Rocks—Their Classification and General Properties

1.1 INTRODUCTION

Rocks are naturally occurring aggregates of one or more minerals. In the case of porosity or fracturing, they also contain fluid phases.

With respect to their geological genesis and processes, rocks are divided into three major groups:

- igneous rocks (magmatites);
- metamorphic rocks (metamorphites);
- sedimentary rocks (sediments).

Figure 1.1 shows the rock cycle. It starts with the magmatic rocks, formed by crystallization from the magma. Chemical processes and processes of erosion, disintegration, and transportation create sedimentary rocks of different composition and texture. Both types can be transformed into metamorphic rocks through the influence of pressure and temperature; a reworking by melting and recrystallization also occurs.
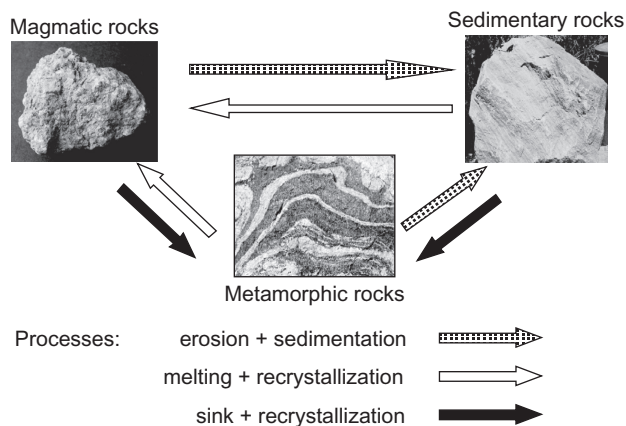

FIGURE 1.1   The rock cycle.

The following sections briefly describe the three rock types. Sedimentary rocks are discussed in more detail with respect to their importance to fluid reservoir exploration (e.g., hydrocarbons, water) and their abundance on the earth's surface. A detailed classification of rocks and their abundances on the earth is given by Best (1995) in *A Handbook of Physical Constants/AGU Reference Shelf 3*.

1.2 IGNEOUS ROCKS

Igneous rocks are formed by crystallization from a molten magma. Three types are characterized by their occurrence and position in the crust:

- plutonic rocks crystallized in great depth and forming large rock bodies;
- volcanic rocks reaching the surface, in many cases forming layers of rocks like a blanket;
- dikes have dominant vertical extension and a horizontal extension in one direction; also, they frequently separate geological units.

Igneous rocks can be classified according to their chemical or mineralogical composition. Chemical classification distinguishes acid, intermediate, basic, and ultrabasic rocks. Mineralogic classification uses the types (Figure 1.2):

- felsic or silicic rocks, for example granite and rhyolite;
- intermediate rocks, for example granodiorite, diorite, dacite, and andesite;
- mafic rocks, for example basalt and gabbro;
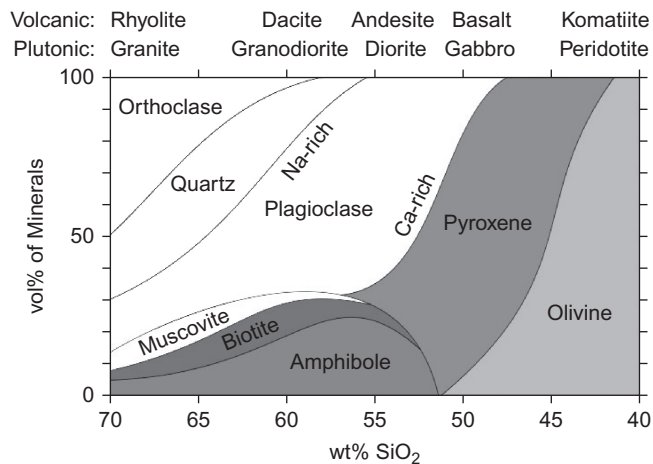- ultramafic rocks, for example peridotite and komatite.

