Reservoir System and Characterization

I. Overview
  a. Reservoir – subsurface rock and sediment materials characterized by porosity and permeability, to allow the migration and accumulation of petroleum hydrocarbons

    a. Reservoir: porous rock/sediment units that have a capacity to contain water, pores can be formed by openings between grains (primary porosity) or by cracks and fractures in the rocks (secondary porosity)

      (1) Common Reservoirs:
        (a) Unconsolidated / Semi-lithified Sands
        (b) Sandstone
        (c) Carbonates (Limestone and Dolostone)

    b. Seal: Impermeable layers which will not transmit or store groundwater, tend to form the upper or lower boundaries of aquifers

      1. Common Seals
        a. Unconsolidated / Semi-lithified Muds (silt and clay)
        b. Shale
        c. Well cemented / recrystallized sandstone

II. Porosity

  2. Porosity: ratio, in per cent, of the volume of void space to the total volume of sediment or rock

$$n\ (\%) = \frac{\text{total volume - volume of solids}}{\text{total volume}} \times 100\%$$

    a. Porosity is the primary governing factor influencing the ability of rock or sediment to store fluids (e.g. groundwater or hydrocarbons)

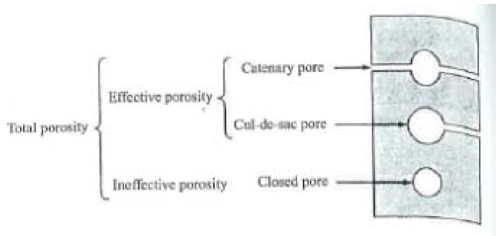
    b. Types of Porous Openings
      (a) Intergranular Porosity = primary pore spaces present between particles of a sediment or rock deposit
        i) Intergranular Porosity influenced by:
          a) sorting
          b) grain packing
          c) grain size
      (b) Fractured Porosity
      (c) Solution Cavities
      (d) Vesicles

TABLE 6.1 Classification of the Different Types of Porosity Found in Sediments

Time of formation	Type	Origin
Primary or depositional	Intergranular, or interparticle Intragranular, or intraparticle	Sedimentation
	Intercrystalline Fenestral	Cementation
Secondary or postdepositional	Vuggy Moldic	Solution
	Fracture	Tectonics, compaction, dehydration, diagenesis

    c. Effective porosity: considers the extent to which pore spaces are interconnected in a deposit, as well as the force of hydrostatic attraction that binds fluid molecules to the surfaces of grains/pore spaces

(1) Hygroscopic Fluids= high surface tension of water + oil creates tendency to coat pores with electrostatically-bound film of water
    (a) effectively reduces porosity of rock/material, represents the porosity available for fluid flow.
(2) Pore Types
    (a) Caternary Opening – through flow pore throat connection
    (b) Cul-de-Sac – one direction of pore throat connection
    (c) Closed Pore – isolated pore space, non-connected



d. Secondary Porosity: can impart a post-depositional secondary or "overprint" porosity on a rock unit via structural fracturing and chemical dissolution.

(1) Solution Porosity
(2) Fracture Porosity

e. Lithologic Control on Porosity
(1) Porosity of Unconsolidated Sediments
    (a) function of grain size and packing
        i) uncompacted clay and silt = very high porosity (up to 50%)

**compacted clay and silt = decreased porosity to 15%

        ii) sand and gravel: porosity of 20-30% typically

(2) Porosity of Sedimentary Rocks
    (a) Primary vs. Secondary Porosity

    (b) Sandstone and conglomerate may possess relatively high porosities (30%)

    (c) Limestone and carbonates may be low or high depending on solution
        i) dissolved limestone ---- high secondary porosity
        ii) hard, dense limestone ----- low primary porosity

(d) Shale – generally low porosity and permeability in subsurface environment due to depth of burial and compaction
    i) Fracture Porosity – secondary overprint may be significant in shales, even though net permeability is low

e.g. “Oil Shale” or “Gas Shale”

