Post-depositional evolution of sedimentary basins

1. Compaction - Diagenesis
2. Fluid circulation in sedimentary basins
3. The case of the organic matter
   What is organic matter?
   Evolution of organic matter and geohistory
   Petroleum system in the light of basin evolution
Diagenesis - introduction

- **0km**: 
  - High porosity
  - Contact with water of the depositional environment
  - Interstitial waters present (interaction with sediment)
  - Onset of compaction and cementation

- **1km**: 
  - Porosity decrease
  - Secondary porosity possible

- **5km**: 
  - Deshydration of hydrated minerals
  - Recrystallisation

- **10km**: METAMORPHISM

**Pressure (1 bar/4 m) & Temperature (1°C/30 m) Gradients**

- **0km**: Water

**Pressure & Temperature Calculations**

- **1 bar = 10^5 Pa**; **1 kbar = 100 Mpa**
- At 4 km depth: pressure ± 4 kbar = 400 Mpa
- **Rm**: for thermal gradient 30°C/km:
  - At 4 km depth: temperature ± 120°C
Compaction of sediments

Physical transformation of sediments

Re-organization of grains (or minerals) with increasing compaction => fabric

Compaction => deformation = volume loss
Compaction => porosity loss with depth
Compaction => density increase with depth
Porosity loss => permeability loss

London Clay (UK) of Eocene age with around 200m burial www.dpr.csiro.au

Early Cretaceous Muderong Shale (Australia) with ~1.1 km burial www.dpr.csiro.au

Jurassic shale (North Sea) from ~3 km depth www.dpr.csiro.au
Compaction => Porosity vs burial

Compaction of sediments is a progressive process. It can be approached by the porosity reduction with depth of burrial

Average sediment porosity curve

Porosity curve for different lithologies

Early compaction of shales
Wide range of carbonate porosity

Note varying Scale

Giles, 1997
Diagenesis

**Chemical (mineralogical) transformation of sediments**

- Early cementation close to water/sediment interface

- Dissolution and precipitation
  - over short distances -> intergranular
  - at very shallow surface pressure and temperature

- Mineralogical phase change (e.g.: illite -> chlorite; Aragonite -> calcite)

- Biological interference -> Bacterial activity enhances precipitation (e.g. Algae, …)

- Strong influence on porosity:
  - cementation decreases porosity
  - dissolution increases porosity (Karst)
Diagenesis: cementation

Cementation: progressive process

Cathodoluminescence: shows successive generations of calcite crystallisation

Calcite cementation develops from inter-granular contacts and fills the remaining porosity.
Carbonate sediment diagenesis

**Dolomitization**

$$2\text{CaCO}_3 + \text{Mg}^{2+} \rightarrow \text{CaMg(\text{CO}_3)_2} + \text{Ca}^{2+}$$

Numerous and complex processes $\Rightarrow$ 1 example

Dolomitization $\Rightarrow$ porosity increase

**Dolomite euhedra in limestone**

**Dolomite (euhedras)** replace calcite ooids

**Dolomite euheдра in limestone**
Eruption of mud due to accidental drilling in overpressured layer (Indonesia)

Still erupting $10^5$ t mud per day, Several km$^2$ covered by 20m of mud
Fluid circulation in basins = fluid pressure gradient

- Pressure gradient between formations => fluids move from zones of higher pressure toward zones of lower pressure

- Causes of fluid pressure variation (overpressure)?

1: Increasing load

- Fluid can move freely within the permeable formation, during burial => equilibrium => Fluid Pr. = hydrostatic Pr.

2: Increasing fluid volume

- Fluid remains trapped by the impervious Fm. (seal) => fluid pressure increases in the permeable Fm => Fluid Pr. > hydrostatic Pr.

- Fluid volume increases due to clay deshyratation, HC generation, diagenesis, connection to overpressure reservoir => fluid pressure increases in the permeable Fm => Fluid Pr. > hydrostatic Pr.
Evolution of pore fluid pressure in basins

- Lithostatic pressure
- Hydrostatic pressure
- Zone of fluid overpressures
- Hydraulic fracturing
- Weight of the overlying column of sediment
- Weight of the overlying column of fluids if perfect permeability

Domain of fluid pressure evolution with depth

Experimental values of pore fluid pressures in wells

- 1 atmosphere = 1 bar = 10^5 Pa
- Water ρ = 1; hydrostatic gradient = 0,1 MPa/m
- Sediment ρ = 2,3; lithostatic gradient = 0,23 MPa/m
Fluid pressure increase and failure

Effective stress = Total stress - fluid pressure

- fluid pressure increases => effective stress decreases
- normal stress decrease => failure envelope => hydraulic fracturing

Failure => seal fracturing => fluid pressure release
Faults and fluid transfer

Fault can be a seal or a drain

Unsealed cataclastic slip band

Quartz sealed shear band

Function of deformation mechanisms

Function of lithology alternance

Labaume & Moretti 2001
Basin-scale fluid movement

Modèle de migration de fluides dans un horizon (surface 3D)

landform

vitesse de migration

fors

réservoirs (accumulation)

null

dysmigration (perte)

chenaux de migration

Stuart Burley (British Gas, & Univ Keele)
http://www.bdrg.esci.keele.ac.uk/Staff/Images/flex2_oil_gl.jpg
Compaction => Fluid explosion
Polygonal faults

Polygonal faulting in sediment allows water expulsion through faults and compaction (Volume decrease) in sedimentary basins. Example from the North Sea.

