Total Dissolved Solids

Example: If 100 g of salt is mixed with 900 g of water we have 1000 g of solution with a total dissolved solids (TDS) of 100‰. The solution is 10% salt by weight, or has a **weight percent** of 10.

TABLE 4.1	Salinity Terminology*
Description	**TDS (‰)**
Fresh	< 1
Brackish	1–10
Saline	10–100
Brine	> 100 (up to ~400)

*Seawater is 35 ‰

1 liter of water is approximately 1000 g
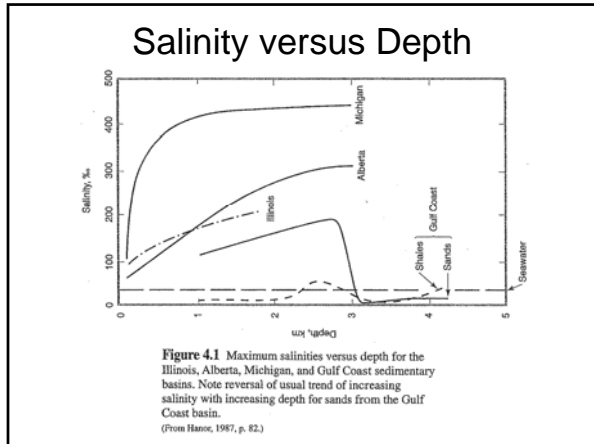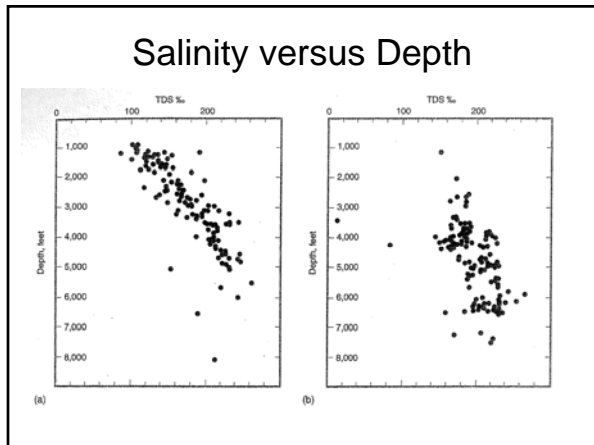so example above is 100 g/l

Molality

The **molality** (m) of a solution is the moles of solute per kilogram of *solvent*. Molality should not be confused with molarity (M). **Molarity** is the moles of solute per liter of *solution*. A **mole** is the amount of a substance that contains 6.02×10^{23} molecules (**Avogadro's number**). The **molecular weight** of a substance is a number equal to what a mole of a particular substance would weigh in grams. The molecular weight of any substance is the sum of the **atomic weights** of a molecule's constituent atoms and may thus be found from the **periodic table**. A comparison of salinity units is given in Table 4.2.
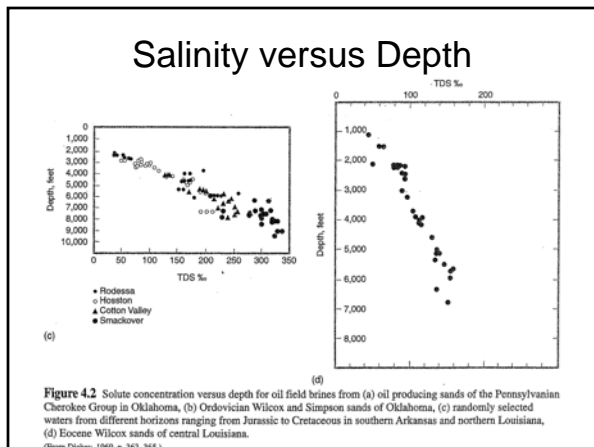
Example: From the periodic table we find that the atomic weight of Na is 22.99; the atomic weight of Cl is 35.45. Thus, the atomic weight of NaCl is 58.44, meaning that 58.44 g of NaCl constitutes one mole of NaCl. Mixing 58.44 g of NaCl with enough water to produce a liter of solution results in a solution with a molarity of one. If we mix 58.44 g of NaCl with 941.56 g of water, we would have a solution with a molality of $1/0.94156 = 1.06$. This salt solution would be 58.44‰ NaCl or have a weight percent of 5.844.

