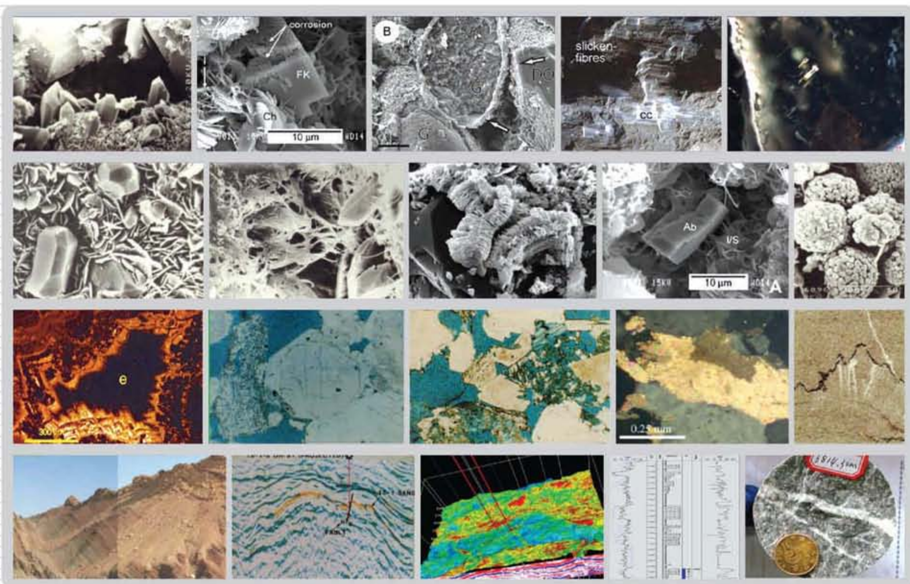
献给中国地质大学建校60周年

Reservoir Diagenesis and Quality Prediction

Compiled by Honghan Chen
Chunquan Li
Hongwei Ping



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China University of Geosciences Press CO.,LTD.

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Chapter 1 Introduction

1.1 Overview

This course has been compiled by the lithology and fluid prediction to document the current understanding of diagenesis and the way it affects reservoir quality. It summarizes the results of in-house research, external work and information from scientific publications.

Our aim is to make what is known about diagenesis and reservoir quality prediction easily accessible to you and to help you apply this information during exploration appraisal and production. Thus, a straightforward and jargon-free style has been adopted and necessary. Specialist terms are explained in the glossary at the end of this overview.

There are two fundamental knowledge chapters:

- Diagenesis of clastic and carbonate rocks
- Rock mechanics related to reservoir

Eight controls chapters:

- Lithofacies
- Carbonate sequences
- Compaction
- Quartz
- Clays
- Carbonate cements in clastics
- Secondary porosity
- Faults and fractures

Three prediction chapters:

- How can we predict porosity?
- How can we predict permeability?
- How can we predict peservoir connectivity and compartmentalization?

And one tools chapter:

- Tools and techniques

1.2 Glossary

This glossary contains classifications of terms highlighted in the controls, tools and prediction chapters.

Allogenic: The derived portion of a sediment (e. g. grains in a sandstone, pebbles in a conglomerate cf. authigenic).

Ankerite: Ferroan carbonate mineral $Ca(Fe_{0.2}Mg_{0.8})(CO_3)_2$ sometime (wrongly) used as a synonym for ferroan *dolomite*. The two minerals are difficult to distinguish optically but XRD or EMP can be used on bulk samples of polished section, respectively. (see Chapter 10)

Aragonite: Orthorhombic polymorph of $CaCO_3$ which occurs naturally in the skeletal parts of many marine organisms. It undergoes recrystallization to *calcite* with burial, hence is rare in all but recently deposited and shallow sediments.

Apatite: Calcium phosphate containing various amounts of F, Cl, CO_2.

Arenite: Sandstone with <15% clay matrix.

Arkose: Sandstone composed of >25% feldspar grains. Sandstones with between 5%~25% feldspar are sub-arkosic.

Authigenesis/Authigenic: The formation of minerals in situ during or after deposition of the sediments in which they occur. Authigeneic cements (e. g. quartz overgrowths) are formed in this way.