FIGURE 1.2   Mineralogical classification of common magmatic rock types. Modified from http://en.wikipedia.org/wiki/File:Mineralogy_igneous_rocks_EN.svg.

TABLE 1.1 Approximate Average Mineral Composition (Volume Percent) of the Earth's (Upper) Crust and of Major Intrusive Rocks

Mineral	Crust	Granite	Granodiorite	Quartzdiorite	Diorite	Gabbro
Plagioclase	41	30	46	53	63	56
Alkalifeldspar	21	35	15	6	3	
Quartz	21	27	21	22	2	
Amphibole	6	1	13	12	12	1
Biotite	6	5	3	3	5	1
Orthopyroxene	2				3	16
Clinopyroxene	2				8	16
Olivine	0.6					5
Magnetite, Ilmenite	2	2	2	2	3	4
Apatite	0.5	0.5	0.5	0.5	0.8	0.6

After Wedepohl (1969); see also Huckenholz (1982) and Schön (1996).

Mineral composition controls physical properties (e.g., density and seismic velocity increases from felsic to mafic rock types).

Table 1.1 shows the mean mineral composition of magmatic rocks.

1.3 METAMORPHIC ROCKS

"Metamorphic rocks are the result of metamorphism. Metamorphism is the solid-state conversion of igneous and sedimentary rocks under the pressure−temperature regime of the crust" (Huckenholz, 1982). During this process the original mineral assemblages (magmatic or sedimentary) are converted into new assemblages corresponding to the thermodynamic conditions over a geologic time.

Through the different metamorphic processes (regional metamorphism, contact metamorphism, cataclastic metamorphism, etc.), the great variety of original rocks and their composition result in a broad spectrum of metamorphic rock types. Typical members of these metamorphic rock types are phyllites, schists, gneisses, skarns, marbles, felses, quartzites, serpentinites, and amphibolites.

As a result of the metamorphic process, many rocks show a typical structure with parallel-oriented elements like mineral axes and/or fractures and fissures. This results in anisotropy of certain physical properties.

1.4 SEDIMENTARY ROCKS

1.4.1 Overview

Sedimentary rocks are highly important for hydrocarbon exploration; most commercial reservoirs occur in this rock type characterized by its porosity and permeability. Sedimentary rocks cover more than 50% of the earth's surface and are therefore also of fundamental importance in many aspects of our lives, from agriculture to the foundation for buildings, and from groundwater resources to the whole environment.

Sedimentary rocks are formed by a sequence of physical, chemical, and biolcical processes.

Magmatic, sedimentary, and metamorphic source rocks are disaggregated by weathering to:

- resistant residual particles (e.g., silicate minerals, lithic fragments);
- secondary minerals (e.g., clays);
- water soluble ions of calcium, sodium, potassium, silica, etc.

Weathered material is transported via water, ice, or wind to sites and deposited:

- mineral grains drop to the depositional surface;
- dissolved matter precipitates either inorganically, where sufficiently concentrated, or by organic processes;
- decaying plant and animal residues may also be introduced into the depositional environment.

Lithification (consolidation) occurs when the sedimentary material becomes compacted; aqueous pore solutions interact with the deposited particles to form new, cementing diagenetic (authigenic) minerals (Best, 1995).

We distinguish two major rock classes of sedimentary rocks:

- clastics (siliciclastics);
- carbonates and evaporites.

Siliciclastics are composed of various silicate grains; carbonates consist mainly of only the two minerals dolomite and calcite. Clastic sediments have been transported over long distances, whereas carbonates are formed on-site (mostly marine). Clastic sediments are relatively chemically stable; they form an intergranular pore space. Carbonates on the other hand are chemically instable; their pore space is very complex and controlled by a variety of influences and pore space geometries.

In addition to the mineral composition for geological characterization of rocks in general and for sedimentary rocks in particular, the term "lithology" is used. The American Geological Institute Glossary of Geology defines lithology as "the

physical character of a rock." This character is influenced mainly by mineral composition (mineralogy) and texture of the solids (Jorden & Campbell, 1984).