TABLE 4.2	Comparison of Salinity Units	
Weight Percent Solute	**‰**	**NaCl Molality**
1	10	0.17
5	50	0.90
10	100	1.9
20	200	4.3
30	300	7.3
40	400	11.4

Salinity versus Depth

Figure 4.1 Maximum salinities versus depth for the Illinois, Alberta, Michigan, and Gulf Coast sedimentary basins. Note reversal of usual trend of increasing salinity with increasing depth for sands from the Gulf Coast basin.
(From Hanor, 1987, p. 82.)

Salinity versus Depth

Salinity versus Depth

Figure 4.2 Solute concentration versus depth for oil field brines from (a) oil producing sands of the Pennsylvanian Cherokee Group in Oklahoma, (b) Ordovician Wilcox and Simpson sands of Oklahoma, (c) randomly selected waters from different horizons ranging from Jurassic to Cretaceous in southern Arkansas and northern Louisiana, (d) Eocene Wilcox sands of central Louisiana.
(From Dickey, 1969, p. 363–365.)

Hypothesis for Formation of Brines

- Evaporation of Sea Water
- Membrane Filtration
- Dissolution of Evaporites
- Fluid-Rock Chemical Interactions

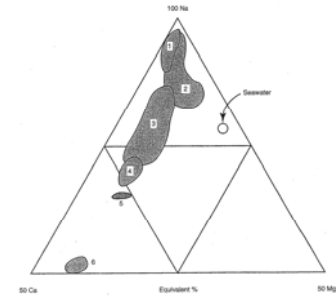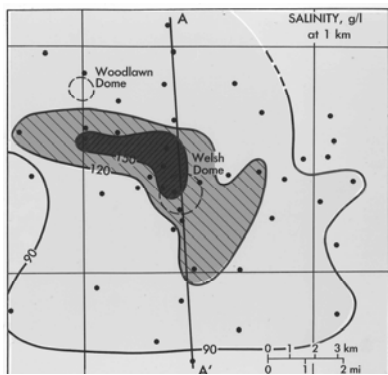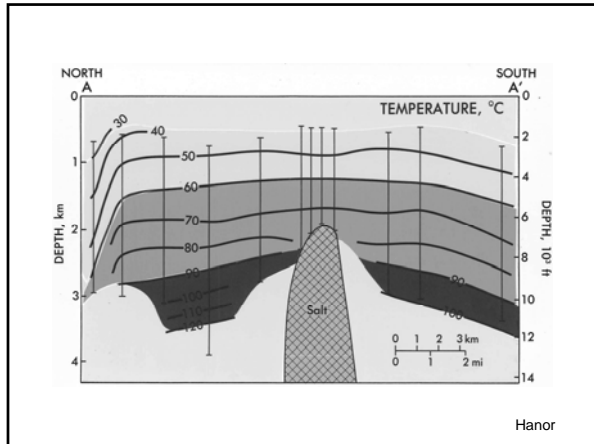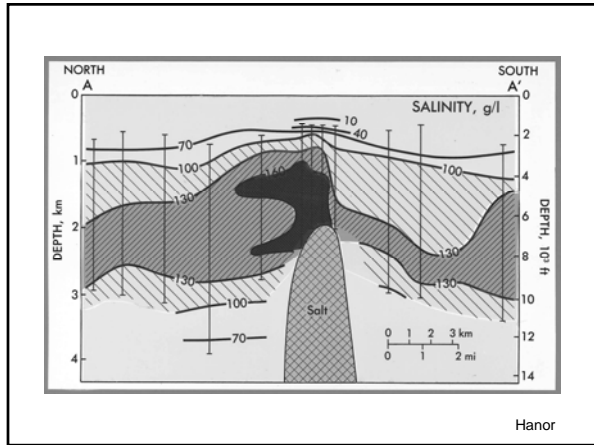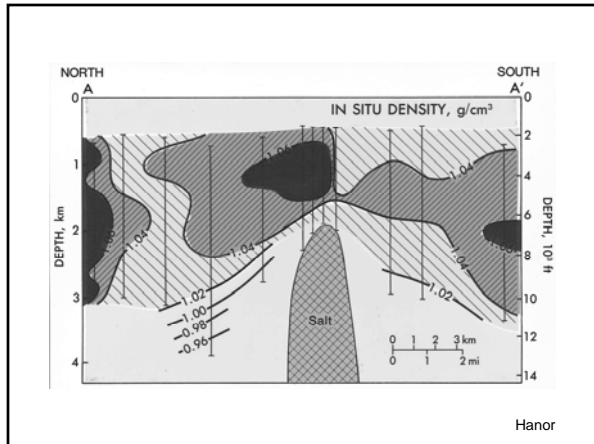## Brine composition not easily explained by evaporation of Seawater