(3) Porosity of Crystalline Plutonic and Metamorphic Rocks
    (a) Very low primary porosity
    (b) Secondary "structural porosity"

i) joints, fractures, faults -----porous zones

a) may achieve 5-10% on avg, up to 50% porosity in some instances

(c) Minimal applicability to petroleum environments

(4) Porosity of Volcanic Rock

(a) Vesicles and columnar jointing may create relatively high porosities

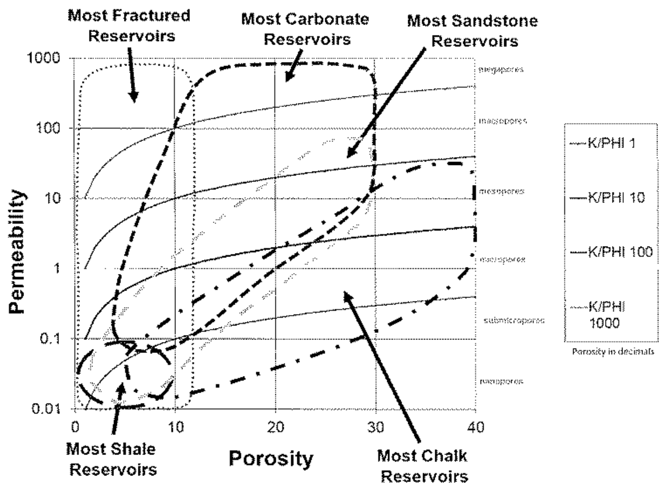
(b) Inter-flow fluvial deposits

(c) brecciated horizons

(d) Minimal applicability to petroleum environments

i. Material Controls on Primary Porosity

1. Lithology - Grain Shape - Grain Sorting - Grain Packing / Fabric



III. Permeability

1. Permeability: the degree of interconnectedness between pore spaces and fractures within a rock or sediment deposit. A measure of the capacity of a porous material to transmit fluids

a. Permeability (K) is largely a function of:

(1) grain size, size of pore space

(2) shape of grains/shape of pore space

(3) degree of interconnected pore space

b. Hydraulic Conductivity = permeability in a horizontal direction in aquifer

(1) Measure of rate of tranmission of fluids horizontally through aquifer, essentially another term for permeability (modification of Darcy's Law)

$$Q = -KIA$$

Where Q = discharge (L^3/T)

K = hydraulic conductivity (permeability) (L/T)

I = hydraulic gradient (vertical head distance between two points of observation) (decimal ratio)

A = cross-sectional area through which flow occurs (L^2)

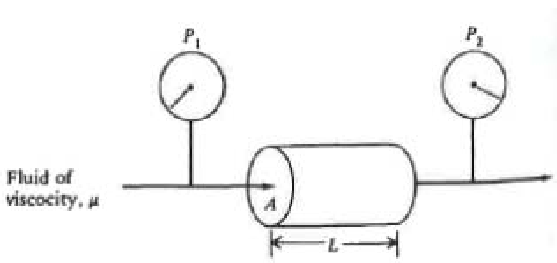
(a) Vertical Conductivity = capacity to transmit fluids in vertical direction

(b) Horizontal Conductivity = capacity to transmit fluids in horizontal direction

c. Darcy's Law

$$Q = \frac{KA(P_2-P_1)}{uL}$$ where,

Q = Volume Discharge Rate (cm^3/sec)
K = Permeability (millidarcy = mD)
A = Cross-sectional area at perpendicular to flow (cm^2)
L = length along which press. diff. is measured (cm)
(P_2-P_1)= pressure difference (atm) between two points separated by distance L
u = viscosity of fluid (centipoises)



Generally, well sorted sand and gravel display high porosity and permeability, however, a poor sorted sand with much matrix material will have a low permeability.

Unpacked clay, may have a very high porosity but very low permeability.

Generally clay/shale make for good permeability barriers, while sand and gravel readily transmit fluids. However secondary overprints such as structural deformation and diagenetic alteration (post-depositional changes in mineralogy) can drastically influence permeabiltiy and porosity.

1. Permeability – Units of Measure an Ranges
   a. The SI unit for permeability is m^2; Practical Unit = darcy (d) or millidarcy (md)

      1 darcy $= 10^{-12}\ m^2$ 1 $cm^2 = 10^{-4}\ m^2 = 10^8$ d

   b. Petroleum Thresholds

      Rocks > 100 md = “reservoir potential”, higher permeability
      e.g. Unconsolidated Sand > 5,000 md

