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Morariu D.
Independent Petroleum Geologist, Geneve, Switzerland, morariu45@gmail.com
Averyanova O.Yu.
All Russia Petroleum Research Exploration Institute (VNIGRI), St. Petersburg, Russia, info@ngtp.ru

CLEAVAGE FABRIC – SIGNIFICANT FACTOR CREATING DISCRETE HYDROCARBON MIGRATION PATHWAYS IN DIAGENETIC TO LOW METAMORPHIC PELITES

From the point of view of petroleum geology, the transformation experienced by pelitic rocks with petroleum potential in the regional burial process in the domain of diagenesis to low metamorphism past a certain point can by a significant risk factor - an important reduction of porosity-permeability, petroleum pathways disturbing, and over maturation of organic matter. The cleavage structures developed during the conversion into the new structural conditions can even produce open space volumes with crenulation distance spaces varying in the presented areas from 20 to 150 μm, spaces that could constitute discrete pathways for a variety of fluids. Certain terrains with a favourable petrogenetic profile (pelitic rocks with cleavage development and temperatures conditions not exceeding 100-150°C) may be considered as potential petroleum discrete pathways. For petroleum prospecting activity the previously described terrains could represent a possible interesting areas.

Keywords: *pelitic rocks, crenulation distance space, cleavage fabric, discrete pathways for petroleum fluids, potential petroleum bearing area.*

An unconventional petroleum system consists of accumulation of hydrocarbons that are found in low-matrix permeability rocks that depend on fracture permeability (either natural or a result of stimulation) for production and contain large amounts of hydrocarbons, but with low recovery factors [Schmoker, 1995].

A shale reservoir is: a continuous organic-rich source rock or a combination of juxtaposed and continuous organic-rich source rock with organic-lean lithofacies. Thus a shale reservoir may consist: only of primary migration or secondary migration (within the source rock itself) or of secondary migration into juxtaposed (overlying, interbeded, or underlying) non-source rocks [Jarvie, 2012 fide Rushing, 2014]. In petroleum geology organic shales are considered source rocks as well as seal rocks that trap oil and gas. In reservoir engineering shale rocks are considered flow barriers [Rushing, 2014].

A conventional reservoir is a reservoir in which buoyant forces keep hydrocarbons in place below a sealing caprock; pore surface - fluid forces have little to no impact on fluid phase behaviour oil and natural gas can to flow readily into wellbores (Tab. 1). The fluid phase behaviour is different in conventional and unconventional reservoirs.

Table 1

Fluid phase behavior in petroleum reservoirs (from [Rushing, 2014])

Conventional reservoirs	Unconventional reservoirs
Rock pore sizes on order of 5 to 50 µm	Rock pore sizes • Tight gas sands: 0.01 to 1.0 µm (10 to 1000 µm) • Shale: 0.01 to 0.10 µm (10 to 100 nm)
Fluid phase behavior depends on • Reservoir pressure, temperature • Fluid composition • Fluid-fluid molecular forces	Fluid phase behavior depends on • Reservoir pressure, temperature • Fluid composition • Fluid-fluid molecular forces
Pore surface-fluid forces have little to no impact on fluid phase behavior	Pore surface-fluid forces have significant impact on fluid phase behaviour because of close proximity
Conventional PVT measurements assume no effect from walls of laboratory cells (no interactions between fluids and rock surfaces)	Should account for fluid-surface forces in phase behavior calculations

A typical shale reservoir has a very low permeability matrix of about 10 minus 5-10 minus 7 mD and a porosity of 4-6% [Rushing, 2014].The host rocks of shale gas accumulation act as source reservoir and seal. They are characterized by complex pore system with ultra-low to low intraparticle permeability and low to moderate porosity.

The pore system in the nanoporosity range presents some extremely complex pore networks within both “inorganic” and “organic” porosity. The gas can be stored interstitially within the pore spaces between rock grains or fractures in the shale or it can be adsorbed to the surface of the organic components in the shale. Generally gas storage in shale gas reservoirs occurs in the adsorbed state within kerogen, in the released or free state within kerogen porosity, in the free state within intergranular pore space (including microfractures), and in natural macro-scale fractures.

Diagenesis-general view

Diagenesis sensu lato (catagenesis included) ecompasses all natural changes in sediments from the moment of deposition, continuing through compaction, lithification, and beyond stopping short of the onset of metamorphose. Metamorphism has begun and diagenesis has ended when a mineral assemblage is formed which cannot originate in a sedimentary environment [Winkler, 1974]. A large number of authors restrict diagenetic processes to those which occur at temperatures below 200°C but for the most unstable types of protolith begins in the range of 60-100°C ± 20°C. The boundary between diagenesis and regional metamorphism is not precise in term of pressure or temperature, nor is there a sharp boundary between diagenesis and weathering. Thus, the diagenesis domain lies somewhere between the ill - defined borders of weathering at its shallow end and low-grade metamorphism at its deep end [Syed et al., 2010].

In a very broad sense, all the changes occurring in sediment-rock transformation process, begin when the sediment mass is no longer in direct contact with the sedimentation medium. The transformations continue with dissolution, precipitation, cementation and lithification as processes main to the beginning metamorphism.

Diagenesis is a continuous process by which the sedimentary deposit has to achieve new pressure and temperature conditions. The nature and rapidity of post depositional changes depends on the sedimentation medium and the nature of the sediment too.

Changes in the composition of the interstitial solution, chemistry, temperature, or pressure can lead to significant chemical changes in the mineralogical components of the sediment.

These changes could begin at relatively low T (60 ± 20°C) and P and lead to important transformations in mineralogy and rock fabric. Chemical and physical processes active during diagenesis, anchimetamophism up to very low metamorphism finally transformed the sediment in sedimentary rocks.

Diagenesis stricto sensu could by delineate between the weathering zone (with pressures and temperatures that characterize the surface conditions) and the limit with anchimetamorphism - very low metamorphism [Syed et al., 2010].

The diagenesis-metamorphism boundary is not very precisely marked in terms of the chemical and protolith mineralogical composition. Heterogeneous character due to depositional and diagenetic processes of shale reservoirs bring numerous challenges to geologists and petroleum geologists.

Prior to onset of diagenesis, porosity and permeability are controlled by sediment composition and condition that prevailed during deposition.

As the pelitic sediment is progressively buried, it dewatered and compacts, reducing the size of the pores. Their interconnections and further compaction and cementation produce sediment lithification. Compaction of sediments is driven towards lower porosities and higher densities as a function of increasing stress and activity of chemical reactions. Mechanical processes are controlled by the effective stress and chemical compaction, by dissolution and precipitations of solid phases. Chemical compaction is a function of thermodynamics; kinetics and silicate reaction in diagenesis are very slow and sensitive to temperature [Bjorlykke et al., 2010]. During diagenesis the gas can be stored interstitially within the pore spaces between rock grains or fractures in the shale or can be adsorb to the surface of the organic components in the shale or it can be adsorbed to the surface of the organic components in the shale.

Generally initial textures are lost in chemical and physical processes during diagenesis – anchimetamorphism and the siliciclastic sequences are transformed in compact rocks.

When sediments are buried, pressure and temperature increase and the digenesis stage of the clay minerals begins. In the first 3-5 km of burial free of weakly bound water is eliminated and the porosity decreases from 80% to about 20%. In general the number of clay minerals diminishes with time and temperature produces mineral-mineral and mineral solutions reactions. The neoblasts are more highly orders and of larger size than the originals minerals.

In pelitic rocks the transformation phases begin immediately after sedimentation and continue to develop in direct relationship with the depth of burial. Many authors agree that in these rocks the lower temperature limit of the metamorphism start is 150 ± 50°C. The first occurrence of the following minerals indicates the beginning of the metamorphism: Fe-Mg-carpholite, glaucophane, lawsonite, paragonite, prehnite, pumpellyte, or stilpnomelane [Bucher et al., 2002]. Transition – diagenesis-metamorphism has a progressive, not steep, character.

The increase in temperature has multiple effects - it causes the recrystallization to increase the size of the crystals, leads to endothermic reactions, exceeds the respective kinetic barriers and creates new equilibrium of mineral phases. These changes occur at relatively low temperatures and pressures, but they cause important changes in mineralogy, rock structure and texture.

