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Porosity in Carbonates

Chapter · January 2020

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Abstract

Porosity in carbonate rocks, most commonly limestones and dolostones, is of great importance to study since around half of world's hydrocarbon reserves are made up of dolomite and limestone, which formed mostly in a shallow marine environment and usually close to where such sediments originate from the source rocks. Carbonates possess both primary and secondary porosities, which reduces with progressive burial leading to increasing rigidity of the rock. Several classifications of carbonate rocks are available. These are based on texture, depositional environments (the three kinds of carbonate factories), energy of the depositional environment, mud to grain ratio (volume-wise), grain to micrite ratio, porosity-permeability parameters, depositional-, diagenetic- and biological issues etc. Out of them, those by Folk and Dunham have been entered most of the text books on sedimentology. Carbonates more commonly display dissolution, cementation, recrystallization and grain replacement than the siliciclastic deposits. The porosity-permeability relation in carbonates may or may not be linear. Several schemes of classification of porosity of carbonates are available. Archi's scheme (based on qualitative evaluation of texture and porosity), the Choquette-Pray

scheme (utilizes depositional and diagenetic changes in the rock), the Lucia scheme (works on inter-relationship between porosity, permeability and the particle size) etc.

2.1 Introduction

Nearly 50% of world's oil and gas reserves are in dolomite and limestone. Dolomites are often more porous than limestones. Carbonates are characterised by multi-porosity characteristics unlike sandstones. Carbonate rocks exhibit various types of pores starting from primary porosity formed at the time of deposition to secondary porosity resulting from diagenesis. Cementation leads to porosity destruction and with time and burial the general trend in pore systems is towards destruction, but there are certain processes that preserve porosity in the overpressured formation. With progressive burial, porosity falls along with increase in framework grain rigidity.

This chapter discusses the followings: (i) the basic characteristics of carbonate sediments, (ii) their genesis, (iii) changes in their fabric, (iv) depositional processes, (v) the ability of certain organisms to build structures and their relevance. This chapter discusses how porosity evolves and diagenetic changes takes place in carbonates.

2.2 Origin of Carbonate Rocks

Studies by Milliman (1974), Wilson (1975), Tucker and Wright (1990) and Moore (2001) indicated that the modern day carbonates are mainly biotic and form mostly in (shallow) marine environment. The formation of carbonates depends on the parameters favourable for carbonate deposition such as suitable temperature, salinity, and presence of hard substrate and absence of siliciclastics (Lees 1975; Moore 2001). Figure 2.1 shows the latitude-wise distribution and abundance of organisms. The growth of most of the corals (i.e., besides the cold water corals) mainly depends on the presence of light, so there is prolific growth of carbonates in the upper part of the marine environment up to ~10 m depth (Moore 2001; Fig. 2.2).

The study on the origin of carbonates with coarser grains can be commented by observing shell fragments, entire foraminifera etc. Genesis of carbonate mud involves several processes including particles derived from erosion of the shells of typically tropical climate (Moore 2001). From the dead green algae, deposited aragonite needles finally produce carbonate mud (Moore 2001). The important aspect of carbonate