      Rocks < 100 md = “seal potential”, lower permeability

<table>
<tr><th>Permeability</th><th colspan="4">Pervious</th><th colspan="4">Semi-Pervious</th><th colspan="5">Impervious</th></tr>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt, Loess, Loam</td><td colspan="4"></td></tr>
<tr><td>Unconsolidated Clay & Organic</td><td colspan="4"></td><td colspan="2">Peat</td><td colspan="3">Layered Clay</td><td colspan="4">Unweathered Clay</td></tr>
<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Dolomite</td><td colspan="2">Fresh Granite</td></tr>
<tr><td>κ (cm²)</td><td>0.001</td><td>0.0001</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td><td>10^{-8}</td><td>10^{-9}</td><td>10^{-10}</td><td>10^{-11}</td><td>10^{-12}</td><td>10^{-13}</td><td>10^{-14}</td><td>10^{-15}</td></tr>
<tr><td>κ (millidarcy)</td><td>10^{+8}</td><td>10^{+7}</td><td>10^{+6}</td><td>10^{+5}</td><td>10,000</td><td>1,000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>0.0001</td></tr>
</table>

B. Hydraulic Conductivity

1. By rearranging Darcy's Law (above):

$$K = \frac{-Q}{A\,(I)}$$

where K = hydraulic conductivity
A = cross-sectional area
I = dh/dL = gradient ("rise over run")

<table>
<tr><td>K (cm/s)</td><td>10^2</td><td>10^1</td><td>$10^0=1$</td><td>10^{-1}</td><td>10^{-2}</td><td>10^{-3}</td><td>10^{-4}</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td><td>10^{-8}</td><td>10^{-9}</td><td>10^{-10}</td></tr>
<tr><td>K (ft/day)</td><td>10^5</td><td>10,000</td><td>1,000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>0.0001</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td></tr>
<tr><td>Relative Permeability</td><td colspan="4">Pervious</td><td colspan="4">Semi-Pervious</td><td colspan="5">Impervious</td></tr>
<tr><td>Aquifer</td><td colspan="5">Good</td><td colspan="4">Poor</td><td colspan="4">None</td></tr>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt, Loess, Loam</td><td colspan="4"></td></tr>
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<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Dolomite</td><td colspan="2">Fresh Granite</td></tr>
</table>

Source: modified from Bear, 1972

2. Intrinsic Permeability (Ki)
   a. Modified K that considers the properties of the porous medium, shape of the pore openings

$Ki = Cd^2$ where C = shape constant, d = diameter of grains

standard units in civil engineering = sq^2
standard units in petroleum eng. = darcy

1 darcy = 9.87×10^{-9} cm^2

3. Relationship of K to Ki
   a. Hydraulic conductivity then is a function of both pore throat geometry and physical nature of the fluid

K = Ki(pg/u) where

K = hydraulic conductivity, Ki = intrinsic permeability, p = density of fluid, g = acceleration due to gravity, and u = visosity of the fluid.

C. Permeameters

1. Defined: lab device to measure hydraulic conductivity of earth materials (see figure included with the note set)

   a. Involves a holding chamber for the seds/soil, and a head of water is established in the medium. The head is known, the length of the material medium is known, discharge is measured.

   b. Equation for solution of constant head permeameter test:

   K = QL/(Ah)

where K = hydraulic conductivity (cm/sec), L = length of sample (cm), A = cross-sectional area of sample (cm^2), h = hydraulic head (cm), Q = discharge (cm^3/sec)

   c. Equation for solution of falling head permeameter test:
   See attached equation sheet.

D. Permeability Vs. Lithology

(1) Permeability of Unconsolidated Sediments

(a) Relationships to Grain Size

i) Perm < with < Grain Size (and vice versa)

a) Perm < with < sorting (and vice versa)

b) Hence well sorted coarse sediment (sand, gravel) display the highest permeability

c) Poorly sorted or very fine sediment (clayey sand, or clay) generally display lowest permeability