Figure 4.3 Variations in proportions of dissolved Na, Ca, and Mg in brines from (1) Texas, (2) California, (3) Kansas and Oklahoma, (4, 5) Appalachia, and (6) Arkansas
(From Hanor, 1987, p. 62; after DeSitter, 1947.)

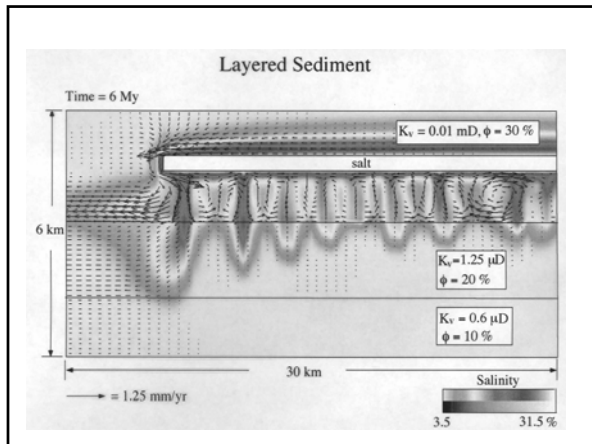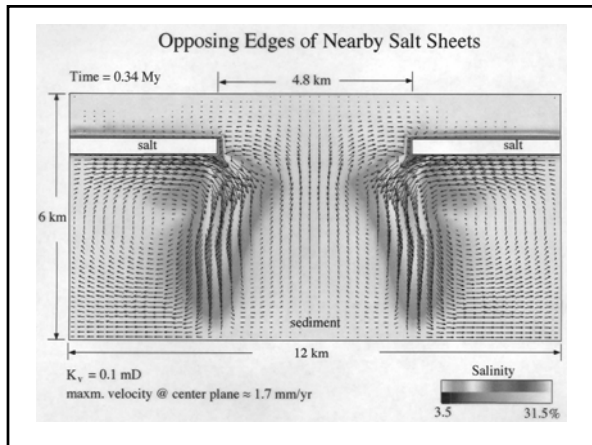

Hanor

NORTH .... SOUTH
A .... A'
TEMPERATURE, °C

DEPTH, km

30
40
50
60
70
80
90
100
110
120
90
100

Salt

0 1 2 3 km
0 1 2 mi

DEPTH, 10³ ft

Hanor

NORTH .... SOUTH
A .... A'
SALINITY, g/l

DEPTH, km

10
70
40
100
100
130
130
130
130
100
70

Salt

0 1 2 3 km
0 1 2 mi

DEPTH, 10³ ft

Hanor

NORTH .... SOUTH
A .... A'
IN SITU DENSITY, g/cm³

DEPTH, km

1.04
1.04
1.04
1.02
1.02
1.00
0.98
0.96

Salt

0 1 2 3 km
0 1 2 mi

DEPTH, 10³ ft

Hanor

Layered Sediment

Time = 6 My

$K_v = 0.01$ mD, $\phi = 30\%$

salt

6 km

$K_v = 1.25$ µD
$\phi = 20\%$

$K_v = 0.6$ µD
$\phi = 10\%$

30 km

→ = 1.25 mm/yr

Salinity

3.5   31.5%

Opposing Edges of Nearby Salt Sheets

Time = 0.34 My   4.8 km

salt   salt

6 km

sediment

12 km

$K_v = 0.1$ mD
maxm. velocity @ center plane ≈ 1.7 mm/yr

Salinity

3.5   31.5%

Sea Water Evaporation/Ice Formation

W   Illinois | Indiana   E
Meteoric water

Pennsylvanian

Brine
(compaction-
driven)   Oil
(buoyant)   Mississippian
Chesterian

anhydrite

Upper limit
Oil generation window   Valmeyeran

Oil & brine
(gravity-driven)   Devonian

Silurian

Brine
oil?   Ordovician

anhydrite

Figure 4.10 Schematic cross-section through the Illinois Basin showing distribution of meteoric water and brine derived from seawater evaporation. Also shown are driving forces that include sediment compaction, topographic gradients, and buoyancy forces.
(From Stueber and Walter, 1994, p. 1438.)