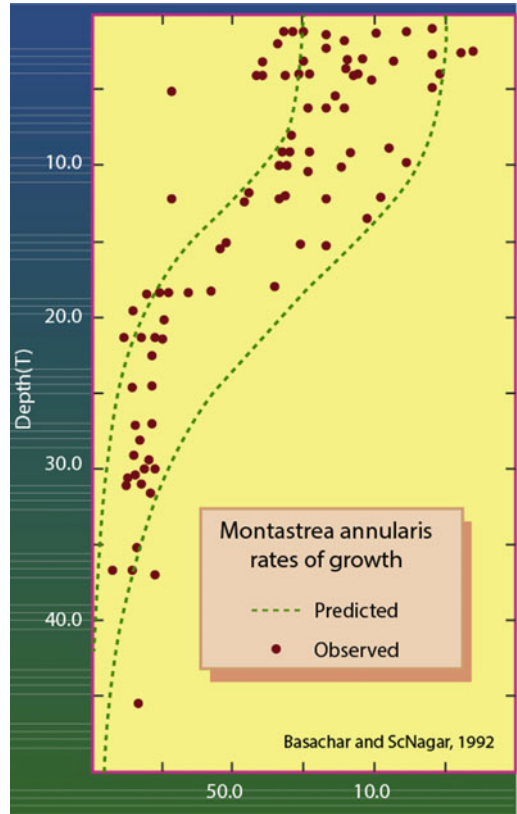
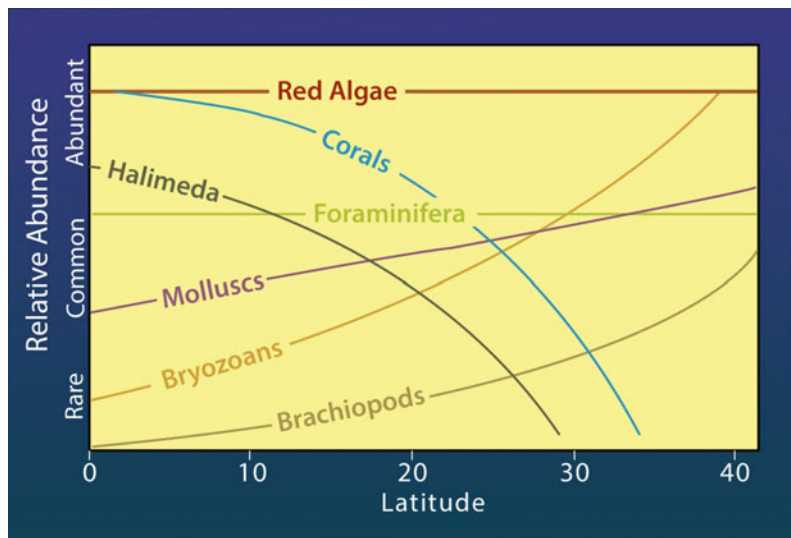


Fig. 2.2 The dashed line represents the predicted growth and the open circles represent the actual growth of the corals (Moore 2001)

Fig. 2.1 Latitude-wise distribution of organisms (Moore 2001)



sedimentation is that unlike siliciclastics, they deposit close to where they originate (Moore 2001).

2.3 Carbonate Classification

The carbonate classifications in the early century was not a priority. With time, however, main issues were addressed: carbonates can deposit in (i) quiet water; and as (ii) current-washed deposits. In this classification calc-arenites and fine-grained limestones were clubbed in the quiet water group and the coarse grained clastics into the current-washed categories. The Upper Jurassic Arabian limestones were classified into different types based on original texture and the abundances of mud/grain ratio. The different types are: (i) aphanitic limestones (<10% particles); (ii) calc-arenitic limestones (mud with >10% particles); (iii) calc-arenites (sand with <10% mud matrix); (iv) coarse clastic carbonates (gravel with <10% mud matrix); and (v) residual organic limestones (in situ reef rocks).

Plumley et al. (1962) classified limestones based on the type of energy of the depositional environment. These are: (i) quiet water; (ii) intermittently agitated water; (iii) slightly agitated water; (vi) moderately agitated water; and (v) strongly agitated water.

Leighton and Pendexter (1962) classified carbonates based on grain to micrite ratio (Mazzullo and Chilingarian 1992). Micrite being very fine-grained, it was characterised by some workers as the place where the sedimentary particles are embedded (Plumley et al. 1962). Dunham (1962) classified micrites as particles with <62 µm size. The organic structures and recrystallization fabrics were identified by Leighton and Pendexter (1962) and his classification is as follows: (i) micritic limestones; (ii) detrital limestones with embedded conglomerates of older limestone units; (iii) skeletal limestones; (iv) pellet limestones; (v) lump limestones; (vi) limestones with coated grains including oolite, pisolites etc. and (vii) mainly reefal limestones.

Leighton and Pendexter (1962) classification scheme was modified by Bissell and Chilingar

(1967) according to micrite to grain ratio. Another scheme by Thomas (1962) where the grain particles and the cement and porosity-permeability parameters were also considered in the classification of Paleozoic limestones is as follows: (i) skeletal part, (ii) non-skeletal part, (iii) organic matter, and (iv) breccia.

Later, Folk's (1959, 1962) and Dunham's (1962) classification became very popular (Ahr 2008). Riding (2002) classified reefs and discussed their geneses.