1.4.2 Clastic Rocks

1.4.2.1 Classification

Clastic rocks are formed by:

- erosion, reworking, and transportation of rock components;
- deposition and sedimentation of the material;
- compaction and diagenetic processes.

Typical members of this important group of rocks are conglomerate, sandstone, siltstone, shale, and claystone.[1]

The classification in the main types (sandstone, siltstone, and claystone) follows the grain size classification for clastic sediments (Figure 1.3).

The nomenclature of clastic sedimentary rock is given by the following rules:

- Sandstone is composed of >50% sand-sized particles. The mineral composition is dominated by quartz and feldspar.
- Siltstone is composed of >50% silt-sized particles; they are generally less rich in quartz than is sandstone (Jorden & Campbell, 1984).
- Claystone is composed of >50% clay-sized particles; they are generally formed by clay minerals.
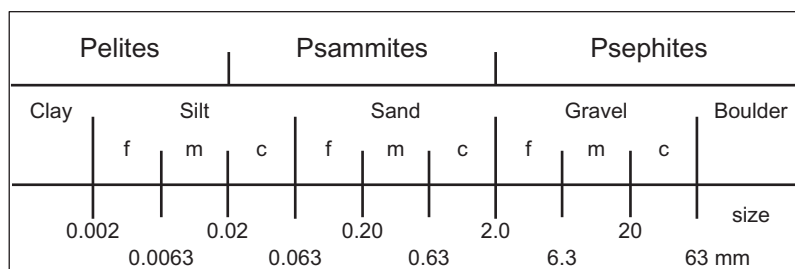

FIGURE 1.3   Classification of clastic sediments according to grain size: f, fine; m, medium; c, coarse. The terms psephites, psammites, and pelites are defined for more than 50% weight of the corresponding grain size range.

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[1]It may be noted that in addition to this main group of clastics (epiclastics), some specific types also exist as, for example, cataclastics (till) or pyroclastics (tuffs).

The term "shale" describes a sedimentary rock type which is a mixture of clay-sized particles (mainly clay minerals), silt-sized particles (quartz, feldspar, calcite), and perhaps some sand-sized particles as, for example, quartz, occasionally feldspar, calcite (Jorden & Campbell, 1984). Serra (2007) wrote "from a compilation of 10,000 shale analyses made by Yaalon (1962), the average composition of shale is 59% clay minerals, predominantly illite; 20% quartz and chert; 8% feldspar; 7% carbonates; 3% iron oxides; 1% organic material; and others 2%. ... Mudstone is a rock having the grain size and composition of a shale but lacking its laminations and/or its fissility . . .." As an example, for Pierre shale, Borysenko et al. (2009) gave the following mineral composition: quartz 29%; kaolinite, chlorite 8%; illite, muscovite, smectite 26%; mica 24%; orthoclase, dolomite, albite 13%.

Many properties of shale are controlled by the clay components (e.g., gamma radiation, electrical properties, cation exchange capacity (CEC), neutron response, permeability). For understanding physical properties of sedimentary rocks it is important to distinguish the different terms referred to as shale and clay:

- clay describes a group of minerals (hydrous aluminum silicates, see Section 1.4.2.3);
- clay also defines a particle size ($<$0.002 mm);
- shale describes a rock type as defined above ("claystone" also refers to a rock type).

The physical properties of clastic sediments are strongly controlled by:

- textural properties (particle dimensions, size, shape, spatial orientation);
- mineral composition, mainly the presence and effect of clay minerals.

1.4.2.2 Textural Properties−Grain-Size Parameters

The term texture encompasses particle size and size distribution, and shape and packing of the solid particles in clastic sediments.

Grain size is the classifying and defining parameter for clastic rocks. In general, particles are of nonspherical shape; thus the "grain diameter" depends on the technique of its determination:

- sieve analysis gives an estimate closed to the minimum cross-sectional axis (corresponding to the used mesh size) or a sphere equivalent measure following Stokes' law (sedimentation analysis);
- image or laser scanned techniques allow the application of numerical algorithms for a representative size description.