5

Wilcox

Hanor

Wilcox

Hanor

Wilcox

INITIAL SALINITIES, LOWER WILCOX

Hanor

Wilcox

TDS TOP OF WILCOX, g/L

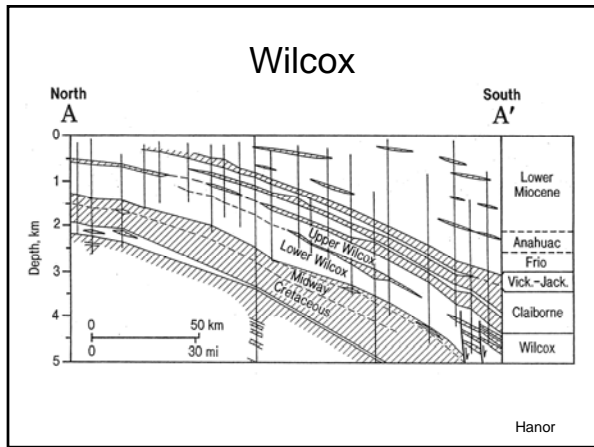Hanor

Phases/Thermal Properties
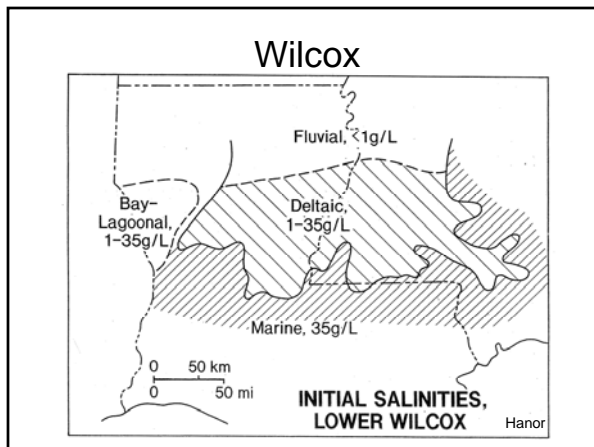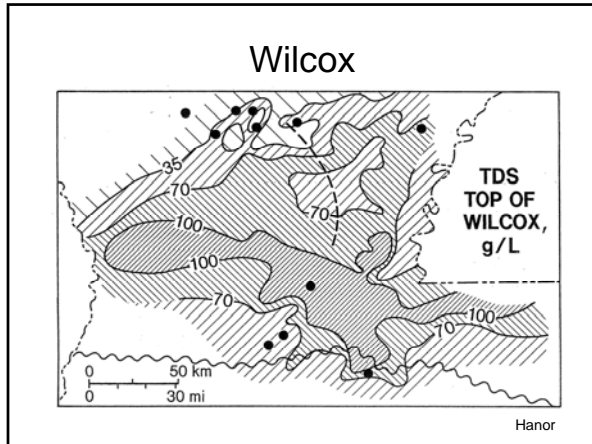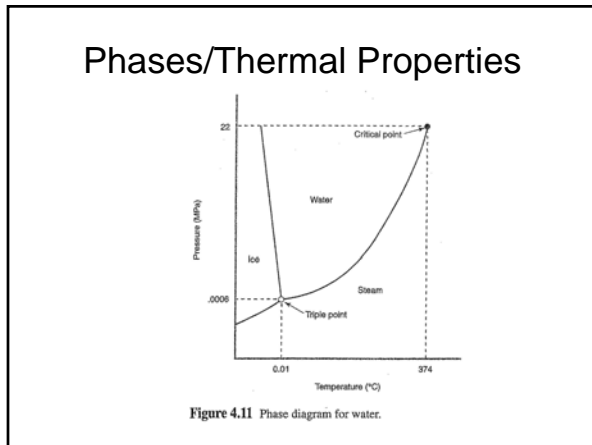

Figure 4.11 Phase diagram for water.