Folk's and Dunham's classifications have some similarities. They depend mainly on the (volume) ratio between the mud and grains, and the packing arrangement of the grains. The pattern of textural maturity plays a major role in sandstone description and similar concepts have been applied in carbonate classification both by Folk and Dunham (Ahr 2008). Rocks with >90% lime mud were designated as mudstone by Dunham and as micrite by Folk. The rocks where grainstones are dominant are referred as sparite by Folk. Dunham referred these rocks as grainstones. Depending on the proportion of the constituent grains and their packing, the rocks are named differently. Commonly Dunham's classification is used in industry for carbonate classification. This is because the reservoir properties can be framed easily from the rock description. The environment of deposition can be easily interpreted from the rock types, as the mudstones form where the winnowing is insignificant. Rocks with high grain percentage are deposited in high energy environment. Grainstones and packstones have highest intergranular porosity and these rock types are also prone to diagenetic alteration leading to early cementation and decrease in pore throat size.

2.4 Carbonate Factories

The carbonate factories are clubbed into three broad categories: T (for tropical, top water), M (mud mound, micrite) and C (cool water and mainly biogenic precipitation) (Fig. 2.3, Schlager 2005). These carbonate factories differ

Fig. 2.3 Three carbonate factories with different mineralogical contents (Schlager 2005)

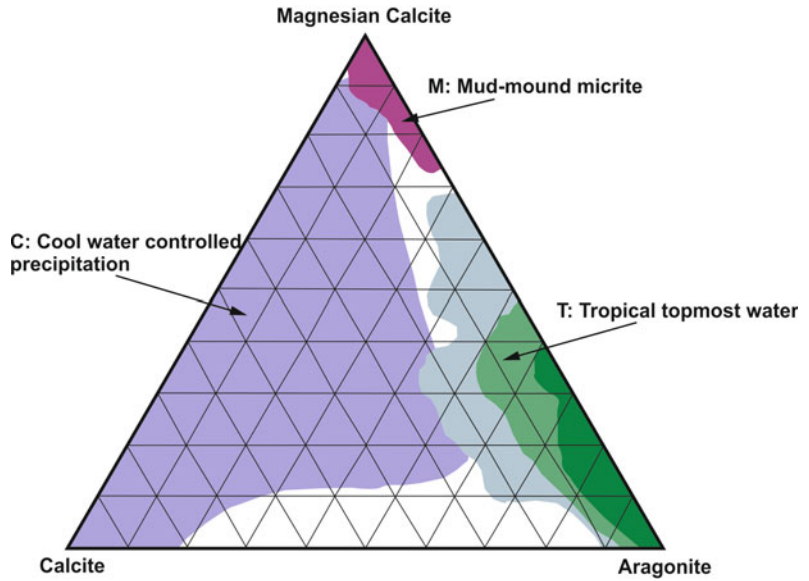
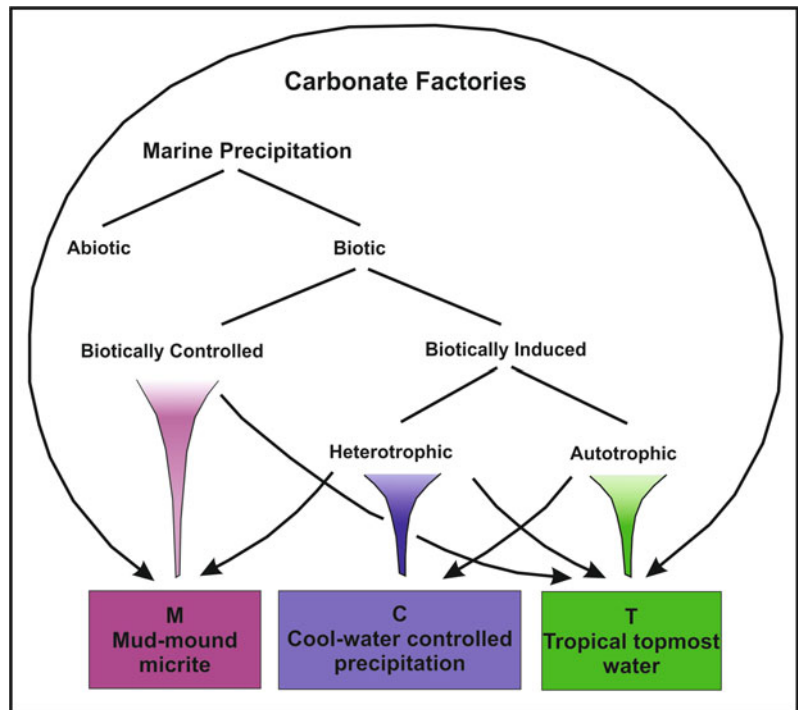


Fig. 2.4 Different modes of precipitation of carbonate factories (Schlager 2005)



in many aspects such as mineralogical content (Fig. 2.3), precipitation mode (Fig. 2.4), different depth ranges, and production potentials.