Diagenesis-metamorphism boundary

The B. Kübler (1967) concept of - anchizone represents it as the transition zone between the diagenesis and very low metamorphism and is fundamental for orientation in metamorphic terrains. The some author has used XDR techniques to measure changes in XRD peak illite-muscovite profiles by creating a specific anchizone index called illite crystallinity [Kübler, 1967]. Thus, it is possible to establish the prograde limit of the diagenesis versus very low metamorphism and -low metamorphism and it is possible to establish areas of different diagenesis intensities. Consequently, mature pelitic sequences can be divided into several zones - diagenetic zone (KI > 0.42), anchizone (KI < 0.42-0.25) and epizone (KI < 0.25). The limit between diagenesis and metamorphism is based on both mineralogical and textural criteria, which do not always coincide [Kisch, 1990].

Depending on the degree of diagenesis, the texture and the structure of the rocks could change very strong. The determination of degree of diagenetic transformation of a rock gives the possibility of indirect estimation of the degree of pores closure, estimation of the degree of the permeability reduction, respectively possibility to deduce important information on the fluid circulation conditions. Sometimes before to reach effectively the metamorphism domain, the rocks can already have a fabric similar to a true metamorphite, but the rock has not yet reached the chemical and mineralogical equilibrium characteristic for a metamorphic rock, so very probably the formation temperature range affected the rock in question has not reached 150 ± 50°C. All transformations on the diagenesis-metamorphic boundary affect the petrophysical characteristics of pelitic rocks in a very significant way; the porosity and permeability of the shales and mudstone rocks that are the major component of shale reservoirs could suffer very much.

Essential events during the pelitic rocks diagenesis

The major factors influencing the diagenetic evolution are of sedimentary and environmental nature: sedimentary factors include sediment particle size, fluid property, mineralogical composition, and OM content; environmental factors include temperature, pressure and chemical conditions.

Generally, the particles in a sediment can undergo the following transformations during diagenesis [Syed et al., 2010]:

compaction	- sedimentary particles move into a more compact space organization due to pressure increase;
cementation	- the particles are coated or stuck in contact with other particles;
recrystallization	- the particles change size or contour without changing the chemical composition;
replacement, substitute	- the particles change composition without changing size or shape particles change composition without changing size or shape particles change composition without changing size or shape particles change composition without changing size or shape;
differential solutions	- in which some particles are partially or totally solved while others are left unchanged;
authogenesis	- chemical transformations cause changes in the size, shape and composition of the particles.

For petroleum geologists, the study of transformations occurring during diagenesis is indispensable because these changes ultimately have a major influence on the prospecting activity, on the specifics of the drilling operations and in the process of production optimization.

Shale microfabric and their porosity-permeability evolution in diagenesis - low grade metamorphism section

In shale sections the pores control the accumulation and production of gas coming directly from the active processes during deposition and especially during diagenesis. The pores formed at this time are of micrometric to nanometers dimensions and not linked to fragmentation porosity that appears later in the burial history. How pelitic rocks are very variable in deposition medium, mineralogical composition and compaction history so varied are the porosity types too.

The pores (Fig. 1) can occur in the framework of granules (framework pores), between granules (inter pores) or they come from granules dissolution (solvopores), or are included in OM (macropores) [Schreiber, 2011].

Considering the ratio matter - content / shale maturity we can distinguish:

1. immature shales with high OM content > 7% - many pores are filled with amorphous kerogen (bituminites);
2. mature shales with interstitial OM that develop macropores whose number is directly proportional to the degree of maturity of the pelitic rock.

In shale containing a relatively small amount of TOC < 7%, there is a large proportion of open frameworks pores and if connected they may be able to transmit the gas.

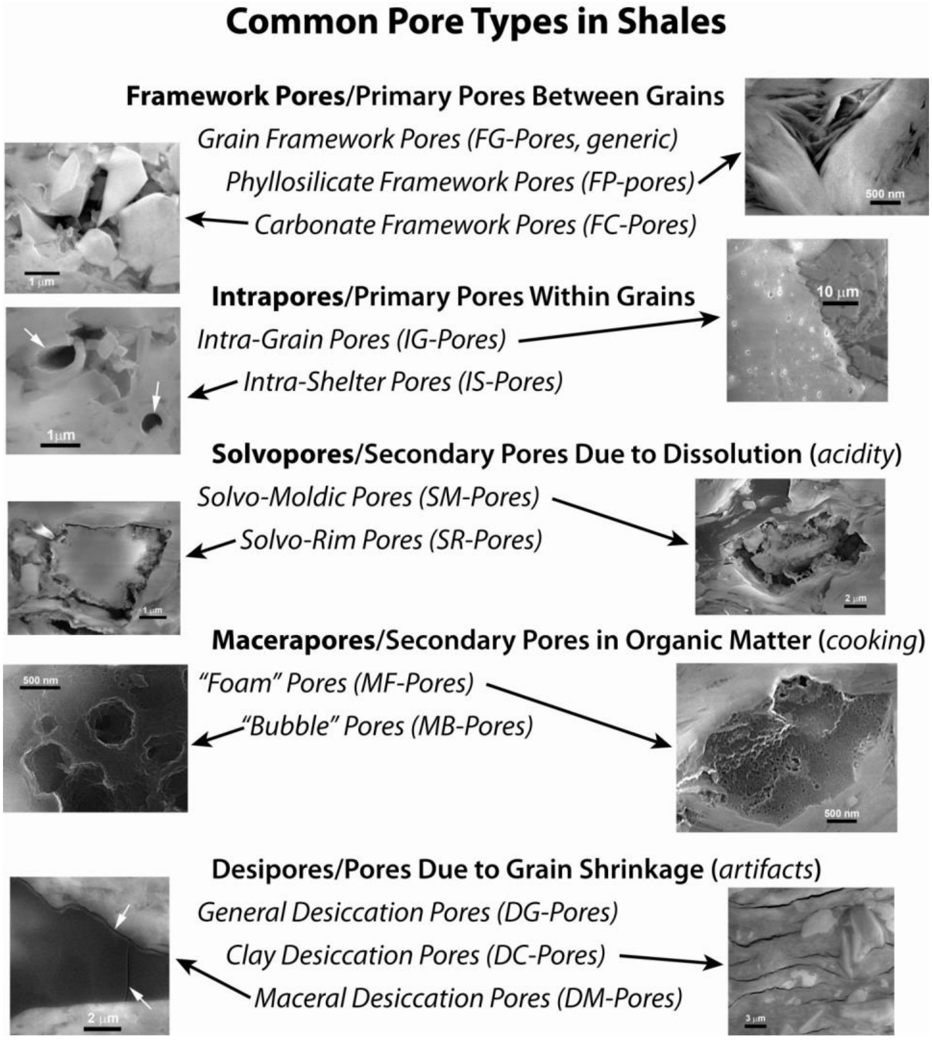

Fig. 1. An overview of pore types observed in shale successions [Schieber, 2011]

On first approximation framework pores probably reflect the original depositional arrangement of detrital grains (clay, carbonate), but may be overprinted by diagenetic growth of clays and carbonate grains. Of intrapores, only those defined by fossil debris are likely important. Both framework and intrapores can at first pass be considered primary porosity, whereas solvopores and macerapores constitute secondary porosity. Desipores appear all to be artifacts and should be readily identified in ion milled sections. Cold-milling with a liquid nitrogen cooled stage can eliminate/reduce artifacts caused by sample heating during milling.

H.P. Nelson (2009) indicated that pore-throat sizes (diameters) are generally greater in conventional reservoir rocks, ranging from about 2 to 0.03 μm in tight-gas sandstones and from about 0.1 to 0.0005 μm in shales [Nelson, 2009] (Fig. 2).

The same author studied pore-and pore-throat sizes in siliciclastic rocks-of conventional reservoir, tight-gas sandstones, and shales, and found that the pore-throat sizes form a continuum from the submillimetre to the nannometer scale (Fig. 2). For measures of central tendency pore-throat sizes (diameters) range from 0.1 to 0.005 μm in shales, are greater than 2 μm in conventional reservoir rocks and range from about 2 to 0.03 μm in tight-gas sandstones.