Brine: Water of salinity higher than that of average seawater, that is, more than 3.5×10^4 mg/l TDS. The majority of oil-field waters are brines according to this definition, whereas only a small fraction could be classified as brines based on the definitions of Davis (1964) and Carpenter et al. (1974), which place the lower salinity limit of brines at 1×10^5 mg/l. *Saline water*-Water of salinity $(1\sim3.5)\times10^4$ mg/l. *Brackish water*-Water of salinity $(0.1\sim1)\times10^4$ mg/l. *Freshwater*-Water of salinity less than 1 000mg/l.

Calcite: Most commonly occurring carbonate mineral. The trigonal polymorph of $CaCO_3$. In unstrained thin sections it generally appears as a high relief, high birefringence mineral, often showing good cleavage. Thin sections are commonly chemically stained which colours calcite pink, ferroan calcite mauve, *ankerite* and ferroan *dolomite* royal blue. Dolomite and *siderite* remain uncoloured (see Chapter 10).

Carbonate cements: Authigenic carbonate which binds sediments grains together.

Cathodoluminescence: Cathodoluminescence (CL) in the combination of fluorescence and phosphorescent light emitted from a mineral under excitation by electrons. The colour and intensity of CL are governed by the presence of various impurities (e. g. Al, Fe, Mn) and defections in the crystal lattice which may be related to the environment of mineral formation.

Cement: Material binding particles together in a sediment.

Cementation: The process by which cement precipitates imparting mechanical strength to the sediment. Cementation usually involves precipitation from supersaturated solutions.

Chamosite: Iron-rich variety of chlorite. It also used to describe green ooids, but not all green ooids contain chamosite chlorite.

Chalcedony: Microcrystalline quartz usually fibrous or feathery with submicroscopic pores. It forms in sediments and low temperature hydrothermal veins. The colour and texture of chalcedony varies with the impurities present and can be brown, red(jasper) or banded(agate).

Chert: A resistant, non-porous rock composed largely of authigenic silica-opal, chalcedony or micro granular quartz. Cherts typically form nodules and lenses in extensive thin beds interstratified with mudstones and limestones. Most appear to have formed by diagenetic alternation of sediments rich in biogenic silica. Chert is common as detrital grains in many sandstones because of its resistance to weathering. *Flint* is the black or grey form of chert.

Chlorite: A clay mineral occurring as detrital matrix of diagenetic cement in sandstones. It is green in thin section and has a platy morphology in SEM. Chlorite is a low temperature cement forming extensive grain rims which inhibit later quartz cement. Chlorite-cemented reservoirs often have anomalously high porosity and flow dry-hydrocarbon despite a high S_w.

Clay minerals: A family of minerals which generally occur as very fine-grained particles($<5\mu m$). They are hydrous silicates of Al(+/−Mg, Fe, K, Na, Ca). Examples include illite, kaolinite, chlorite and smectite.

Compaction: Reduction in bulk rock volume usually vertically in response to an applied stress. Compaction is reduction in porosity and volume while cementation involves a reduction in porosity only.

Compaction curves: Curves describing the progressive reduction of porosity with depth due solely to compaction.

Connate water: The word connate(Latin for "born-with") was introduced by Lane(1908) to describe what he presumed to be seawater of unaltered chemical composition trapped in the pore spaces of a proterozoic pillow basalt since the time of extrusion onto the seafloor. The term has since taken on a variety of meanings. While some authors prefer to use connate in its original sense(Hanor, 1987), others have used it to refer to waters that have been modified chemically and isotopically, but have been out of contact with the atmosphere since their deposition, although they need not be present in the rocks with which they were deposited.

Detrital: Term describing mineral or rock fragments derived from pre-existing rock by weathering and/or erosion.

Depositional environment: The conditions under which a sediment was originally deposited. Environment may be continental or marine and subdivided on the basis of water depth, climate etc.

Diagensis/Diagenetic: Process describing the transformation of sediments into sedimentology rock during burial. Diagenetic cements are minerals which form the rock during this process.

Dissolution: Removal of material(e. g. cements, sediment grains) by the action of liquid undersaturated with respect to that material.

Dolomite(Ferroan Dolomite): Carbonate mineral $CaMg(CO_3)_2$. In unstained thin section, it can be very difficult to distinguish from calcite. As a diagenetic mineral, ferroan dolomite is more common than the non-ferroan form in sandstones. Ferroan dolomite is very similar to *ankerite* but has an Mg/Fe ratio greater than 4.

Effective depth: In an overpressured situation, the stress of grain contacts will be equivalent to those of a shallow depth with normal pressures. This shallower depth is referred to as the effective of apparent depth.