The T carbonates are generally formed within the 30°N to 30°S latitude in ~20 °C warm

waters. Reef building corals and some molluscs are the common sediment building organisms that are mainly photosynthetic symbionts (Moore and Wade 2013). Abiotic components of carbonates such as ooids and whittings are also

common and are composed of aragonite and magnesian calcite (Schlager 2005).

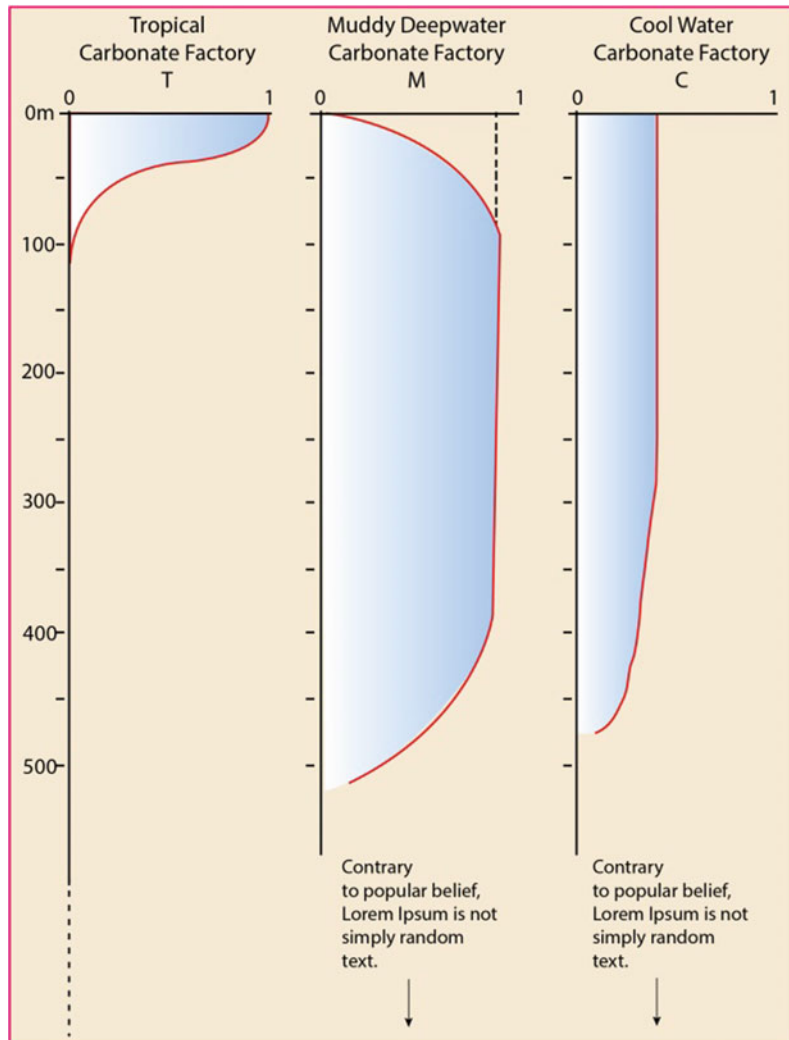
The C carbonates/cool water carbonates form with prolific supply of nutrients from cold waters (Schlager 2005). The sediment producers are mainly heterotrophs and cement precipitators. Mineralogy of such carbonates is dominantly calcite since in cold waters aragonite and magnesian calcite may dissolve (Fig. 2.3). The production is insensitive to light and thus may occur in deep water (Fig. 2.5).

The M carbonates/mud mound consists of micritic calcite muds. Mud mounds were prolific

during the Paleozoic. Abiotic cement comprises of mud mounds forming stromatactis fabric (Schlager 2005). It forms in the low-light intensity zone and the mineralogy is commonly calcite (Fig. 2.3).