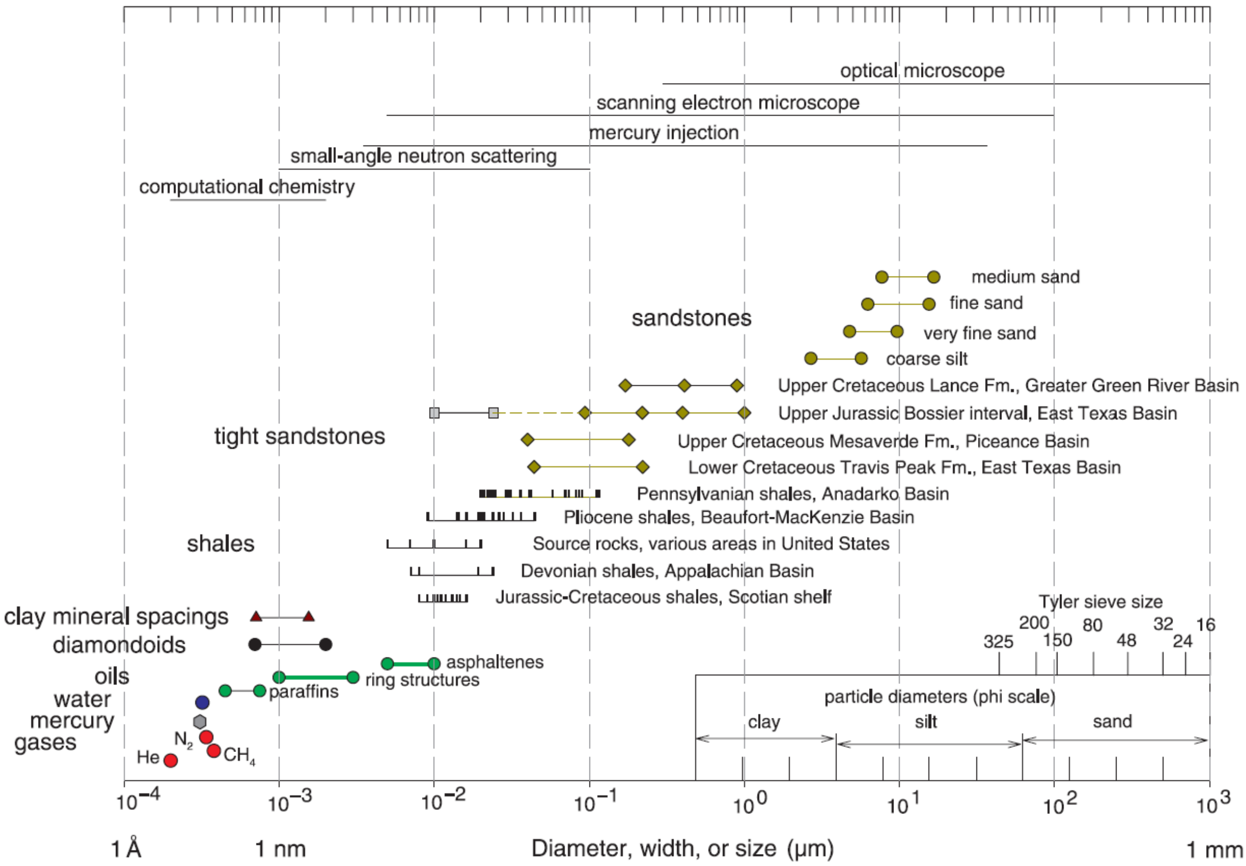

Fig. 2. Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude [Nelson, 2009]

Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diamondoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.

Mudrock pore characters

In mudrocks the pores network belonging to the matrix is composed of pores with diameters of nanometric size to micrometric. In shale-gas systems this type of pores together with natural fractures form a flow path from mudrock to fractures produced during production. The upper limit of pore size in mudrock is generally less than a few microns with most pores smaller than 1 μm. The micropores have a diameter of < 2 nm, mesopores have a diameter between 2 and 50 nm and macropores have a diameter > 50 nm [Rouqueral et al., 1994; Chalmers et al., 2009].

R.G. Loucks et al. (2012) indicate that matrix-related pore networks in mudrocks are composed of nanometer- to micrometer – size pores [Loucks et al., 2012]. In shale-gas systems, these pores, along with natural fractures, form the flow-path (permeability) network that allows flow of gas from the mudrock to induced fractures during production. A pore classification consisting of three major matrix-related pore types was presented by [Loucks et al., 2012]. Two pore types are associated with the mineral matrix; the third pore type is associated with OM;

interparticles (interP) - pores between particles and crystals and intraparticles (intraP) located in the particles). OM matter pores are located in interP and in intraP (Tab. 2).

Table 2

Comparison of pore terminology from other publications with terminology suggested by the present classification [Loucks et al., 2012]

Pore Types (this article)	Terminology Used by Other Authors	Reference
Interparticle	Intergranular	Milliken and Reed (2010)
	Type III: large jagged	Desbois et al. (2009)
	Phyllosilicate	Curtis et al. (2010)
	Phyllosilicate framework	Schieber (2010), Milner et al. (2010)
	Type IV: occurs at face-to-edge arrangement of clay plates; type V: pores at interfaces between clay and rigid grains	Kwon et al. (2004)
Intraparticle	Type I: elongate ; type II: crescent shape	Desbois et al. (2009)
	Phyllosilicate	Curtis et al. (2010)
	Carbonate dissolution; phyllosilicate framework	Schieber (2010), Milner et al. (2010)
	Type I: cleavage-parallel pore; type II: cracks through several grains; type III: pore at terminations of stacked clay platelets; type VI: intragranular fractures	Kwon et al. (2004)
Organic matter	Intraparticle (primary in fecal pellets)	Milner et al. (2010)
	Organophyllic	Curtis et al. (2010)
	Organic matter	Schieber (2010), Milner et al. (2010)

Another classification based on the width of the pores was presented by the same authors. It can be used to quantify matrix-related pores and related them this pore networks (Fig. 3).

The interrelationships between grains and pores form the basis for this classification schemes. R.G. Loucks et al. (2012) relate directly the pores distribution and classification to permeability; using this interpretation system may be a future aid in modelling and predicting reservoir quality relative to porosity and permeability. The types of pores within the net-work are a major controlling factor for storage, permeability, and wettability.

The same authors consider that in the burial-compacting process a large number of interP and intraP are destroyed especially in muds rich in ductile grains where the pore volume can fall to 88% at a few kilometers of burial (Fig. 4). J.S. Bridge and R.V. Demicco (2008) noted that major large-scale mineral transformations do not begin until temperatures of approximately 100°C are reached and that the fastest rates of compaction occur in the first kilometer of burial (0.6 mi), which is before major mineralogical diagenesis starts, except for limited carbonate, phosphate, and early pyrite diagenesis. The diagenetic products commonly form concreations and hardgrounds, the process having as end effect as important reduction of sediment thickness (Fig. 4).

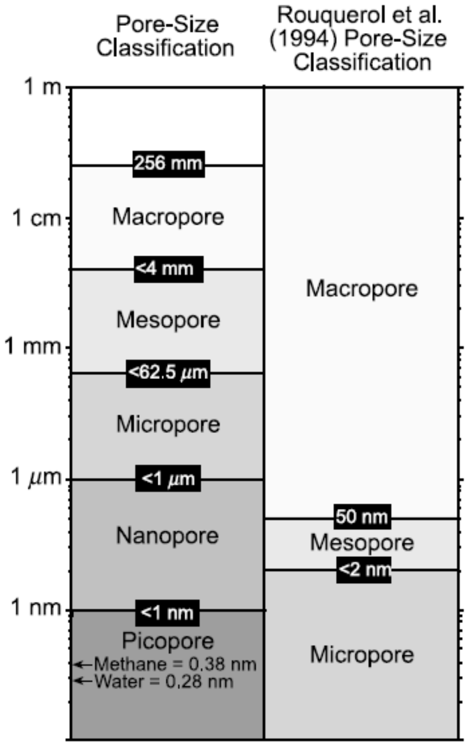

Fig. 3. Pore-size classification for mudrock pores [Loucks et al., 2012]

Classification is modified from the Choquette and Pray (1970) classification. New pore classes include a picopore defined as being less than 1 nm and a nanopore defined as being equal to or greater than 1 nm and less than 1 mm. Rouquerol et al. (1994) pore-size classification is also presented because this classification has been suggested as a pore classification for mudrocks. The sizes of methane and water molecules are shown for reference.