Effective porosity: Interconnected porosity which will contribute to permeability.

Effective pressure: The difference between lithostatic pressure and pore pressure.

Fabric: The arrangement of the grains which make up the sediment. This includes grain orientation, packing, sorting and grading.

Facies/Lithofacies: Body of rock with specified characteristics obtained directly from outcrop or core or indirectly from seismic or log data. Direct observations refer to feature such as colour, bedding, composition, texture, grain size and sedimentary structures. Generally, facies can be identified to a particular depositional system or environment.

Feldspars: Important rock forming silicate mineral consisting of an aluminum silicate framework with varying proportions of potassium, sodium, calcium and (rarely) barium. Feldspars are grouped into alkali feldspar and plagioclase feldspar.

Flocculation: Clumping of clay minerals in water causing them to be out of suspension.

Formation damage: Damage occurring from well operation, e. g. drilling and completion, resulting in reduction in well permeability.

Flint: See chert.

Fluid inclusions: Tiny samples of fluid trapped within single crystal of authigenic cement. Fluid inclusion may contain more than one fluid phase (gas, liquid) and may contain petroleum.

Formation water: Water present in the pores and fractures of rocks immediately before drilling. This term is used extensively in the petroleum industry, but has no genetic or age significance.

Glauconite: A name used for both a clay mineral and green pellets. Also, not all green pellets are composed of glauconite and not all glauconite occurs as green pellets. Glauconite mineral is just Fe-rich illite.

Hydrostatic pressure: The pressure that would be estimated by a column of fluid at height equivalent to the depth. It is a function of depth and fluid density.

Illite/Illitic clay: A clay mineral occurring as detrital matrix and diagenetic cement. Illite cement forms as fibrous pore-filling seriously improving permeability.

Initial/Depositional porosity: The porosity of sediment immediately after deposition.

Ineffective porosity: Porosity which is not connected and does not contribute to permeability.

Intergranular volume(IGV): IGV is the space between the framework grains, more or less synonymous with the term "pre-cement porosity".

Isotope(Stable): See stable isotope.

Isotope(Radiogenic): See radiogenic isotope.

Karst: A type of topography that formed on limestones, dolomites, evaporites and rarely sandstones as a result of dissolution. It is characterized by link holes, caves and underground drainage.

Kaolinite: A clay mineral occurring as detrital matrix and as diagenetic cement. Kaolinite cement forms as pore-filling partially reducing porosity.

Lithic sandstone: Sandstone containing greater than 25% rock fragments. Sandstones with 5%～25% rock fragments are sub-lithic.

Lithofacies: A mappable subdivision of a stratigraphic unit distinguished on the basis of lithologic variations.

Lithosome: A sedimentary unit comprising one or more beds of sedimentary uniform or uniformly heterogeneous lithologic character.

Lithostatic pressure: Weight per unit area of all the overburden both rock matrix and pore fluids, and which is transmitted through the subsurface by grain-to-grain contacts. Lithostatic pressure varies according to depth and density of overburden rocks and fluids.

Macroporosity: Pore body is greater than or equal to 5 microns. Pores are visible under the microscope.

Meteorite: Related to an associated with atmospheric manifestation most notably rain, snow and the resulting percolating ground waters derived here from.

Meteoric water: Water derived from rain, snow, streams, and other bodies of surface water that percolates in rocks and displaces interstitial water that may have been connate, meteoric, or of any other origin.

Microporosity: Pore body is less than 5 microns. Normally this pore space is not resolvable using a standard petrographic microscope.

Minus-cement porosity: The void volume a sandstone would have if the intergranular cement were removed, i. e. pore volume plus volume of intergranular cement.

Mixed-layer clays: Clay minerals containing complex mixtures of the four types of clay minerals: illite, smectite, kaolinite and chlorite.

Natural gamma-ray spectrometry (NGS) logs: Measure the natural radioactivity of formations. Unlike the GR log which only measures the rock radioactivity. This measures both the number of gamma rays and the energy level of each and permits the determination of the concentration of radioactive potassium, thorium and uranium in the formation.

Net pay: The cumulative thickness of reservoir quality and their contain recoverable reservoirs.

Opal: Hydrous silica ($SiO_2 \cdot nH_2O$) containing up to 10% water in sub-microscopic pores. Opal is metastable and changes structures as a function of time, burial depth and temperature.

Overbalance: Excess mud-weight pressure over formation-fluid pressure generally maintained in anticipation of penetrating an overpressured formation.