Grain size *d* frequently is given in millimeters or in micrometers (1 μm = 1 micron = 10^{-3} mm). The phi-scale is also used
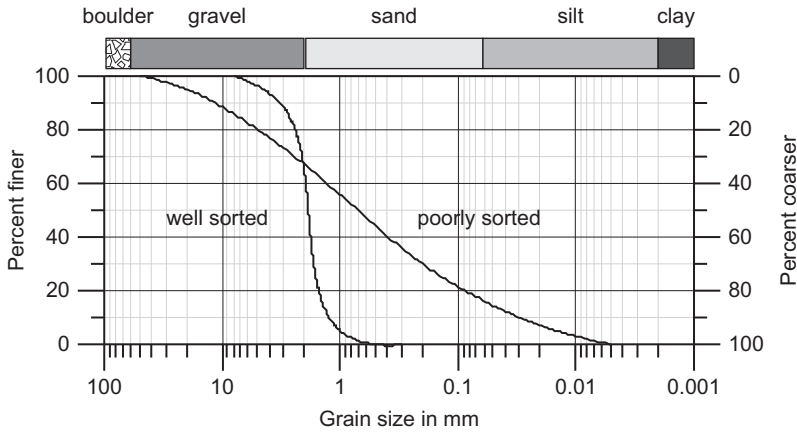
FIGURE 1.4 Grain size distribution curve for two sediments.

$$\text{phi} = -\log_2(d) \qquad (1.1)$$

where d is in millimeters.

Rocks show a distribution of grain sizes. This is described normally by a cumulative distribution curve (grain size distribution curve). Figure 1.4 gives an example.

From the grain size distribution various statistical measures or parameters can be derived using defined percentiles referred to as the cumulative weight-percent (weight %):

- Median grain size gives the midpoint of the curve at d_{50} (grain size in millimeters of 50th percentile).
- Grain sorting describes how narrow the distribution is to a single grain size $S_0 = (d_{25}/d_{75})^{0.5}$, where d_{25} is the grain size (mm) of 25th percentile and d_{75} the grain size (mm) of 75th percentile.
- Skewness expresses the symmetry of distribution $S_k = (d_{25} \cdot d_{75}/d_{50}^2)$.

Grain shape (sphericity) describes how nearly a particular grain approaches the shape of a sphere. Grain roundness (angularity) measures the sharpness of edges and corners. Comparison charts are used for both properties.

Grain packing is a measure of the density of the grain aggregates. In terms of physical properties, the spatial arrangement of the individual particles can be defined as internal structure—it controls, for example, anisotropy properties.

1.4.2.3 Some Fundamental Clay Properties

Particularly in logging practices, the terms shale and clay are used interchangeably; the difference was previously discussed in Section 1.4.2.1. Shale is a fine-grained rock; it contains a fraction of clay minerals and silt.

Clay minerals are aluminosilicates with a sheet structure. The principal building elements are two types of sheets or units:

- a tetrahedral unit of a central Si atom and surrounding O atoms;
- an octahedral unit of O atoms and OH groups around a central Al atom.[2]

Clay minerals (kaolinite, illite, montmorillonite, chlorite) are characterized by different stacking combinations or "architecture" of the two building elements (Figure 1.5). Individual figures always represent one crystal.

Montmorillonite has a water layer between the two units; the amount of water varies so that the size also ranges between $9.7 \cdot 10^{-10}$ and $17.2 \cdot 10^{-10}$ m (9.7 and 17.2 Å). Water trapped between the units or layers influence electrical conductivity (see Section 8.5) and contributes to total porosity (but not to effective porosity).