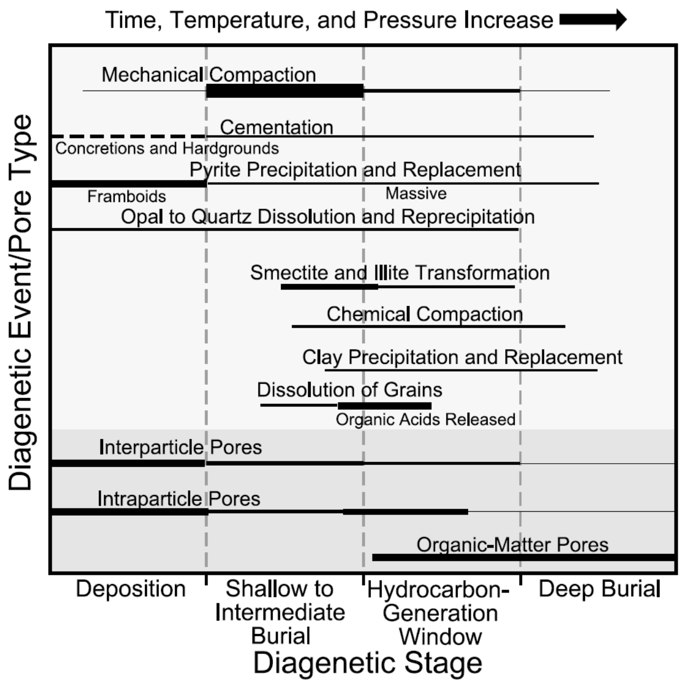

Fig. 4. Generalized parasequence summary diagram of the major stages in mudrock burial diagenesis and the relationship of these stages to the evolution of pore types and abundances in mudrocks
[Loucks et al., 2012]

This sequence of diagenetic events does not reflect any particular case history of a specific mudrock.

Pore type, size, and arrangement can have different effects on permeability and wettability and consequently can influence the storage quality and the petroleum resources calculation. These observations show how important it is to study the degree of diagenesis because using this approach we can indirectly estimate the degree of pore closure and thus estimate the degree of porosity and permeability of mudrocks. In high diagenetic pelites, the pores diameters reach the nano scale with all the consequences on the gas transport. The shales permeability depends on pores pressure, porosity, and throat pores size, and gas type.

Compaction (mechanical and chemical) is an interplay of changes in porosity, permeability and hardness. Compaction generally reduces sediment permeability considerably. T.J. Katsube and M.A. Williamson (1998) indicated that diagenesis (degree of cementation and dissolution) significantly affects porosity and inter-connectivity of the nano-pores (0.3-60 nm), the pores constituting the main pore-throats for tight shales [Katsube, Williamson, 1998]. Diagenesis obliges tight shale permeabilities to vary over a range exceeding n order of magnitude (10-21–6 x10-20 m^2) and porosity to vary between 1 and 2%. In addition diagenesis significantly influences shale nano-pore resistance to collapse during compaction and burial, mainly at depth > 2-3 km, affecting hydrocarbon trapping, overpressure and selling capacities. Burial compaction could produce a large pore-throat distribution with diameters of about 40 nm at depth of 4.5 km. Mineral diagenesis that occurs in burial processes at 2-5 km depth changes the percentage of clay minerals in the mudstone composition. The significance of diagenesis is evidently reduced to shallower depths but the diagenetic processes tend to continue as long as porosity exists.

T.J. Katsube (2000) determined the evolution characteristics for a set of shale pore-structure components (storage porosity, connecting porosity, flow-path size, and flow-path density) with compaction to generate information for use in analysis of problems related to fluid expulsion and entrapment in shales. The some author has used two pore structure models for characterising shale pore-structure (Fig. 5). The storage porosities are generally constant but that connecting porosities always decrease with increased pressure, implying that connecting pores are more flexible and susceptible to pore-pressure changes.

Pelitic sediments diagenesis

Burial diagenesis and mud to mudstone transformation is a complex process with several variables like original mineralogy, fabric, organic content, fluid hydrogeology, and deep rate during burial, temperature gradient, burial temperature, mechanical compaction rate and the mud rheological properties. In the hydrocarbon bearing mudstones the change in pores volume related to percent of total porosity during mudstone maturation represents a very complex process (Fig. 6).

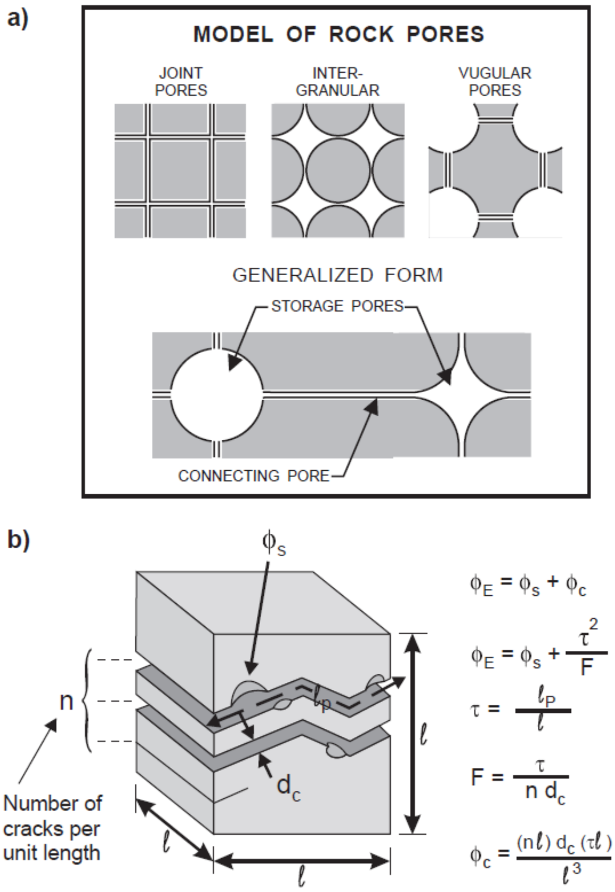

Fig. 5. Two pore structure models used for characterizing shale [Katsube, 2000]
a) storage-connecting pore model, and b) tortuous connecting and pocket pore model.

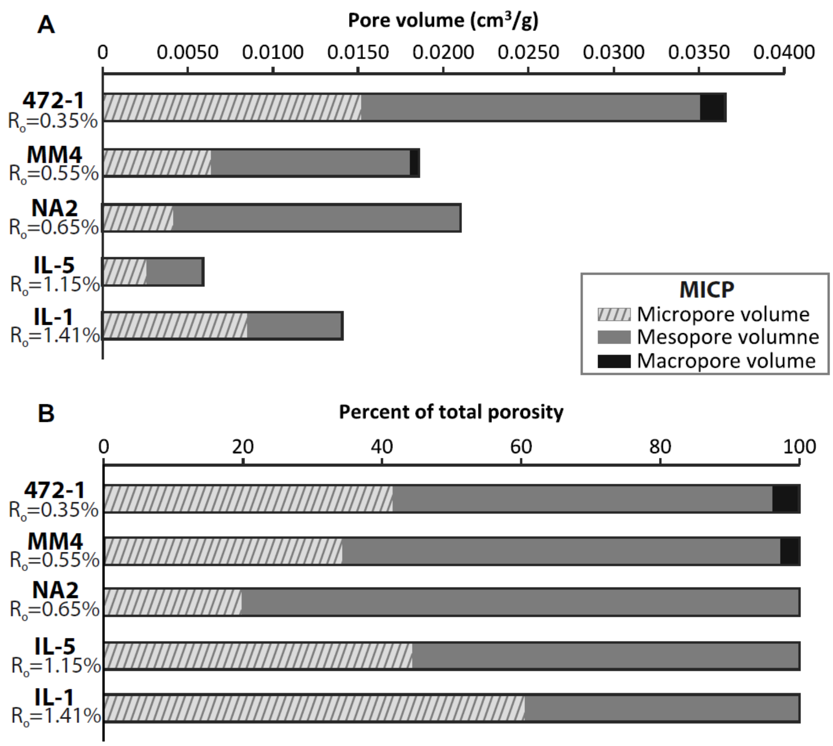

Fig. 6. Absolute micro-, meso-, and macropore volumes (A) and percentages of micro-, meso-, and macroporosities with increasing maturity based on the mercury intrusion capillary pressure (MICP) technique (B) [Mastalerz et al., 2013]

With further thermal maturation, the subsequent increase in porosity would be caused by secondary cracking of oil and bitumen to gas, unblocking of previously filled pores and expulsion of several fluids. Concomitant very important changes in porosity related to OM maturation and hydrocarbon generation are produced (Fig. 7).