Paragenesis/Paragenetic: The relationship of mineral expressed in terms of time sequence. A paragenetic scheme describes the temporal relationship between diagenetic events.

Permeability: The capacity of a rock to allow fluids to pass through if permeability is measured in Darcies.

Petrography: The description of rocks in hand specimen and thin section.

Phreatic: With respective to the zone of saturation below the permanent free water level (table).

Plasticity: Describes the extent to which a material exhibits flow (rather than fracturing) during deformation.

Point counting/Point count: A method of measuring the relative volume of minerals in a rock by recording their frequency of occurrence during a stepwise traverse across the specimen (usually a thin section). Between 200 and 500 points are routinely counted depending on the accuracy and precision required.

Pore fluid pressure: The pressure exerted by the fluids in the pores of a buried rock. In a normally pressured situation, where there is vertical pore fluid continuity with the surface, pore fluid pressure approximates to hydrostatic pressure. However, if fluids are confined under burial, for example in a sand pod isolated by impermeable mudstone, then pore fluid pressure may be higher. This is an *overpressured* situation.

Porosity: The void volume of a rock, usually expressed as a percentage of the bulk volume.

Porosity anomaly: Porosity data that are significantly displaced (to low or high porosity values) from the regional porosity-depth trend for the formation of interest.

Provenance: The source area or areas for material accumulating in a sedimentary basin.

Pressure dissolution: Dissolution of material of points of relatively high intergranular stress (grain contacts or cracks).

Psi and MPa: 1MPa=145psi

Psi/ft and MPa/km: 1psi/ft=22.655 9MPa/km

Quartz: Crystalline silica chemically very simple SiO_2.

Quartzose: Term describing sandstones with abundant (>95%) detrital quartz grains.

Radiogenic isotope: An isotope (a form of an element with a specific number of neutrons in the atom's nucleus) which is the daughter product of the natural radioactive decay of another isotope.

Radiometric dating: The determination of the age of rocks by quantifying the proportions of the radioactive parent and radiogenic daughter isotopes in a rock or matrix. Various decay elements are used for dating (e.g. K-Ar, Rb-Sr, U-Pb) each with their own decay half life.

Salinity: Synonymous with total dissolved solids(TDS), generally reported in milligrams per liter(mg/l) as determined either (a) directly by summing measured dissolved constituents or by weighing solid residues after evaporation, or (b) indirectly from electrical conductivity or spontaneous potential response.

Secondary porosity: porosity developed in a rock by dissolution of grains or cements.

Shaly-sand correlation: A term used by petrophysicists to describe the effect of clay minerals on the electric log response of sandstones. Clay minerals(specifically smectite) increase formation conductivity through an additional component of surface conductivity thus requiring an appropriate correction of the resistivity log.

Siderite: Carbonate mineral $FeCO_3$. It may be distinguished optically from other common carbonate minerals(calcite, dolomite, ankerite) by its greater birefringence or in some cases by darker colour resulting from inclusions of iron oxides.

Smectite: A clay mineral occurring as detrital matrix and diagenetic cement. Smectite cement is rare, and it forms pore-filling fibrous seriously reducing porosity. Smectite is highly sensitive to water, swelling to cause severe formation damage.

Solidity: The complement of porosity(100-porosity)%.

Stable isotope: Isotopes which are neither radioactive nor radiogenic. The stable isotope ratio of an element in a mineral can reflect the conditions under which the mineral precipitation or the origin of its component material. Stable isotopes of C, O, H, S, N are often used in the study of diagenesis.

Stress of grain contacts: Stress is force per unit area. The effective pressure divided by the grain contact surface area is the stress of grain contacts. The forces acting at grain contacts tend to produce deformation. These forces result from the weight of the overlying sediments and the pressure of the porefluids. Grains deform to minimize the stress by increasing the area of the grain contacts.

Supersaturated solution: Solution containing dissolved components in concentrations greater than that at which a specific mineral should precipitate under equilibrium conditions.

Surface conductivity: A property arising from transport of exchangeable cations associated with absorbed or surface bounded water on clay mineral surface. The phenomenon is most marked on smectite.

Swelling: A property of smectite which occurs when it is immersed in fresh water. Swelling of smectite cement results in a large increase in apparent volume.

Texture: The relationship between grains forming a rock including grain size and the distribution, morphology and surface roughness of grains and the contacts between grains.