In the tetrahedral sheet, silica (Si^{+4}) is sometimes partly replaced by aluminum (Al^{+3}); in the octahedral sheet, aluminum (Al^{+3}) can be replaced by magnesium (Mg^{+2}) or other atoms (e.g., iron). Such a replacement by atoms of lower positive valence results in an excess of negative charge. This excess is compensated for by adsorption of cations (Na, Ca, Mg) from the adjacent water and an electric double layer is formed. The compensating cations on the surface layer can be exchanged by other cations. The number of the exchangeable cations is measured by the Cation Exchange Capacity (CEC) Montmorillonite has a high CEC value, but kaolinite and chlorite without interlayer cations have low CEC. Clays with high CEC play a leading role in the electrical conduction of shales and shaly sands (see Section 8.5). The ability of clay minerals to adsorb ions results in case of "radioactive ions" in a contribution to natural radioactivity (see Section 5.2) (Table 1.2).

The effect of clay minerals in the rock depends on the mineral properties and the type of clay distribution. There are three fundamental types:

1. Dispersed: clay is formed within the sediment when clay crystals precipitate from pore fluids.
2. Laminated: clay is of detrital origin, that is, formed outside the sandstone framework.
3. Structural: clay is of diagenetic origin, that is, formed within the sandstone framework as a deposit of clay clasts.

1.4.3 Carbonate and Evaporate Rocks

1.4.3.1 Introduction

The nonclastic carbonate and evaporate rocks are formed mainly by chemical and biochemical precipitation in special environments (typically warm, shallow, clear marine water in low latitudes).

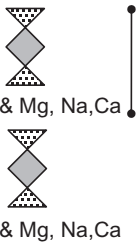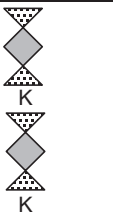[2]In some cases also Mg or Fe.

Clay building blocks Silica tetrahedral sheet Alumina octahedral sheet (Gibbsite, Brucite)	
Montmorillonite $(Ca,Na)_7(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4$ density = 2.33 g cm^{-3}	unit layer 9.7 ... 17.2 * 10^{-10} m n-H_2O & Mg, Na,Ca n-H_2O & Mg, Na,Ca
Illite $K_{1-1.5}Al_4(Si_{7.0-6.5}Al_{1-1.5}O_{20}(OH)_4$ density = 2.76 g cm^{-3}	unit layer 10 * 10^{-10} m K K
Chlorite $(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$ $(Mg,Al,Fe)_6(Si,Al)_4°_{10}(OH)_8$ density = 2.77 g cm^{-3}	unit layer 14 * 10^{-10} m
Kaolinite $Al_4(Si_4O_{10})(OH)_8$ density = 2.69 g cm^{-3}	unit layer 7.2 * 10^{-10} m

FIGURE 1.5   Clay minerals and some clay mineral properties. Compiled after Jorden and Campbell (1984).

A fundamental description of carbonates and their properties is given in the textbook written by Lucia (1999, 2007). Regarding the need to understand carbonate reservoirs better, a special section on carbonates appears in the May 2005 issue of The Leading Edge. For log interpretation problems, Akbar et al. (1995, 2000) gave an overview.

With respect to its abundance and economical importance, it is of interest that "though carbonate rocks make up only 20% of the sedimentary rock record, carbonate reservoirs hold 60% of the world's petroleum reserves . . ." (Chopra et al., 2005).

TABLE 1.2 Typical Values for Clay Mineral Properties (Ellis & Singer, 2007)

Clay Mineral	Specific Internal Surface in $m^2 g^{-1}$	CEC in meq/100 g	Wet Clay Porosity in p.u.
Smectite/ Montmorillonite	700−800	80−150	40
Illite	113	10−40	15
Chlorite	42	10−40	15
Kaolinite	15−40	3−5	5

Note the trend: with increasing specific surface (see Section 2.3) CEC and wet clay porosity increases. p.u., porosity units.

1.4.3.2 Composition

Carbonates originated autochthonous (formed very close to the depositional site) whereas clastics sandstone and shale are formed of transported sedimentary particles mostly from sources outside the depositional site.