The **specific heat capacity** of a substance is the amount of energy or heat necessary to raise the temperature of a specified mass of that substance by a specified amount. The specific heat capacity (C, J-kg^{-1}-°K^{-1}) of pure water at 0°C and 1 atm pressure is

$$C = 4184 \text{ (J-kg}^{-1}\text{-°K}^{-1}) \qquad (4.18)$$

Specific heat capacity may also be expressed in units of calories per gram per degree Celsius (cal-g^{-1}-°C^{-1}). To convert from cal-g^{-1}-°C^{-1} to J-kg^{-1}-°K^{-1}, multiply by
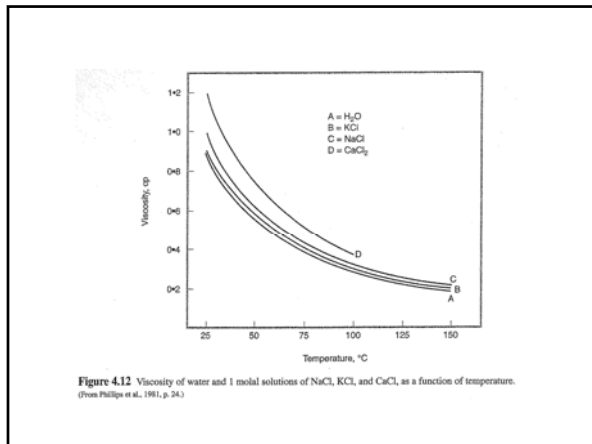
$$1 \frac{\text{cal}}{\text{g-°C}} \times 4.184 \frac{\text{J}}{\text{cal}}$$
$$\times 1000 \frac{\text{g}}{\text{kg}} \times 1 \frac{\text{°K}}{\text{°C}} = 4184 \frac{\text{J}}{\text{kg-°K}} \qquad (4.19)$$

The **heat of fusion** is the amount of heat or energy necessary to change a specified mass of a substance from a solid to a liquid while maintaining a constant temperature and pressure. The heat of fusion of pure water is about 80 cal-g^{-1}. To convert to J-kg^{-1}, multiply by

$$80 \frac{cal}{g} \times 4.184 \frac{J}{cal} \times 1000 \frac{g}{kg} = 3.35 \times 10^5 \frac{J}{kg}$$

(4.20)

The **heat of vaporization** is the amount of heat or energy necessary to change a specified mass of a substance from a liquid to a vapor while maintaining a constant temperature and pressure. The heat of vaporization of pure water is about 540 cal-g^{-1}. To convert to J-kg^{-1},


TABLE 4.3	Effect of Pressure and Temperature on Fluid Density		
Depth (km)	Fluid Pressure (MPa)	Temperature (°C)	Fluid Density (kg-m^{-3})
1	10	42	1146
2	20	67	1125
3	30	92	1113
4	40	117	—
5	50	142	1092

Temperature in the Earth's crust is controlled by the geothermal gradient and the ground surface temperature. The **geothermal gradient** is the rate at which temperature increases with depth. The geothermal gradient is largely determined by the thermal conductivity of crustal rocks and heat flow from the Earth's interior. Surface ground temperature is controlled by climate, and ranges from about 25°C near the equator to as low as −22°C at polar extremes. The mean annual air temperature for Earth is about 15°C, however, ground temperatures tend to be 2–3°C warmer than air temperatures, so the average ground surface temperature on Earth is about 17 to 18°C. The average geothermal gradient ranges from about 10°C-km^{-1} to as high as 60°C-km^{-1}. A nominal estimate of the average geothermal gradient on the continents is 25°C-km^{-1} (see Kappelmeyer and Haenel, 1974; Jessop, 1990).

Figure 4.12 Viscosity of water and 1 molal solutions of NaCl, KCl, and CaCl, as a function of temperature. (From Phillips et al., 1981, p. 24.)

