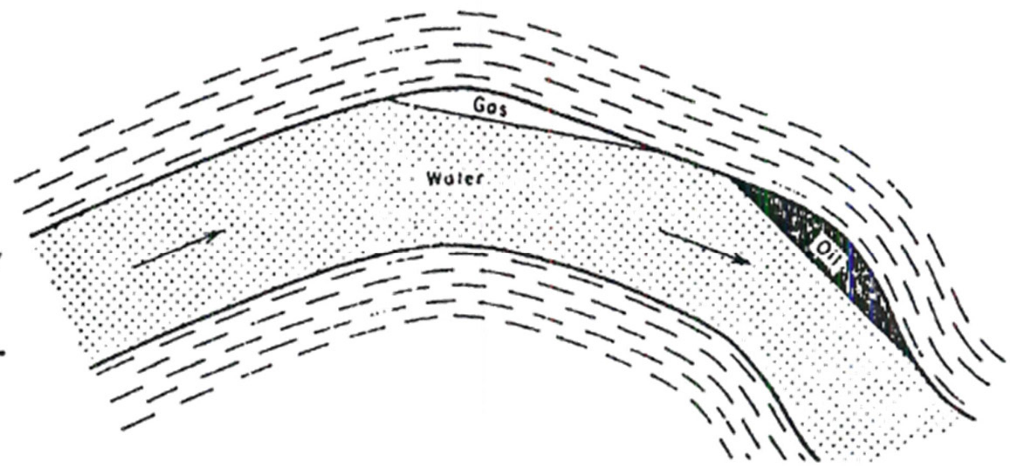
Structural Trap



Stratigraphic Trap



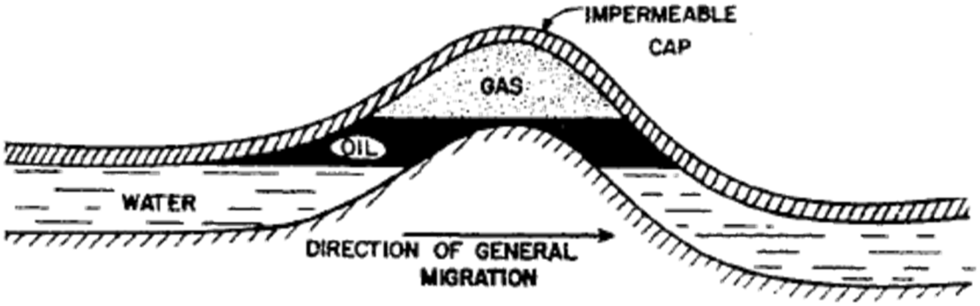
Fault Trap



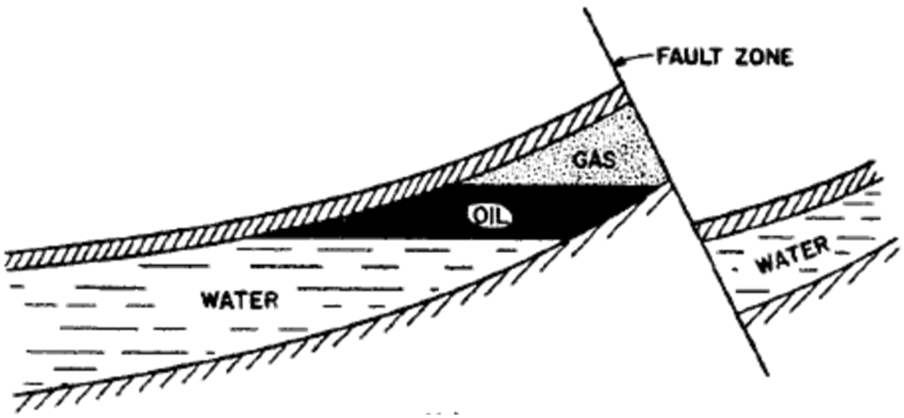
Hydrodynamic Trap

From: Towler, Brian F. Fundamental Principles of Reservoir Engineering. (2002)
Society of Petroleum Engineers, Richardson Texas.

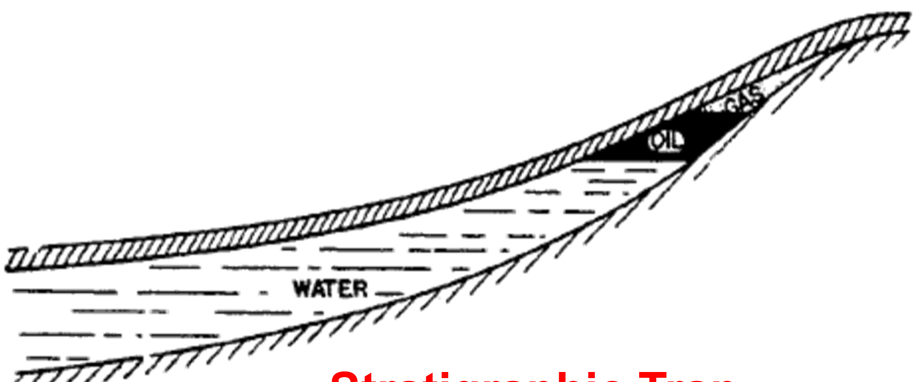
History: Trapping Mechanisms (Comments from Muskat)



Structural Trap



Fault Trap



Stratigraphic Trap

From: Muskat, M.: The Flow of Homogeneous Fluids Through Porous Media, McGraw-Hill Book Company, New York (1946).

Extracted text from Muskat:

- ***The question naturally arises regarding the ultimate loss of oil and gas from the original reservoir. In some cases involving fault zones, such losses are evident.***
- ***Assuming, therefore, that as long as abnormal pressures exist the gas accumulations are slowly expelled through the overburden, such leakage must stop when the reservoir pressure is in equilibrium with that in its surroundings.***
- ***Obviously, variations from this condition will exist if over a consider-able area the overlying cover is truly impermeable. Likewise, if rapid subsidence or uplift is in progress and the pressure adjustments are insufficiently rapid to keep pace, abnormally high or low pressures will prevail.***

Introduction to Reservoir Engineering

(*End of Lecture*)

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