The most abundant carbonatic minerals are calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Secondary minerals are anhydrite, chert, and quartz. Accessory minerals are phosphates, glauconite, ankerite, siderite, feldspars, clay minerals, pyrite, etc., depending on the environment of deposition and diagenetic history.

The two main rock types are as follows:

1. Limestone: composed of more than 50% carbonates, of which more than half is calcite.
2. Dolomite: composed of more than 50% carbonates, of which more than half is dolomite. Dolomite can precipitate directly from a solution containing Mg, Ca, and carbonate ions or by chemical alteration of limestone or calcareous mud (dolomitization). Dolomite frequently forms larger crystals than the calcite it replaces (Al-Awadi, 2009) and forms good reservoir properties.

Carbonates are modified by various postdepositional processes such as dissolution, cementation, recrystallization, dolomitization, and replacement by other minerals. Dolomitization is connected with an increase of porosity.

The interaction with meteoric pore fluids can result in a leaching of grains and influence reservoir quality in both directions (new pore space, cementation).

Fracturing as a result of stress and stylolithification are diagenetic processes in carbonates; they can create high-permeability zones and permeability barriers or baffles.

Evaporate sediments are a special type of sedimentary rock that is formed from the concentration of dissolved salts through evaporation (e.g., rock salt/halite).

1.4.3.3 Classification

Carbonates are biologically deposited and contain fossil fragments and other particles with complicated morphology and shape. This results in complex pore structures in general. Dissolution, precipitation, recrystallization, dolomitization, and other processes increase this complexity over scales.

Different types of porosity and complex pore size distributions also result in wide permeability variations for the same total porosity, making it difficult to predict their producibility. Therefore, the analysis of carbonate pore geometries is the key to characterize the reservoir properties of this group of rocks.

For carbonates, two main types of classification have been developed:

1. Textural classification (Dunham, 1962) based on the presence or absence of lime mud and grain support and ranges from:
   a. grain-supported grainstones, mudstones, and packstones to;
   b. mud-supported wackestones and mudstones;
   c. crystalline or boundstones.
2. Fabric selective and nonfabric selective pore type classification (Choquette & Pray, 1970) including:
   a. fabric selective (interparticle, intraparticle, intercrystal, moldic, fenestral, shelter, and framework);
   b. nonfabric selective (vug and channel, cavern, and fracture) porosity.

In his fundamental description of carbonatic rocks, Lucia (1983, 1999, 2007) gives the classification as presented in Figure 1.6.

The complex pore system of carbonate reservoirs ranges from microcrystalline pores to large vugs or caverns. The petrophysical characteristics are

Classification (Lucia 1983)		
Interparticle	Vuggy	
	Separate	Connecting
Pore types		
Intergrain intercrystal	Moldic Intrafossil Shelter	Cavernous Fracture Solution-enlarged fracture

FIGURE 1.6 Petrophysical classification of carbonate pore types, based on Lucia (1983, 1999, 2007).

controlled by connected networks of interparticle pores (matrix), vuggy pore space, and fractures, where:

- a matrix occupies the major portion of the reservoir, stores most of the fluid volume but has a low permeability;
- fractures (and vugs) occupy a small portion of reservoir volume but have high permeability and control the fluid flow (Iwere et al., 2002).

A classification and description of carbonate pore geometries is also given in Schlumberger's "Carbonate Advisor" (www.slb.com/carbonates) as follows:

- "Micropores, with pore-throat diameters <0.5 μm, usually contain mostly irreducible water and little hydrocarbon.
- Mesopores, with pore-throat diameters between 0.5 and 5 μm, may contain significant amounts of oil or gas in pores above the free-water level (FWL).
- Macropores, with throats measuring more than 5 μm in diameter, are responsible for prolific production rates in many carbonate reservoirs, but often provide pathways for early water breakthrough, leaving considerable gas and oil behind in the mesopores above the FWL.
- Vugs are cavities, voids, or large pores in rocks. Vugular porosity is common in rocks prone to dissolution, such as carbonates."