(2)Permeability of Lithified Rocks

(b) Function of interconnected nature of pore spaces

i) Sandstone, Conglomerate = high primary permeability

ii) Limestone = low primary permeability

a) Dissolved Limestone ----- high secondary permeability

iii) Shale and Well-cemented Siltstone = low primary permeability

a) Fractured Shales and Siltstones = high secondary permeability

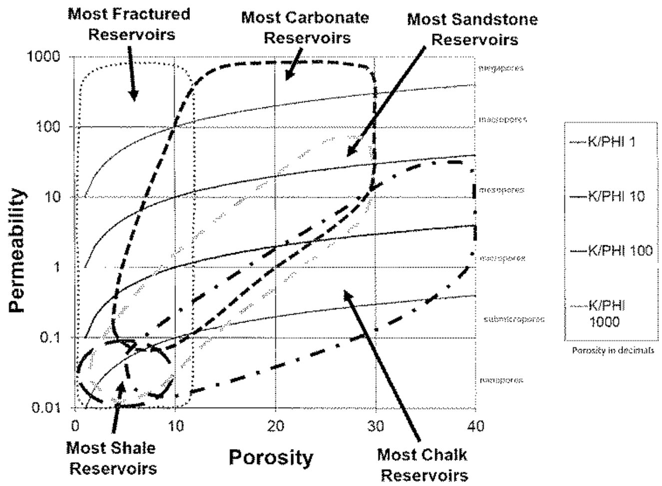
b) Crystalline Igneous and Metamorphic Rocks = low primary permeabiltiy

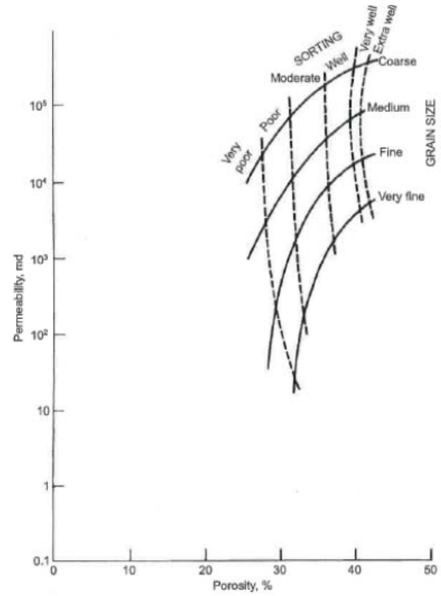
c) Fractured Shales and Siltstones = high fractured (secondary permeability

iv) Volcanic Rocks = high primary permeability associated with columnar jointing

2. Material Controls on Permeability

   a. Lithology - Grain Shape - Grain Sorting - Grain Packing / Fabric



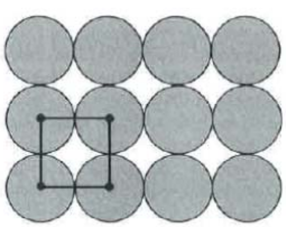


E. Homogeneity and Heterogeneity of the Reservoir

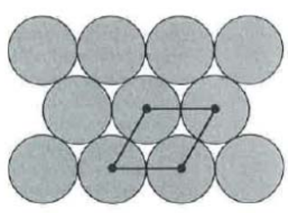
1. Controlling Factors: Lithology-Grain Shape-Grain Sorting-Grain Packing / Fabric

2. Homogeneous Hydraulic Unit- a homogeneous porous medium with uniform hydraulic properties in 3-dimensions (X,Y,Z)
   a. Permeability of similar value vertically and horizontally in all directions
   b. e.g. uniform, porous sandstone of constant thickness

2. Heterogeneous Hydraulic Unit-
heterogeneous porous medium with non-uniform hydraulic properties (vary according to X,Y,Z directions)
   a. Permeability varies vertically and horizontally in all directions
   b. e.g. fractured shale



Cubic packing
(48% porosity)



Rhombohedral packing
(26% porosity)

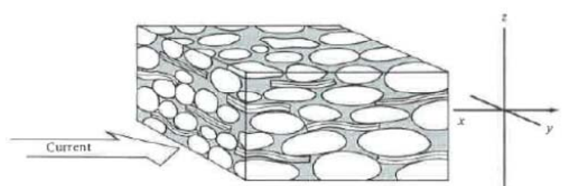


FIGURE 6.22 Block diagram of sand showing layered fabric with grains oriented parallel to current. Generally, $K_x > K_y > K_z$.