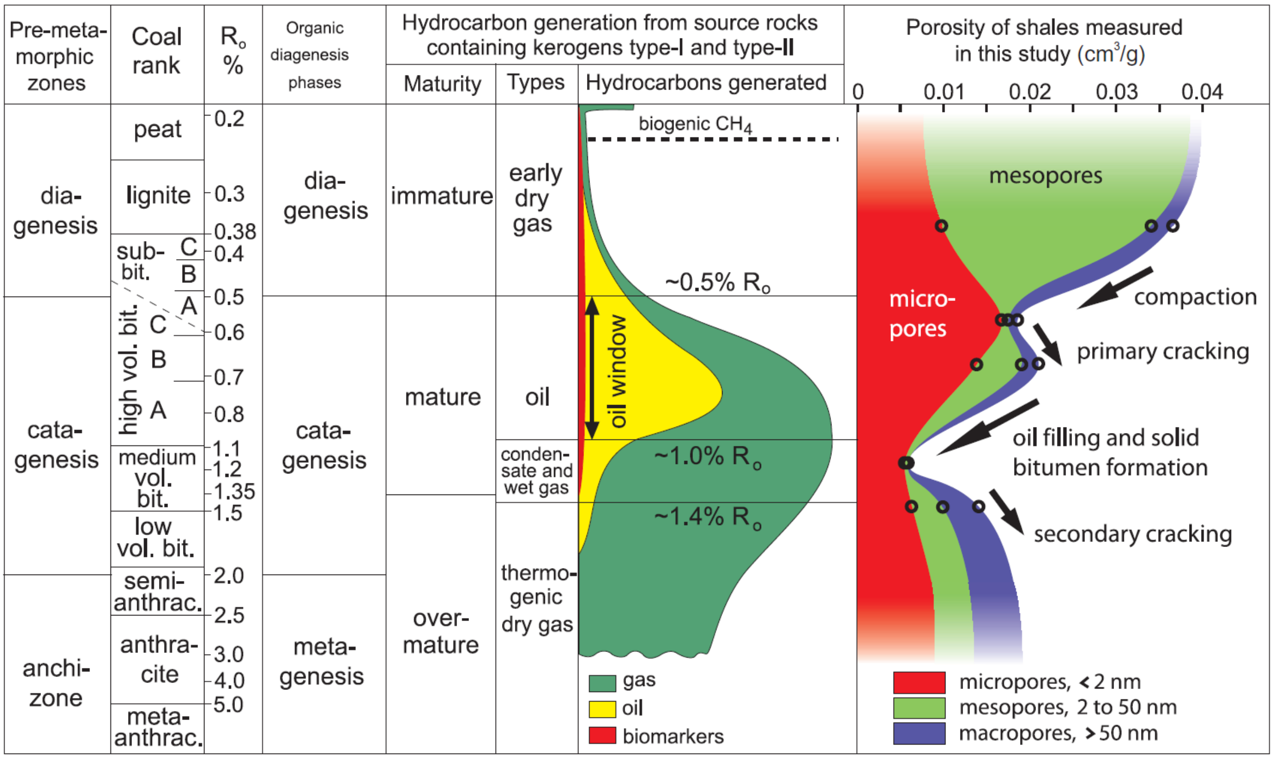

Fig. 7. Schematic diagram relating the observed changes in porosity to maturation and hydrocarbon generation [Mastalerz et al., 2013]

Open circles on the porosity curves indicate the positions of the samples studied.

The process is associated with exposure to higher temperature and higher pressures and consequently drastically reduce the volume of the initial pelitic sediment that is converted by lithification into a sedimentary rock. R.G. Loucks et al. (2012) shows that initial mud porosity that is about 60-80% during deposition can be reduced to several percent by lithification due to the burial stage. The same authors show porosity values in different shale gas systems that display a wide dispersion depending on their burial and diagenesis degree (Tab. 3).

For petroleum geologists, the study of transformations occurring in diagenesis is very important because these changes ultimately have a major influence on the prospecting activity, in the specifics of the drilling operations and in the process of production optimizing.

Pelitic sediments diagenesis represent a complex process consisting of several variables like original mineralogy fabric, texture, organic content, rheology fluid and burial rate - gradient temperature, temperature burial, mechanical compaction rate and rheological properties of the pair mud-mudstone.

Diagenesis domain can be subdivided into shallow and deep burial sections, the boundary between is very difficult to trace [Day-Stirrat et al., 2010]. The shallow burial section has a relatively low temperature and pressure (temperature about 75°C) allowing for this section an open pore network with a several components stream that is in balance with the surrounding environment. Such early diagenetic reactions may involve OM, volcanic glass, iron oxides and amorphous aluminium oxides.

Table 3

Some porosities values in several USA shale formations

Shale Formation	Porosity, %
Barnett	from 4.0 to 9.6
Haynesville	from 8.0 to15.0
Fayellville	from 4.0 to 5.0, 4.0
Pearsall	from 6.0 to 14.6
Eagle Ford*	from 3.4 to 14.0

* - *[TXCO Resources, 2009].*

By progressing of burial process and consequently temperature and pressure rising, new appearing mineral reactions produce quartz, feldspar and clay minerals formed by transformation, recrystallization, dissolution or precipitation reactions.

The newly formed minerals have a direct influence on the forming microfabric, determining the fundamental control of permeability in shales none fractured. Chaotic microfabrics have the highest permeability and laminated microfabrics have the lowest permeability. In addition, shale permeability can be influenced by an important way of composing of a dominant mineral clay that controls grains contour and grains to grains relationships [Microstructure…, 1991].

Lucks et al. (2012) show that in relatively young mudrocks the pores are interP and intraP. By burial up to several km interP and intraP are compacted and affected by chemical diagenesis and the volume of the two types of pores could decreases in a very strong way. The porosity versus depth curves presented by N.H. Mondol show that porosity may decreases up to less as 10% at 2.5 km depth suggesting that 50% up to 70% even till 88% porosity units could be globally lost during compaction and diagenetical processes (Fig. 8) [Mondol et al., 2007].

Cementation is a very important factor in the diagenesis of pelitic rock. It can take the form of precipitations of clays in pores, cements, overgrowth on quartz grains, carbonates and feldspar or as cement that fills pores. Pores of all kinds are able to remain still open to depths of over 4751 m [Loucks et al., 2012].

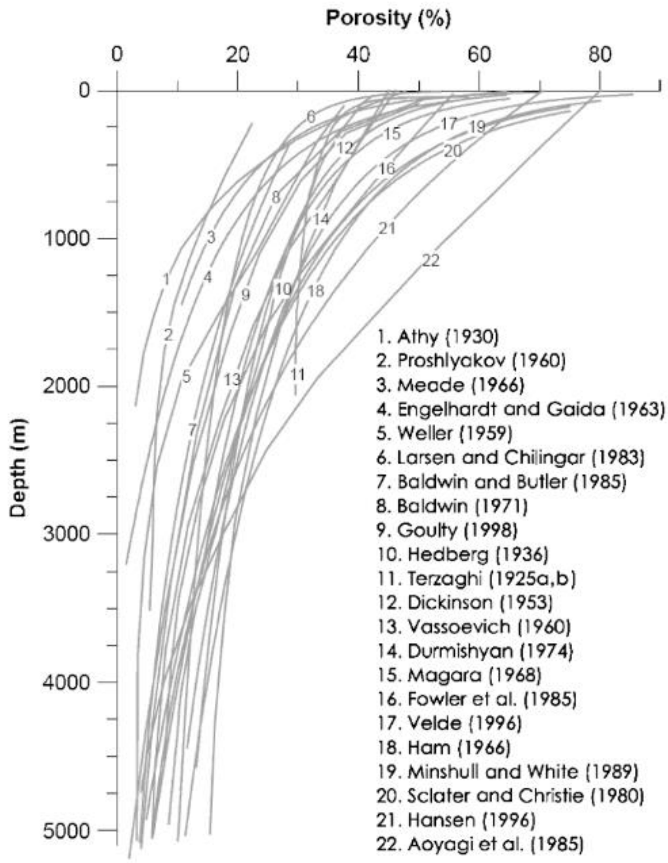

Fig. 8. Selected porosity – depth curves for mudstone [Mondol et al., 2007]

Variation of porosity and permeability depending on depth

Pores classification by Loucks et al. (2012) uses the interrelationships between grains and pores and forms a relatively direct correlation with mudstone permeability, a relationship that can be used as a quick way to appreciate the quality of the mudstone reservoir in terms of porosity and permeability.