Thin section: A thin slice of rock(usually 300 microns in thickness) mounted for examination using an optical microscope.

Unconformity: A planar or irregular surface separating groups of rocks of different ages. The older of which have been uplifted and eroded, the younger being laid down on the eroded surface.

1.3 Abbreviations

BSEM: Back Scattered Electric Microscope
CCRS: Composite Common Risk Segment
CRS: Common Risk Segment
EMP: Electron Micro-Probe
FI: Fluid Inclusion
RSA: Residual Salt Analysis
SEM: Scanning Electron Microscope
SMAC: Synchronous Migration and Cementation
TEM: Transmission Electron Microscope
TG/EWA: Thermaogravimetry/Evolved Water Analysis
T_H: Temperature of Fluid Inclusion Homogenization
XRD: X-Ray Diffraction
PIA: Pore Image Analysis
POROPERM: Porosity and Permeability
IGV: Intergranular Volume

Chapter 2　Tools and Techniques

To predict reservoir quality, we need to measure the effects of diagenesis on porosity and permeability. It requires a quantitative understanding of what cements occur in a reservoir and how they are distributed. We also need to know when cementation took place with respect to other geological events. The tools and techniques that can be used, in addition to geophysical methods, borehole logging and core analysis, are the subject of this chapter.

This chapter is not concerned with how individual tools work, but with how those tools can help in quantifying diagenesis. The tools have been grouped according to their application, and appear under four main problem areas:

- What mineral cements occur in our reservoir, how are they distributed and what is their effect on poroperm (Fig. 2-1)?
- Has diagenesis contributed to segmentation/compartmentalization of our reservoir (Fig. 2-2)?
- When did diagenesis (compaction, cementation, mineral dissolution) occur (Fig. 2-3)?
- How can we put these data together to predict reservoir quality (Fig. 2-4)?

2.1　At what stage of exploration or production can the tools be applied?

Application of the tools is not restricted to any particular sector of exploration or production. Rather, various combinations of tools can be selected to attack specific problems (Table 2-1 and Table 2-2).

2.2　How reliable are the tools?

The data from most of the tools described here are both precise and accurate, and techniques are generally tried and texted. As with most other techniques used in petroleum geosciences, the interpretation of these data may be uncertain. The degree of this uncertainty will depend at least as much on the nature of the problem, and the amount of corroborative data from other sources, as on the reliability of the tools.

New tools and techniques will be added to the current portfolio as the work progresses and as new needs arise.

2.3　Further reading

The study of sediment diagenesis is a rapidly expanding field, and there are no really up

Table 2 - 1　Which techniques can we use for which cements?

Technique \ Poroperm Modifier	Whole rocks*	Clays	Quartz	Sulphate	Calcite	Dolomite	Sulphides	Halides	Feldspar	Compaction	Water
Optical microscopy	√	√	√	√	√	√	√	√	√	√	
Scanning electron microscopy	√	√	√	√	√	√	√	√	√		
Transmission electron microscopy		√									
Electron microprobe analysis		√		√	√	√	√	√	√		
Cathodoluminescence microscopy			√		√	√			√	√	
Back-scattered electron microscopy	√	√	√	√	√	√	√	√	√		
X-ray diffraction	√	√		√	√	√	√	√	√		
Thermogravimetriy/Evolved water analysis		√									
Pore image analysis	√									√	
Fluid inclusion analysis(Temperature of growth)			√	√	√	√	√	√	√		
Fluid inclusion analysis (Water salinity)			√	√	√	√	√	√	√		√
Fluorescence microscopy			√	√	√	√	√	√	√		
Radiometric dating (K/Ar, Ar/Ar)		√							√		
Radiometric dating (Sm/Nd)	√										
Radiometric dating (Rb/Sr)		√									
Stable isotope determination (δD)		√									√
Stable isotope determination (δ^{18}O)		√	√	√	√	√			√		√
Stable isotope determination (δ^{13}C)					√	√					
Stable isotope determination (δ^{34}S)				√			√				√
Thermal modelling	√										
Apatite fission track analysis	√										
Aqueous geochemistry	√	√									√
Porosity-permeability modelling	√									√	
Geochemical modelling	√	√									√
Fluid flow modelling	√										√
Residual salt analysis (^{87}Sr/^{86}Sr)	√										√
Strontium isotope labeling					√	√	√				√
Shale geochemistry	√										

* "Whole rock" means that the technique is applied to the rock as a collection of minerals/grains rather than as individual components.