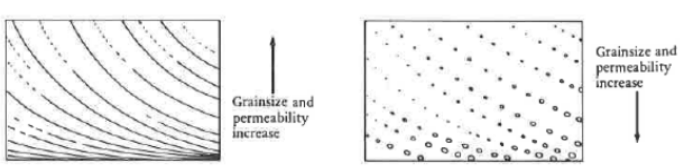


FIGURE 6.23 Permeability variations for (A) downward-fining and (B) downward-coarsening avalanche cross-beds.

a) Directional Permeability Control

c. Isotropic Medium: intrinsic permeability same in all directions (3-D)

(1) Kv = Kh vertical and horizontal permeability equal

d. Anisotropic Medium: intrinsic permeability varies according to preferred orientations

Kv not equal to Kh vertical and horizontal permeability not equal

b) Reservoir Saturation Conditions ("Wettability") – oil/water content of pore space

1. Water Wet Reservoir (common)

2. Oil Wet Reservoir (rare)

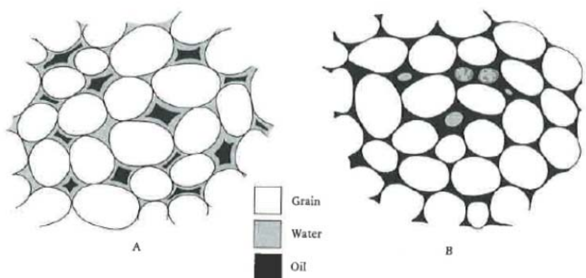


FIGURE 6.14 The concept of wettability in reservoirs. (A) A water-wet reservoir (common). (B) An oil-wet reservoir (rare).

II. Reservoir Pressure Conditions

1. Confined Reservoir: reservoirs that are separated from atmospheric pressures by impermeable zones or confing seals

a. Confined aquifer and artesian conditions, relative to hydrostatic pressure

(1) Potentiometric surface: analogous to water table, but is elevation of water of confined aquifer that rises to equilibrium in open well penetrating confined aquifer

(a) may contour elevations to form potentiometric contour map

i) confined fluid flow generally perpendicular to contour of potentiometric surface.

(b) confined aquifers commonly under hydrostatic pressure in response to rock compaction and pore fluid pressures

b. Artesian Reservoirs: identified as water in a well that rises under pressure above the saturated confined aquifer horizon

(1) Conditions of formation:

(a) confined reservoir between two impermeable layers

(b) Limited hydraulic flux into the aquifer from water cycle

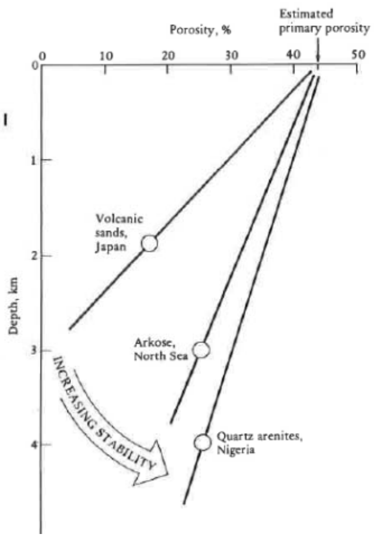
III. Diagenetic Effects on Reservoir Quality

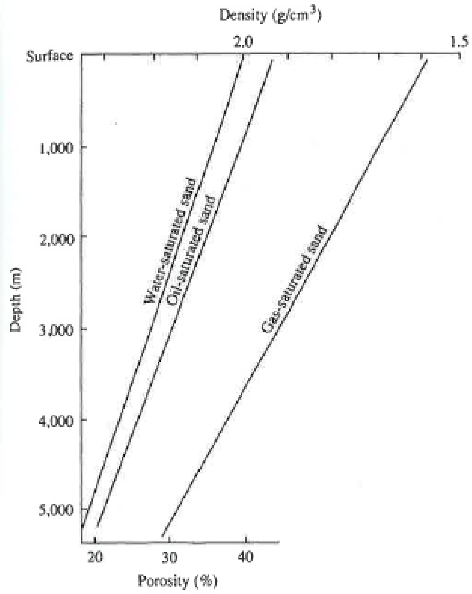
1. Diagenesis – post-depositional alteration of sediments and sedimentary rocks

i. "low grade" metamorphism

1. > depth of burial
2. >temperature and pressure
3. Clay alteration and dewatering

4. Cementation





2. Diagenetic Effects on Sandstone Reservoirs
    i. Porosity Loss by Cementation – Dependent upon pore fluid chemistry and time
        1. Quartz (SiO_2)
            a. Quart Sand Overgrowths
        2. Calcite ($CaCO_3$)
    ii. Porosity Loss by Clay Alteration
        1. Authigenic Clay (hydrous alumino-silicates)
        2. detrital matrix clay
    iii. Porosity Enhancement by Secondary Dissolution
        1. Carbonate leaching and dissolution
        2. Enhanced carbonic acids and humic acids in formation water