Cations (Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , Zn^{2+} , Ba^{2+} and Sr^{2+}) and anionic complexes form carbonates. Depending on the crystal lattice structure carbonates can be grouped into different families. Hexagonal, orthorhombic and monoclinic are the common crystallographic systems that represent these families. The common minerals are calcite (hexagonal system) and aragonite (orthorhombic

Fig. 2.5 Depth of occurrence of carbonate factories along with production rate (Schlager 2005)



Schiager, 2006

system). In dolomites there is loss in rotational symmetry as the Mg ions, smaller than the Ca ions, enter the structure and alter the lattice. Limestones and dolostones commonly constitute carbonates (Reeder 1983).

The texture of siliciclastic rocks strongly depend on the type of parent rock, weathering type and the transportation duration. Such rocks are composed of quartz, feldspar, rock fragments and matrix. Ham and Pray (1962) first identified the distinct attributes of carbonate rocks. Biological, chemical and detrital processes may involve in carbonate formation. Their mineralogy is independent on the composition of the weathered and parent rocks, and their texture is also depends on the flow stream patterns of the rivers unlike the siliciclastics. Carbonates are mainly made up of skeletal remains and biological constituents such as lime mud, fecal pellets and microbial cements (Folk 1980). Siliciclastic grains do exist in carbonates and these could either be clasts of older rocks or lithified fragments or reworked sediments. Their main difference with the siliciclastics is that the carbonate development can depend on biological activities and many times the carbonate stratifications are destroyed by the burrowing activities. Finally unlike siliciclastics, carbonates alter diagenetically by rapid dissolution, cementation, recrystallization and replacement of grains. Because of these secondary processes fractures are more common in carbonates unlike siliciclastics (Ham and Pray 1962). Major differences between siliciclastics and carbonates are listed by Choquette and Pray (1970).

The petrophysical properties of sandstones and carbonates differ. In sandstones the porosity is mainly classified as inter-particle and the permeability is closely related to the inter-particle porosity. The petrophysical lab measurements made on few inches of core represents the entire rock volume. Carbonates exhibit a wide variety of pore types with varying sizes, shapes and origins. In this case, porosity does not always bear a linear relation with the permeability. Thus in case of carbonates, lab measurements made on few inches of core does not always represent the entire facies. To improve the situation, one foot

(0.305 m) long core would be required for reliable correlation between the core and the facies (Ahr 2008).

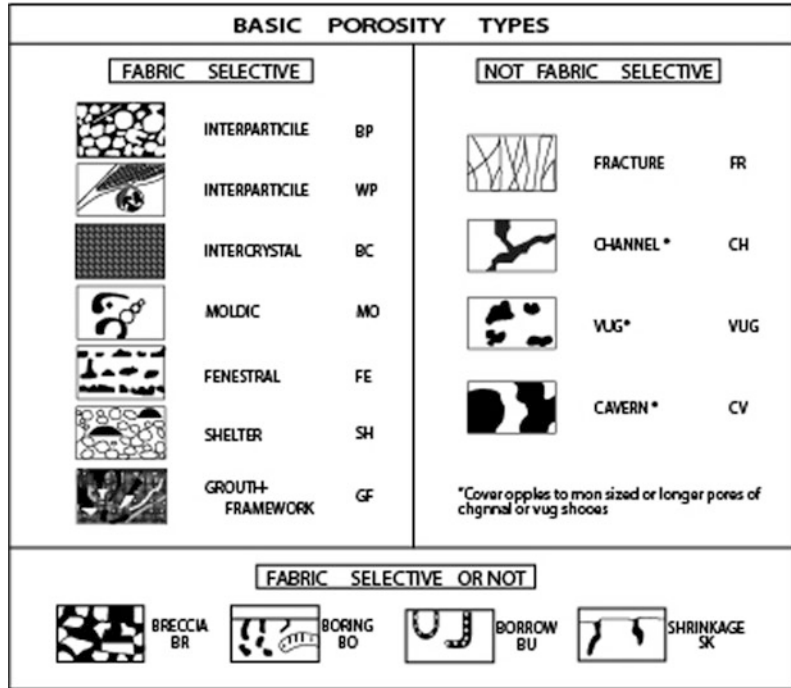
2.5 Porosity and Its Classification

The porosities of Holocene carbonate sediments are very high: ~40–75% and these higher values are common in micritic limestones (Fig. 2.6; Moore 1989). High porosities are associated in the deep water facies that are mainly oozes and these have both inter- and intra-particle porosities (Schlanger and Douglas 1974). Reefs represent that section of the carbonates where the framework pores represent a large portion of porosity and permeability in reefal rocks.