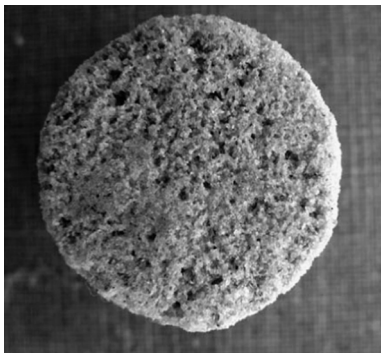### 1.4.4 Comparison of Siliciclastic and Carbonate Sediments

In siliciclastic rocks, many physical properties (elastic wave velocity, electrical resistivity, permeability) show a strong correlation to porosity. In carbonate rocks, correlations are controlled or superimposed by the heterogeneous pore distribution, pore type, pore connectivity, and grain size (Westphal et al., 2005).

Table 1.3 compares some prominent properties of the two main groups of reservoir rocks.

1.5 PHYSICAL PROPERTIES OF ROCKS—SOME GENERAL CHARACTERISTICS

The term "petrophysics" was created for physics of reservoir rocks. "'Petrophysics' is suggested as the term pertaining to the physics of particular rock types. ... This subject is a study of the physical properties of rock which are related to the pore and fluid distribution ..." (Archie (1950), the

TABLE 1.3 Some Prominent Properties of Siliciclastic and Carbonate Rocks

Clastic Rocks	Carbonate Rocks

Origin:
   Largely inorganic transported material (particles), deposited in dirty water

Largely organic material, accumulated in place, deposited in clean water

Mineral composition:
   Broad variety

Relatively simple

   Quartz, feldspar, clay minerals; minor diagenetic change

Dominant calcite and dolomite major diagenetic change

Porosity:
   Relatively simple intergranular pore structure, porosity predictable

Complex interparticle and intercrystal porosity, fractures, vugs, . . . porosity difficult to predict

Influences on porosity:
   With diagenesis and geological processes, a more complicated pore system results; it is influenced and formed by compaction, cementation, solution/dissolution, clay-filling, fracturing

With diagenesis and geological processes, a very complicated pore system results; it includes vugs, channels/caverns; it is influenced and formed by compaction, cementation, solution, grain growth, shrinking (dolomitization), cavity-filling, fracturing

pioneer in the application and quantification of rock physical relations to geosciences and petroleum engineering).

Rocks in most cases are heterogeneous composite materials; only monomineralic rocks like rock salt or anhydrite contain only one mineral type. Heterogeneity becomes more contrasted if pores and fractures, filled
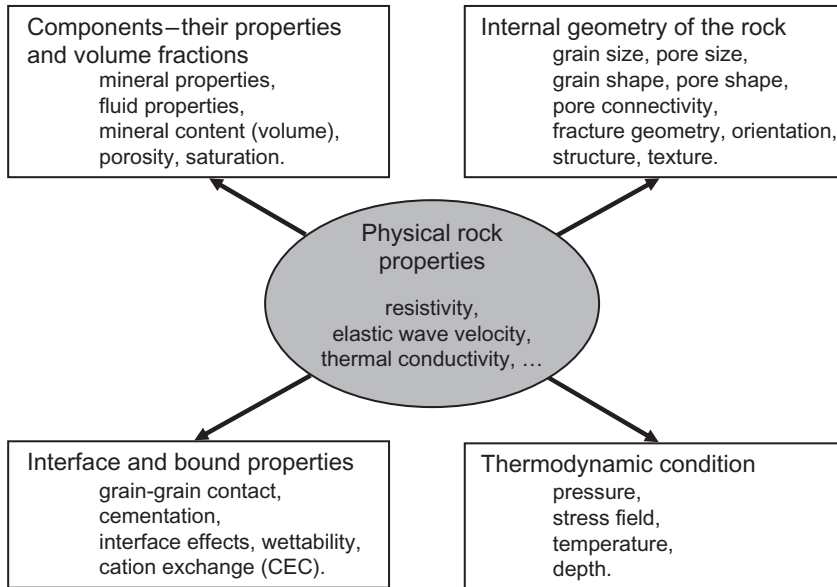
FIGURE 1.7   Rock properties and their main influence parameters and dependencies.

with fluids, are present. Mineral composition, porosity/fracturing, and internal rock structure therefore influence the physical rock properties (Figure 1.7).