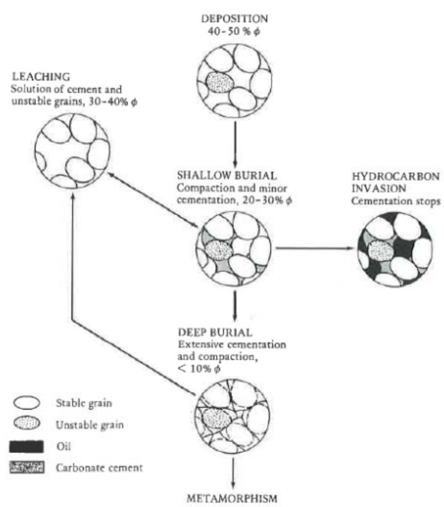


FIGURE 6.33 Simplified flowchart of the diagenetic pathways of sandstones.

3. Diagenetic Effects on Carbonate Reservoirs
    i. Dissolution and Cementation process

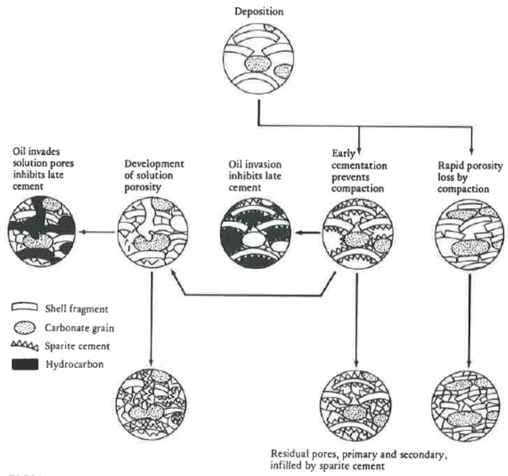
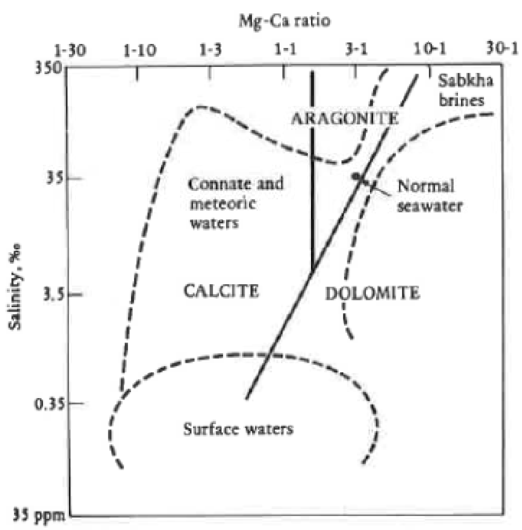


FIGURE 6.34 Simplified flowchart of the diagenetic pathways of lime sand.

ii. Dolomitization Process

$$2CaCO_3 + Mg^{2+} = CaCO_3MgCO_3 + Ca^{2+}.$$



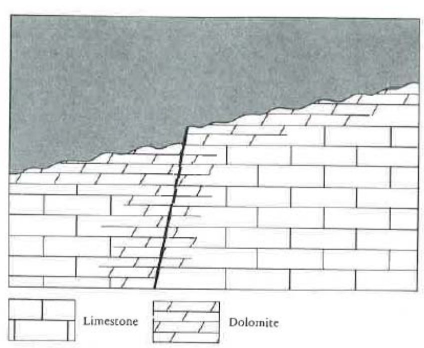


FIGURE 6.36 Cross-section showing how secondary dolomites are often related to faults and unconformities.

1. Important reactions involving CO_2, H_2O, $CaCO_3$, and pH.

a. Dissolution of Carbon Dioxide (gas) in water results in production of Carbonic Acid, which subsequently dissociates into free H^+ ions and the bicarbonate anion (HCO_3^-), hence increasing hydrogen ion activity, and by definition decreasing pH (becoming more acidic).

$CO_2 + H_2O$ ------ H_2CO_3

H_2CO_3 ------- H+ + HCO_3-

$CO_2 + H_2O$ ---- H+ + HCO_3-

b. As Calcium Carbonate (solid) reacts with water in presence of free hydrogen ions, the solid Calcium Carbonate dissolves forming free Ca^{+2} ions and free bicarbonate ions, hence consuming free hydrogen ions, decreasing hydrogen ion activity, and by definition increasing pH (becoming more basic). i.e. Calcium Carbonate acts to neutralize or buffer the solution by consuming hydrogen ions.