In recent unconsolidated carbonates, porosity arises mainly by: (i) boring processes in reefs due to advent of algae, bacteria or fungi. Bivalves and sponges show boring features in hard bases; (ii) animals and plants show bioturbation; (iii) fenestral structures formed by micro-organisms; and (iv) dissolution feature such as evaporate dissolution.

Porosity in modern carbonates ranges 40–70% (Choquette and Pray 1970), whereas in lithified old samples it is merely 5–15%. Porosity reduces in carbonates mainly by compaction and/or cementation (also see Mukherjee and Kumar 2018). Porosity reduces in ancient rocks mainly by cementation and pressure dissolution. Commonly carbonates do not have regular pores/pore throats and in order to identify the rock properties, the porosity classification becomes important (Ahr 2008). The common classification is inter-particle and secondary porosities like vugs and fractures. Another way of classification is grouping into shape, size of pore, rock properties i.e. mainly petrophysical properties and the mode of origin. Rock typing is a common methodology to characterise the reservoir where the porosity, permeability and pore throat sizes are linked to classify according to hydraulic units (Ahr 2008). The evolution of the carbonate reservoir pore systems are very well explained in the schemes by Archie (1952), Choquette and Pray (1970) and Lucia (1983).

Fig. 2.6 Porosity classification incorporating the details about the depositional as well as the diagenetic changes and are as categorised as fabric selective, not fabric selective and fabric selective or not category (Scholle 1978)



2.6 Porosity Classification

2.6.1 Archie’s Scheme

Carbonates were first classified by Archie (1952). Archie’s classification was primarily based on textural description and the type of visible porosity. Textural categories are from type I to III and are based on visible porosities of four classes from A to D. At a magnification of 10×, class A has no visible porosity, any porosity between 1 and 10 μm is referred to as class B. Class C has a visible porosity of more than 10 μm.

Type I carbonates are referred as crystalline, dense, hard and under a microscope it shows no visible porosity. The Solenhofen Limestone (Germany) is the example of Type I carbonates (Ahr 2008). Type II porosity are mostly chalky and wackestone type and the pore size does not exceed 50 μm. The granular carbonates are mostly referred as type III carbonates and they come under the grainstones and packstones categories (Ahr 2008). Archie’s classification follows an integrated approach where the capillary

pressures, electrical properties and the saturation characteristics of the rock type were integrated. The composition of the rock, its mineralogical content as well as the provenance was not considered into Archie’s classification (Ahr 2008). It was difficult to use Archie’s porosity classification to address and relate porosities along with their genesis.

2.6.2 Choquette-Pray Classification

In the Choquette and Pray classification (1970), 15 types of pores were categorised into three subgroups: (i) fabric selective, (ii) non-fabric selective, and (iii) may or may not be fabric selective. In this type of classification, all the information including the depositional and diagenetic changes is incorporated. The main examples of fabric selective pores are oomoldic porosities and intercrystalline porosity as encountered in dolomites. Grain moldic pores are mainly intergranular. Non-fabric selective pores fall mainly into category of fractures or dissolution cavities that cut across the fabrics.

Mechanical stratigraphy and fracture stratigraphy helps in identifying the fracture patterns as well as understanding the attributes for fracture studies away from the well (Laubach et al. 2009).

Certain types of porosities represent a category that may or may not be fabric selective such as desiccation cracks, burrows and boring. Details about the Choquette-Pray classification are given in Fig. 2.6.

2.6.3 Lucia Classification

This classification came up after the work from the Shell oil company during the 1960s. The inter-relationship amongst porosity, permeability and the particle size was investigated by Lucia (1995). The Lucia classification allowed to distinguish between inter-particle and vuggy porosities. Also different vugs were distinguished based on their separable as well as touching characteristics. Craze (1950) and Bagrintseva (1977) studied the relationship between porosity, permeability, some aspects of capillary pressure and particle size. They studied the main rock types using this classification. In Lucia classification the main work was to delineate petrophysically inter-particle pores and vugs. The porosity is classified in terms of particle size as fine- (<20 μm), medium- (20–100 μm) and large pores (>100 μm). The classification mainly characterises the pores in limestones, dolostones and mudstones. The geological origin about the pore spaces were not explained by Lucia's classification whereas the highlight of this classification is the inter-relationship between rocks and their petrophysical properties. Further, Lønøy (2006) subdivided pores into inter-particle and inter-granular types and this scheme better correlates porosity and permeability.