Pore-throat sizes in siliciclastics rocks form a continuum from the submillimeter to the nanometer scale [Nelson, 2009]. That continuum is documented in by the same using previously published data on the pore and pore-throat sizes of conventional reservoir rocks, tight-gas sandstones, and shales. Measures of central tendency (mean, mode, median), of pore-throat sizes (diameters) are generally greater than 2 μm in conventional reservoir rocks, range from about 2 to 0.03 μm in tight-gas sandstones, and range from 0.1 to 0.005 μm in shales. Hydrocarbon molecules, asphaltenes, ring structures, paraffins, and methane, form another continuum, ranging from 100 Å (0.01 μm for asphaltenes to 3.8 A (0.00038 μm) for methane. The pore-throat size continuum provides a useful perspective for considering (1) the emplacement of petroleum in consolidated siliciclastics and (2) fluid flow through fine-grained source rocks now being exploited as reservoirs [Nelson, 2009].

Pelitic rocks compaction

Initially the compacting stage is controlled by the mechanical arrangement of the grains and the ductile deformation - the process is more pronounced in the clay and muds than in the psammitic sediments.

During initial inhumation up to several kilometers, interP and intraP are compacted and affected by chemical diagenesis, and the volume of interP and intraP pores greatly decreases. Porosity versus depth curves Van Sickel et al., (2004) for mud dominated strata show that porosity can drop to less than 10% by 2.5 km (1.6 mi) of burial, suggesting that 50 to 70% porosity units or 83 to 88% volume is lost by compaction and diagenetic processes [Day-Stirrat, 2010]. Cementation associated with burial is variable.

Permeability can vary in magnitude orders for the same porosity [Neuzel, 1994] depending on grains size and grains size distribution. The size distribution of grain at a certain porosity may be essential for permeability.

Mudstone compaction is determined by compressibility or in other words compaction mudstones significantly alters porosity and permeability. The composition, mechanical behavior and diagenetic evolution of pelites vary greatly depending on burial pressure and temperature (Fig. 9).

Sedimentation, diagenesis and regional metamorphism are phenomena that interact with multiple variables as a result of the specific composition and mechanical behavior of the pelites and they could have very different effects depending on the temperature and the depth-pressure (Fig. 10). The petro-structural evolution produce several chemical, mineralogical, structural and textual transformations and markedly diminution of porosity and permeability. In this context, it is obvious that the pore-throat size (diameters) can provide important indirect indications on the degree of diagenesis of the studied section

Loucks et al. (2012) observed that in the deep burial domain practically all diagenetic transformations are already made. Only in the case of OM matter pores the number and their diameter are only partially reduced and they can still cross the hydrocarbon generation window area and may still remain functional in the deep burial transformation section (Fig. 4).

Mudrocks have a variety of pore networks that can be any combination of pore types. The development of the pore network depends on the original mineralogy and fabric that may vary at the milimeter lamination level. The evolution of the pore networks relative to the temperature and pressure increases should be fully understood before a reliable reservoir quality reservoir prediction will be made.

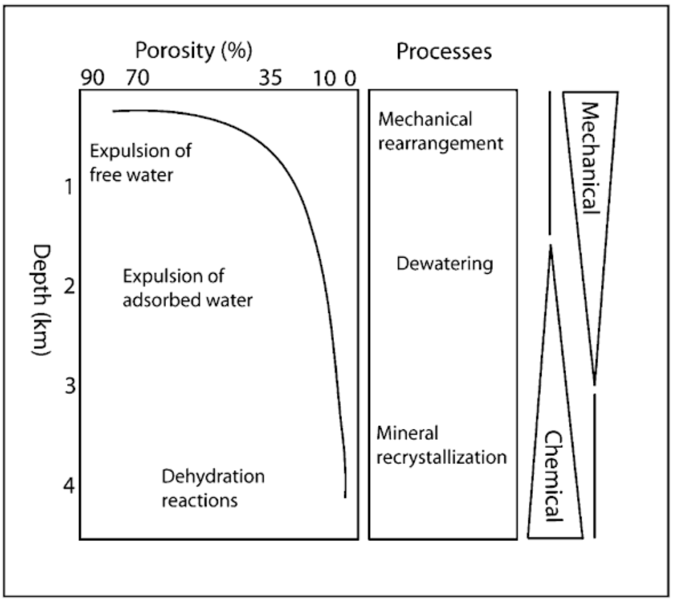

Fig. 9. Model showing processes that drive porosity reduction as a function of depth
[Day-Stirrat et al., 2010]

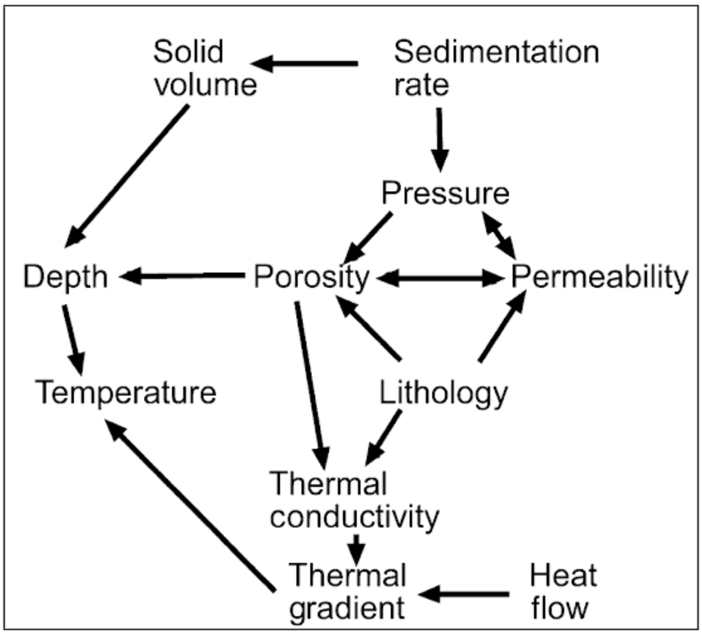

Fig. 10. Interconnectedness of burial regime parameters [Day-Stirrat et al., 2010]

Diagenetic-low metamorphic fabric

Fabrics defined by the alignment of parallel particles with stratification are generated by dewatering and diagenesis compaction [Kisch, 1991]. Discordant fabrics resulting from polyphasic deformation are generally attributed to more recent structural events – an early structural element is overprinted by a later planar fabric (crenulation or crenulation cleavage). It is a planar fabric formed by small scale folding or of a pre-existing tectonic element. Mechanism of crenulation cleavage formation involves buckling of the pre-existing folia on a mezzo- micro- scale. Progressive deformation can lead to pressure solutions and migration of components, in particular quartz, to microlithons resulting in a segregation fabric. (Fig. 11, 12). They are considered to be formed by occurrence of cleavage planes in transitional conditions between the high-diagenesis domain and the regional low grade-metamorphism [Glasmacher et al., 2004; Kisch, 1991]. Microfabric exerts a fundamental control of permeability in non-fractured shale. Random microfabrics (Type A) show the highest permeability > 1 μd, laminated microfabric (Type C) has the lowest permeability < 1 μd.