$CaCO_3 + H_2O + CO_2$ ------ Ca_{+2} + $2HCO_3$-

f. Dissolution of Calcium Carbonate as a Function of pH

c. General relationship: as Carbon Dioxide content of water increases, hydrogen ion actvity increases, pH decreases (more acidic)------solid Calcium Carbonate undergoes dissolution

(1) Dissolved Carbon Dioxide content is temperature dependent, as T >, Carbon Dioxide content <, hence hydrogen ion activity decreases, pH increases (conducive to calcium carbonate precipitation)

As T <, Carbon Dioxide content >, hence hydrogen ion activity increases, pH decreases (conducive to calcium carbonate dissolution)

Hence >T, <P, <CO2, >pH, Calcium Carbonate Precipitation
<T, >P, >CO2, <pH, Calcium Carbonated Dissolution

d. In Sum: carbon dioxide in water creates carbonic acid and limestone dissolves
(1) If carbon dioxide is decreased (lossed) in groundwater system, pH > and calcite precipitates

4. Nonconventional Reservoirs
    i. Fractured Reservoirs
        1. Shales
        2. Chalk

IV. Reservoir Geometry
1. Three-Dimensional Shapes
    i. Sheets (polygons)
        1. E.g. transgressive shoreface / beach deposits
    ii. Belts
    iii. Ribbons (elongate)
        1. E.g. fluvial channel sands
        2. Stacked ribbons
    iv. Pods (oval / circular)
        1. E.g. Reefs, bioherms

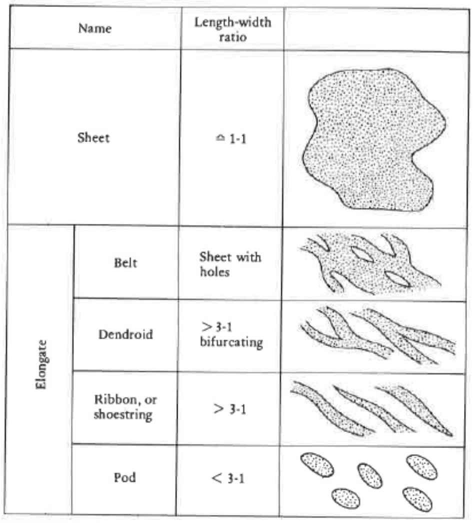


FIGURE 6.39 Nomenclature of sand body geometry. (After Potter, 1962.)

TABLE 6.2 Maximum Lateral Continuity Indices (LCI) and Vertical Continuity Indices (VCI) for Holocene Sand Bodies of the Rio Grande Delta

	Average LCI			
Environment	**Perpendicular**	**Parallel**	**Average VCI**	**Average sand thickness (m)**
Fluvial	0.49	0.83	0.75	5–7
Fluviomarine	1.0	1.0	0.84	7–8
Pro-delta	0.3	0.17	0.56	1.5

From Pryor and Fulton, 1976. Reprinted with permission.

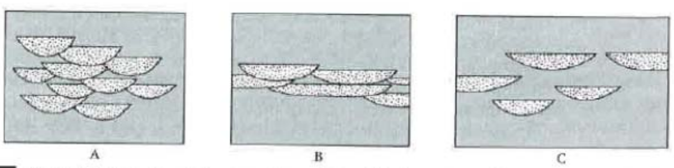


FIGURE 6.40 Descriptive terms for vertical sand body continuity: (A) vertically stacked (multi-storey), (B) laterally stacked, and (C) isolated. (After Harris and Hewitt, 1977.)

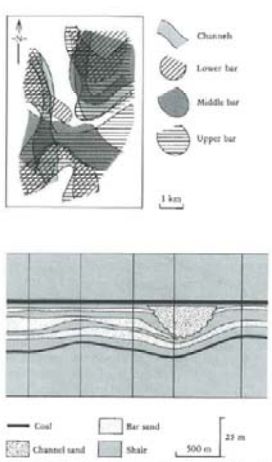


FIGURE 6.42 Map and cross-section of part of the Handil field, Indonesia, indicating the degree of vertical and lateral continuity of reservoirs found in shallow fluviomarine sands. (Modified from Verdier et al., 1980, reprinted by permission of the American Association of Petroleum Geologists.)