At places where the sediments are deposited and the pores formed contemporaneously, a genetic correlation between the primary pores and the rock facies can be made (Ahr 2008). The genetic classification between secondary pores such as vugs and fractures and the rock facies seems not possible.

2.7 Permeability Classification

Much of the work was done by Henri Darcy and Charles Ritter on the flow of water through sands around 1856. The flow rate was determined by passing water through the cylinder made of sands and gravels (Todd and Mays 2012).

Same as porosity, permeability can develop by several processes. Processes involved in changing the rock properties may act more than once in the geological history. Sorting and grain size variation are the important properties affecting permeability (Ahr 2008). As the smaller grains enter the pore spaces, the pore throat clogs thereby decreasing permeability. The deliverability/economics of a carbonate reservoir mainly depends on the permeability.

The main factor that enhances the permeability of the carbonate reservoir is the presence of fracture porosity (Watts 1983; Tucker and Wright 1990). In general, lithologies like chalk that are fine-grained have low permeability but certain processes such as re-sedimentation that control mineral concentration enhances the permeability of the matrix. Radial and concentric fractures resulting from doming/diapirism also increase the flow network as seen at the doming of Zechstein evaporites (Watts 1983).

2.8 Diagenetic Processes and Porosity Development

Diagenetic processes involve dissolution that increases porosity, recrystallization, and replacements of minerals, mineralogical transformation, evaporitization and cementation (Mazzullo and Chilingarian 1992). Diagenesis is broadly defined as the chemical and textural changes, which occur in rocks during post-depositional procedure during the contact of active fluids in the whole process (Mazzullo and Chilingarian 1992). Compositionally these fluids are different: marine, brackish, normally saline, or hypersaline.

The diagenetic phases viz. eogenetic, mesogenetic and telogenetic stages correlate to various

physical or chemical or both processes (Choquette and Pray 1970). In eogenetic stage, diagenesis of sub-aerially exposed marine sediments involving meteoric water takes place (Mazzullo and Chilingarian 1992). As explained by Harris et al. (1985), the mesogenetic diagenetic stage corresponds mainly to the burial diagenesis zone where the porosity changes and the diagenesis results in the change in bulk volume. Telogenetic diagenesis occurs by weathering of old carbonate rocks after uplift. This causes porosity formation in subaerial unconformity zones (Mazzullo and Chilingarian 1992).