Compaction with stretching of the layer (left) in extensional basins.
Compaction without stretching (right) most frequent. Associated with volume loss (grain repacking and fluid expulsion).
Geometry & dynamics of polygonal faulting

Aurelien Gay 2002
Fluid expulsion structures

Polygonal faults network

Chimneys (polygona faults nodes)
Fossil fluid expulsion structures

Chimneys (« Terres Noires » Oxfordian, Nyons)

Ca CO3 concretion around conduit

Conduit (crystallization)

« Septaria », Digne Thrust nappe
Synthesis: «plumbing system» of fluid expulsion

Which Fluids?
- syndepositional water
- interstitial water
- Brines
- biogenic methane
- hydrocarbons
Fluid(s)-circulation(s)

South Pyrenean Foreland basin

- Geochemical tracing (Sr, C\(^{13}\)) distinguish marine and meteoric waters

- Precipitation of diagnostic minerals (dikite) => long distance fluid migration (basement)

- Close relationship with tectonics

- Retroaction of fluids on tectonics = lubricate thrusts planes

\(Rm\): long-distance brine circulation in basins

=> Convective circulation

=> Transport & precipitation along basin margins

=> Mineralizations (« MVT »)

\(\begin{align*}
\text{INTERGRANULAR FLOW} & \quad \text{INTERGRANULAR FLOW} \\
\text{INTERGRANULAR FLOW} & \quad \text{INTERGRANULAR FLOW}
\end{align*}\)
Evolution of Organic Matter
Evolution of organic matter in basins

In basins, the increase of pressure and temperature is acquired by burial of sedimentary layers containing organic matter. It requires time (over geologic time scale).

=> Reconstruction of the Basin geohistory is pivotal!
Organic carbon cycle

Organic matter results from photosynthesis => sun energy

Quasi-balance between storage and emission of organic $CO_2$

Unbalance comes from man-made emissions.

99% of OM is oxidized

0.4% of OM is preserved by burial to become Kerogen, then Hydrocarbons
Evolution of organic matter

3 types of organic matter characterised by their content of $C,H,O$
I: cyanobacteria & freshwater algae, anoxic lakes
II: marine plancton
III: terrestrial plant matter
Each kerogen type evolves with (P,T) increase, mostly expressed by oxygen loss, along distinct paths.

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Type I: Sapropelic kerogen (algal)
Type II: Lipid-rich kerogen (phyto & zooplankton)
Type III: humic kerogen (land-plants)
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Hydrocarbon formation function of burial of source rock.

Modified from Tissot & Velde 1978
Monitoring OM maturation and HC generation

Evolution of the rate of transformation of different kerogens, with time.

It takes some 20 to 30 My before anything happens: this the time necessary for burial. Then fast transformation (15My)

The inset give the thermal history (simple)

Vitrinite is one component of OM with slow rate of transformation => used to calibrate maturation
Monitoring HC generation

Vitrinite evolution for three different thermal histories: 1= fast then slow burial, 2= Constant burial, 3= slow then fast burial

The Oil and Gas Windows are the domain where OM maturation has reached the appropriate conditions for oil and gas generation respectively. Passed the Gas window, all HC has disappeared.

Whence HC are generated they must migrate where they can be kept safely!

Mode of burial (= basin geohistory) fast burial => fast HC generation; slow burial => delayed HC generation. Fast rates of subsidence preferred!
Burial of source-rock

Burial curve (total subsidence history of each stratigraphic interval) in the Central Graben of the North Sea. Assuming a geotherm constant through time, isotherms remain horizontal. The source rock is buried and enters the oil window in Paleocene time; it is presently in the gas window. 

Modified after Selley 1980
**Oil systems : Passive margin**

**Burial history** of different sediment m. (total subsidence curves), superimposed onto the **thermal history** (from basin modeling) => delineate the domain of oil window.

The lower part of the synrift has now passed the oil window. If the tectonics has not allowed migration of the generated HC, they are now cracked.

The HC found in the Tertiary cannot be generated in these Fm. They have migrated here.

**Basin Modeling** provides the kinematics, temperature history & distribution, timing of deformation (to allow migration toward reservoirs)

**Basin analysis** => basin modeling
Oil system in the W. African Margin

Source-rocks:
- Synrift (type I and type II),
- Early post-rift lagunal (type II),
- Post-rift slope & delta (type II & type III)

Reservoirs:
- Clastic in syn-rift tilted blocks,
- Roll-over in Albian-Cenomanian carbonate platform
- Turbidites channels in Oligo-Miocene

Migration:
- Along syn-rift faults
- Laterally beneath salt layer
- Along growth faults (reactivated)
- Through turbidite channels
Oil system: Foreland basin

NW Canadian Foreland Basin

Northwest Territories

- Nordegg Fm
- Duvernay Fm

Source rock

Geohistory

Structure

Seal

Creaney & Allan