TABLE 4.4	Effect of Temperature on Water Viscosity
Temperature (°C)	Water Viscosity (kg-m^{-1}-s^{-1})
0	1.8×10^{-3}
50	5.4×10^{-4}
100	2.8×10^{-4}
150	1.8×10^{-4}

Water EOS

DENSITY (Kg/m^3)

Water EOS
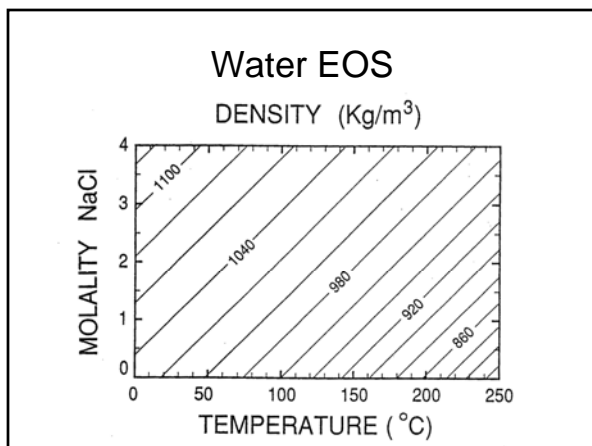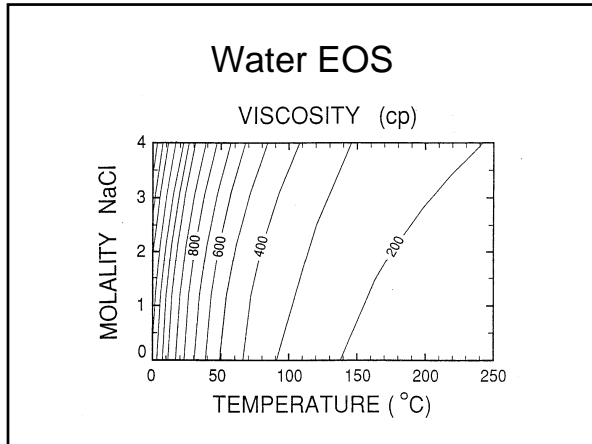
VISCOSITY (cp)

EOS for Various Fluids

Air (STP)
Density: 1.2 kg/m^3
Viscosity: 20 μPa-s

Water
Density: 1,000 kg/m^3
Viscosity: 0.001 Pa-s

Methane
Density: 6.5-330 kg/m^3
Viscosity: 11-55 μPa-s

API 37 Oil
Density: 840 kg/m^3
Viscosity: 0.01 Pa-s

Table 2. Methane Physical Properties as a function of Depth.
Constant Density and Temperature Gradients

Depth (km)	Temperature (°C)	Pressure (MPa)	CH$_4$ Density (kg/m^3)	CH$_4$ Viscosity (μPa-s)	ΔDensity (kg/m^3)
0	25	1.0	6.5	11.2	2243.5
1	50	23.5	137.7	19.5	2112.3
2	75	46.0	205.3	27.3	2044.7
3	100	68.5	242.5	33.0	2007.5
4	125	91.0	266.8	37.5	1983.2
5	150	113.5	284.2	41.3	1965.8
6	175	136.0	297.4	44.5	1952.6
7	200	158.5	307.9	47.4	1942.1
8	225	181.0	316.4	50.0	1933.6
9	250	203.5	323.6	52.4	1926.4
10	275	226.0	329.7	54.5	1920.3

Methane EOS

Density (kg/m³)   Viscosity (μPa-s)
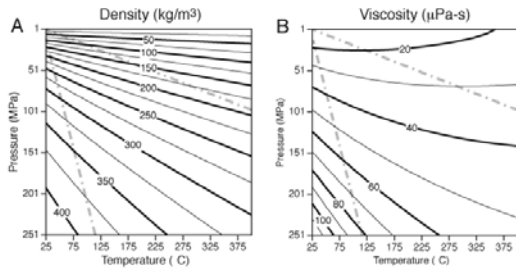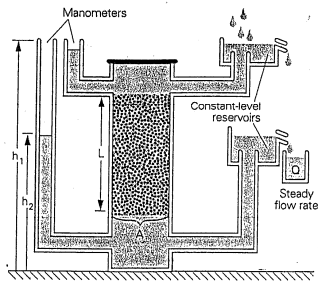
Darcy's Experiment

Figure 1.1 Schematic diagram of the apparatus used in Henry Darcy's sand-filter experiments.