References

- Ahr WM (2008) *Geology of carbonate rocks*. Wiley Publication, New York
- Archie GE (1952) Classification of carbonate reservoir rocks and petrophysical considerations. *AAPG Bull* 36:278–298
- Bagrintseva KI (1977) *Carbonate rocks, oil and gas reservoirs*. Izdatel'stvo Nedra, Moscow, 231 pp
- Bissell HJ, Chilingar GV (1967) Classification of sedimentary carbonate rocks. In: *Carbonate rocks—origin, occurrence and classification*. Elsevier Publishing Company, Amsterdam-London-New York, pp 87–168
- Choquette PW, Pray LC (1970) Geological nomenclature and classification of porosity in sedimentary carbonates. *AAPG Bull* 54:207–250
- Craze RC (1950) Performance of limestone reservoirs. *J Petrol Technol* 189:287–294
- Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: *Classification of carbonate rocks*. In: Ham WE (ed) *Classification of Carbonate Rocks—A Symposium*. AAPG Memoir, pp 108–121
- Folk RL (1959) Practical petrographic classification of limestones. *AAPG Bull* 43:1–38
- Folk RL (1962) Spectral subdivision of limestone types. In: Ham WE (ed) *Classification of carbonate rocks*. AAPG Memoir No 1, Tulsa, OK, pp 62–84
- Folk RL (1980) *Petrology of sedimentary rocks*. Hemphill Publishing Company
- Ham WE, Pray LC (1962) Modern concepts and classifications of carbonate rocks. In: *Classification of carbonate rocks*. AAPG Memoir No 1, pp 2–19
- Harris PM, Christopher G, Kendall C, Lerche I (1985) Carbonate cementation—a brief review. *Society for Sedimentary Geology*, Vol 36. <https://doi.org/10.2110/pec.85.36.0079>
- Lønøy A (2006) Making sense of carbonate pore systems. *AAPG Bull* 90:1381–1405
- Lucia FJ (1983) Petrophysical parameters estimated from visual descriptions of carbonate rocks: a field classification of carbonate pore space. *J Pet Technol* 35:629–637
- Mazzullo SJ, Chilingarian GV (1992) Diagenesis and origin of porosity. In: Chilingarian GV, Mazzullo SJ, Rieke HH (eds) *Carbonate reservoir characterization: a geologic-engineering analysis, Part I*: Elsevier Publ. Co., Amsterdam, *Developments in Petroleum Science* 30, pp. 199–270
- Milliman JD (1974) *Recent sedimentary carbonates*. Springer-Verlag, Berlin, p 375
- Moore CH (1989) *Carbonate diagenesis and porosity*. Elsevier, Amsterdam
- Moore CH (2001) Carbonate reservoirs: porosity evolution and diagenesis in a sequence stratigraphic framework. Elsevier, Amsterdam, p 444
- Moore C, Wade WJ (2013) *Carbonate reservoirs: porosity and diagenesis in a sequence stratigraphic framework*, 2nd edn, vol 67
- Mukherjee S, Kumar N (2018) A first-order model for temperature rise for uniform and differential compression of sediments in basins. *Int J Earth Sci* 107:2999–3004
- Laubach SE, Eichhubl P, Olson JE (2009) Fracture diagenesis and producibility in tight gas sandstones. In: Carr T, D'Agostino T, Ambrose W, Pashin J, Rosen NC (eds) *Unconventional energy resources: making the unconventional conventional*. 29th Annual GCSSEPM Foundation Bob F. Perkins research conference, pp 438–499
- Lees A (1975) Possible influence of salinity and temperature on modern shelf carbonate sedimentation. *Mar Geol* 19:159–198
- Leighton MW, Pendexter C (1962) Carbonate rock types. In: Ham WE (ed) *Classification of carbonate rocks*, American Association of Petroleum Geologists, Mem. 1, pp 33–61
- Lucia FJ (1995) Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *AAPG Bull* 79(9):1275–1300
- Plumley WJ, Risley GA, Graves Jr, Kaley ME (1962) Energy index for limestone interpretation and classification. American Association of Petroleum Geologists. <https://doi.org/10.1306/M1357>
- Reeder RJ (1983) Carbonates: mineralogy and chemistry. *Reviews in Mineralogy*, vol 11. Mineralogical Society of America, 394 pp
- Riding R (2002) Structure and composition of organic reefs and carbonate mud mounds; concepts and categories. *Earth Sci Rev* 58:163–231
- Schlager W (2005) *Carbonate sedimentology and sequence stratigraphy*. SEPM Concepts in Sedimentology and Paleontology. SEPM, Tulsa. ISBN 1-56576-116-2
- Schlanger SO, Douglas RG (1974) The pelagic ooze-chalk-limestone transition and its implications for marine stratigraphy. *Pelagic Sed* 1:117–148

- Scholle PA (1978) *A Color Illustrated Guide to Carbonate Rock Constituents, Textures, Cements, and Porosities*. American Association of Petroleum Geologists, Memoir 27. xiii + 241 pp., numerous colour plates. Tulsa, Oklahoma. IJF 115(6):473. <https://doi.org/10.1017/S0016756800041881>
- Thomas GE (1962) Grouping of carbonate rocks into textural and porosity units for mapping purposes. In: Ham WE (ed) *Classification of carbonate rocks—a symposium*. Am. Assoc. Petrol. Geol. vol 1, p 193
- Todd DK, Mays LW (2012) *Groundwater hydrology*, 3rd edn. Wiley-India Edition, pp 86–145
- Tucker M, Wright VP (1990) *Carbonate sedimentology*. Blackwell Scientific, Oxford, p 482
- Watts NL (1983) Microfractures in chalks of Albuskjell Field, Norwegian Sector, North Sea: possible origin and distribution. AAPG Bull 67:201–234
- Wilson JL (1975) *Carbonate facies in geologic history*. Springer-Verlag, New York, p 471