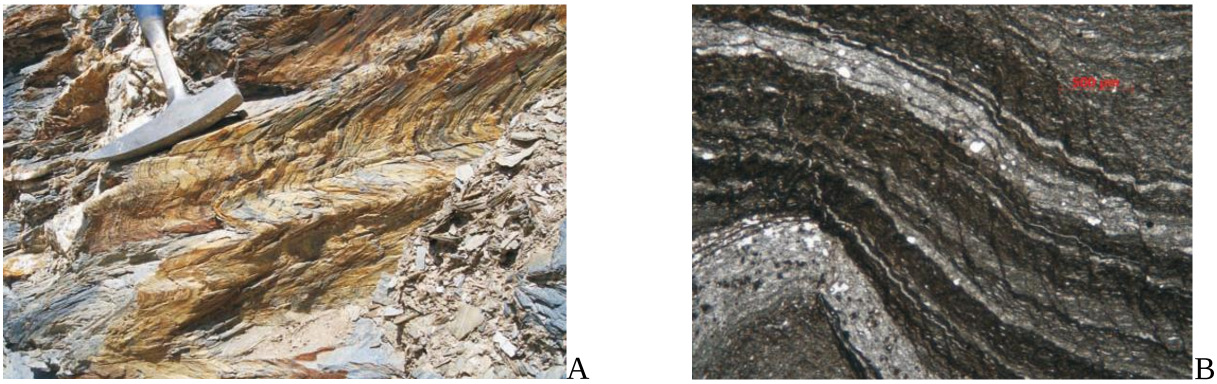

Fig. 11. Crenulation cleavage: macroscopic and microscopic view (from [Vazquez et al., 2013])

A. View of an outcrop of the Aptian–Lower Albian pelites of the Tanger-Ketama Unit B. Thin-section views of sample KET-4, which corresponds to the Berriasian–Hauterivian pelites of the Tanger-Ketama Unit.

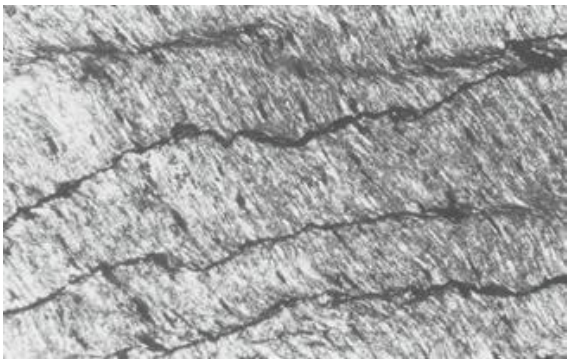

Fig. 12. Discrete crenulation cleavage (S2 subhorizontal) overprinting a slaty cleavage (S1 trending from top left to bottom right) [Passchier, Trouw, 2005]

The crenulation cleavage is defined by horizontal dark seams with wriggly to smooth appearance. The seams are interpreted as accumulations of insoluble material along dissolution surfaces. Concepcion, Chile. Width of view 1.8 mm. PPL.

As mud sediments are progressively buried temperature and pressure increasing cause mineral reactions to move to silicate phases (quartz, feldspar and clay minerals). This results in a variety of reaction mechanismus including transformation, dissolution or precipitation [Day-Stirrat et al., 2010]. These reactions cause progressive organisation of the rock fabric. Compaction of sediments is driven toward lower porosities and higher densities as a function of increasing stress and chemical reactions. Mechanical processes are controlled by the effective stress and chemical compaction by dissolution and precipitations of solid substances. As the metamorphism is approached increase in crystal size, changes in anisotropy, chemical compaction and changes in anisotropy, porosity and permeability are the most important changes in pelitic rocks.

Diagenetic foliation

A.F. Park (2010) shows that the cleavage in the Weldon Formation (New Brunswick, Canada) is formed later than compaction-dewatering but very early in the diagenetic history of these rocks (prior to hydrocarbon migration.). The demonstration of a tectonic relationship for a very early apparition of cleavages here implies that a mechanism other than dewatering-compaction may be important elsewhere. So and Sb cleavage formed as early response to bedding - parallel bulk shortening .The most anchizone cleavages are considered as the precursors to the slaty cleavage that is more fully developed in higher grade anchizone and greenshists facies pelites. The conditions under which the So and Sb cleavages are formed are temperature around 50°Celsius and maximum burial depth of about 1.5 km. The fissile fabric in claystone is well documented [Kisch, 1991].

Regardless of the developing mechanism, it is obvious that new planes of mechanical discontinuity may have already appear in the diagenetic conditions in the shale-cleavage planes (Fig. 13).

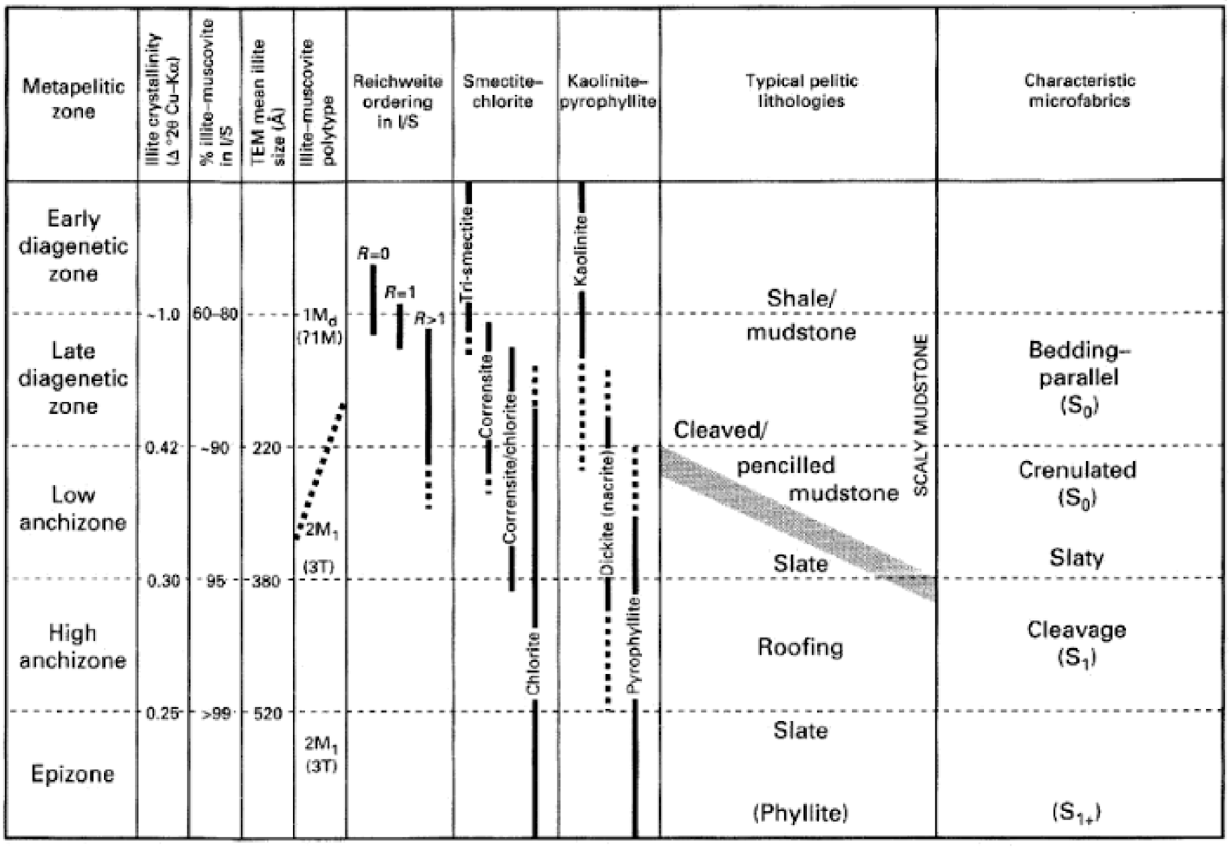

Fig. 13. Metapelitic zones showing associated lithologies and microfabrics [Merriman, Peacor, 1999]

C.W. Passchier and R.A.J. Trouw (2005) studying the diagenetic foliation consider that this foliation (also known as bedding-parallel foliation) forms by diagenetic processes such as compaction in sediments with detrital mica (i.e. pelites). This foliation defined by the parallel orientation of thin elongate detrital grains with frayed edges is observed in diagenetic section and in very low and low grade metamorphic pelites which have undergone little deformation. Mica is commonly subparallel to bedding; mica preferred orientation is due to their passive orientation. The diagenetic foliation is not associated with folds, and it precedes the formation of secondary foliation in pelites.

G. Jacob, H.J. Kisch, and B.A. Van der Pluijm (2000) studied Swiss Alps sections representing a sequence of fine, silty shales, mudstones, slates and marly claystones with a smooth incipient slaty or crenulation cleavage (the samples belonging to Upper Eocene-Lower Oligocene paraauchtone and appertaining to the North Helvetic Flysch tectonic unit of the Swiss Alps) and Sweden metasediments (the Swedish Caledonides of Jämtland samples collected from the Ordovician Föllinge Graywacke Formation from two anchimetamorphic areas) (Tab. 4).

This sections represents several sequence of siltitic shale, mudstone and claystone presenting a crenulation cleavage (mostly zonal or even discrete crenulation cleavage) or smooth incipient slaty cleavage. The crenulation cleavage is predominantly discreet, sometimes deflecting the field cleavage. Metamorphic degree of studied sections was determined as low to medium-grade anchizonal with one high-grade diagenetic exception. There is no significant crystallisation of the mica in the cleavage but abundantly bedding-parallel clastic mica. The crenulation distance space (CDS) in the studied areas varies from 20 to 150 μm depending of lithology, cleavage morphology and deformation intensity of analysed rocks.

In the Southern Appalachian Paleozoic a vast area belonging to the diagenesis - anchizone section up to the green schist facies was described [Weaver, 1984]. In the Great Smoky area in the shale diagenesis- anchizone section is developed an incipient slaty cleavage with (CDS) 30-70 μm.

B.A. Van der Pluijm and C.H. Kaars-Sijpesteijn (1983) investigated chlorite-mica aggregate developed (late diagenesis – very-low-grade - metamorphism section) from the northern Spain. The behaviour of the aggregate during deformation provides several informations on the cleavage development mechanism: microfolding and/or kinking are the most common deformation mode - large chlorite-mica aggregate (up to 120 μm) show multiple kinking and are usually cross-cut by the cleavage, with an average cleavage distance spacing of less than 30 μm. In all presented areas occur new structural ductile discontinuity planes formed in the section diagenesis to metamorphism: the morphology of the cleavage varying from slaty cleavage to domainal cleavage and to crenulation cleavage (CDS varies from 20 to 150 μm).

Table 4

Locations, lithology and cleavage type of samples (from [Jacob, Kisch and Van der Pluijm, 2000])

Sample No.	Locality	Lithology/size of detrital grains	Cleavage morphology
Z 91-1	1.5 km SSE of Linthal, northern end of second road tunnel	claystone / < 10 μm	discrete and locally zonal crenulation, CDS 30-100 μm
Z 91-2A		slaty mudstone / < 20 μm	discrete and locally zonal crenulation, CDS 30-100 μm
Z 91-8	Wanneler Bach, Vorder Schächental	slaty calcareous mudstone / 10-40 μm	discrete and zonal crenulation, CDS 50-100 μm
Z 91-9		mudstone with laminae of calcareous siltstone / < 30 μm	zonal and some discrete crenulation in mudstone layers, CDS 40-150 μm
Z 91-10	Fritertal, N of Friteren, Vorder Schächental	calcareous slaty mudstone / 10-40 μm	local zonal crenulation, CDS 30 μm
Z 91-13	SE of Trübsees, S of Engelberg	marly siltstone / 20-70 μm	domainal anastomosing, no crenulation, CDS 30-50 μm
N78-8A	NW Föllinge	silty mudstone / 20-100 μm	discontinuous, locally zonal crenulation, CDS 50 μm
N78-44B	E Järpen	bedded silty mudstone with claystone and quartz-rich siltstone layers / < 10 μm in claystone layers; 20-70 μm in silty layers	discontinuous anastomosing, no crenulation, CDS 70 μm
N78-47A	Mörsil - Järpen	siltstone / 20-100 μm	discontinuous anastomosing, no crenulation, CDS ~100 μm
N92	E Mörsil	siltstone / 10-100 μm	domainal, discontinuous anastomosing, no crenulation, CDS 50-80 μm
N92-15G	W Föllinge	slaty claystone / < 10 μm	domainal, locally zonal crenulation, CDS 30 μm
N92-18A	Föllinge Skärvängen	silty mudstone with layers of quartz-rich siltstone / < 10-100 μm	domainal, discontinuous, no crenulation, CDS 20-50 μm
N92-18B		claystone / < 10 μm	domainal, locally zonal crenulation, CDS 20 μm

- Swiss Alps — - Sweden

Discussion

During the burial process of pelites porosity and permeability, two very important parameters conditioning petroleum migration are severely reduced. Mudstones and shales can become nearly impervious rocks and the transport of fluids is reduced in a very important manner.

When pelitic rocks crossed the diagenesis stage to reach the field of anchimetamorphism - low metamorphism, adapting to the new temperature and pressure conditions allows the development of new fabrics conforming to the new physicochemical conditions.

At the end of diagenesis in the late diagenesis-metamorphism section there are important transformations of the pelite fabric, which in the new temperature and pressure conditions significantly change the textural relationships of the mineral constituents. The ductile deformation and recrystallization builds a new fabric on macroscopic and microscopic scale. At the end of this stage the porosity and permeability are very low and the pelitic rock becomes almost impermeable and the petroleum fluids migration becomes very difficult.

From the petroleum geology point of view, certain petrogenetic transformation of pelitic rocks in the burial process represents a conversion with a "negative" aspect (important reduction of porosity and permeability, OM over maturation). In certain regions subjected to high-grade diagenesis to metamorphic-stage the development of new fabric like cleavage respective crenulation cleavage allows the formation of mechanical discontinuity planes produced under penetrative, ductile conditions with CDS cleavage between 20 and 150 μm. Hydrocarbon molecules, the diameters of asphaltenes, ring structures, paraffins, and methane, form another continuum ranging from 100 A° (0.01 μm) for asphaltenes to 3.8 A° (0.00038 μm) for methane [Nelson, 2009]. It means that the crenulation CDS is "large" enough to permit the migration of hydrocarbons from methane to asphaltenes.

High diagenesis conditions can transform shales and mudstones practically in impervious rocks; but eventually the apparition of crenulations cleavage could bring these rocks on the level of unconventional reservoir (concerning the porosity-permeability properties). Macroscopically the fabric of some claystone and mudstone may give the impression of a true metamorphic rock at the first sight. The structural aspect may show crenulation, structure spaced cleavage eventually axial planar cleavage but petrogenesis clearly shows that the formation temperatures did not exceed 100-120°C. This means that in this area crenulation cleavage structure can allow the migration of potential hydrocarbons and so the region could become interesting for the prospecting works.

In fact the high-grade diagenesis to anchimetamorphism-low grade metamorphism conditions can have globally a "destructive" action concerning petroleum geology; however, paradoxically during crenulation cleavage development (under similar PT conditions) hydrocarbon migration process can be facilitated.

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Морариу Д.
Независимый эксперт – нефтяной геолог, Женева, Швейцария, morariu45@gmail.com
Аверьянова О.Ю.
Акционерное общество «Всероссийский нефтяной научно-исследовательский геологоразведочный институт» (АО «ВНИГРИ»), Санкт-Петербург, Россия, info@ngtp.ru

ОБРАЗОВАНИЕ КЛИВАЖА ПЕЛИТОВЫХ ПОРОД В ДИАГЕНЕЗЕ-НАЧАЛЕ КАТАГЕНЕЗА - ВАЖНЫЙ ФАКТОР СОЗДАНИЯ ПУТЕЙ МИГРАЦИИ УГЛЕВОДОРОДОВ

Литификация пелитовых пород, обладающих углеводородным потенциалом, на стадии диагенеза, и дальнейшее их уплотнение на стадии катагенеза приводят к сокращению пористости-проницаемости, закрытию путей миграции флюидов и возможному «перегреву» органического вещества. В определенных тектонических условиях развитие вторичной структуры осадочных пород в виде густой сети трещин первичного и вторичного кливажа может создавать достаточные объемы пространства с расстояниями между слоями сланцеватости, варьирующими от 20 до 150 мкм, которые в свою очередь могут представлять собой пути миграции флюидов и углеводородов. Участки с развитием пород, обладающих благоприятным петрогенным профилем (пелитовые породы со сложной сланцеватостью при устойчивых температурах, не превышающих 100-150°С), могут рассматриваться как потенциальные пути миграции углеводородов.

Изучение участков пород, потенциальный миграционный потенциал которых резко уменьшается с повышением температуры во время погружения и затем частично компенсируется образованием кливажа, может представлять собой определённый интерес для оценки потенциала и перспектив нефтегазоносности.

Ключевые слова: *пелитовая порода, расстояние между слоями сланцеватости, первичный и вторичный кливаж, пути миграции углеводородов, нефтегазоносность.*