On the other hand, physical rock properties (e.g., elastic, electrical, nuclear properties) can be used to characterize rocks with respect to properties and parameters of interest (e.g., reservoir properties, geomechanical properties). This leads to a classification of rock properties into the following two main groups:

- Properties of direct interest for application: reservoir properties (porosity, saturation, permeability), geomechanical properties (deformation, strength), mineralogical characteristics (shale content, fractional mineral composition), content of substances of interest (ore content);
- Properties relevant to the various geophysical methods (elastic/seismic properties, density, electrical properties, nuclear properties, nuclear magnetic resonance (NMR) response).

"Properties of interest" are subjects of interpretation of geophysical data from surface and borehole measurement. This interpretation is a process of transformation of the second type into the first using additional input information. For the transformation, relationships are applied resulting from:

- empirical correlations (e.g., Archie's equation);

TABLE 1.4 Physical Rock Properties: Classification

Type	Scalar Properties	Tensorial Properties
Properties of direct interest for reservoir and geotechnical application	Porosity Fluid saturation	Permeability Deformation modulus Strength properties
Properties measured by geophysical methods	Density	Elastic properties/wave velocities
	Nuclear cross sections (Gamma−Gamma Density, Neutronlog)	Electrical properties
	Natural Gammalog	Thermal properties
	NMR response	Magnetic properties

- model-based theories (e.g., Gassmann's equation for fluid substitution, capillary pore channel models); in most cases "theoretical" equations need an empirical modification or calibration with experimental data.

In this book, the most frequently used properties are described. For the physics behind the individual properties, it is important to characterize them with respect to their character as a "scalar property" (given as one value for the property, no directional dependence of the property) or a "tensorial property" (given as a tensor with several components with directional dependence). Table 1.4 gives an overview to the properties.

Tensorial character is relevant for rocks with an anisotropy (originated by lamination, preferred direction of fractures, grain axis or mineral orientation, etc.). The terms isotropy and anisotropy refer to directional dependence of considered (tensorial) properties. Isotropic expresses that a vectorial property has at any point the same magnitude for all directions; if the magnitude shows a directional dependence, then the material is anisotropic.

Another set of terms is important: homogeneity and inhomogeneity. Homogeneity expresses that any property (scalar or vector) is the same at different points (locations) within the volume; if the properties have different values, then the material is inhomogeneous or heterogeneous.

In rocks we find all four combinations as schematically presented in Figure 1.8.

Both anisotropy and heterogeneity are terms connected with the scale of consideration and definition of a property. A small sample size (core, plug)
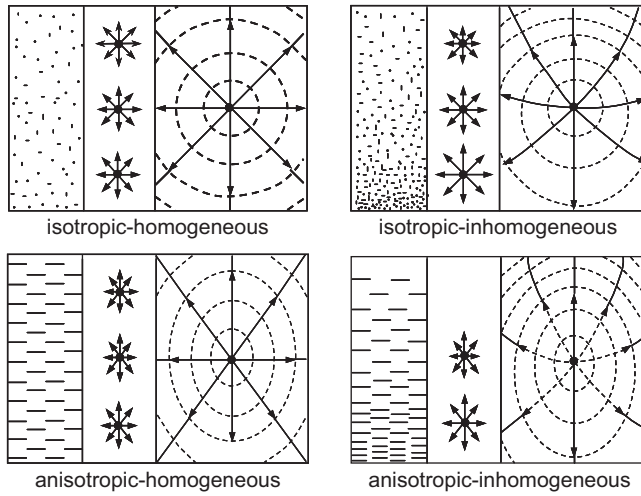
FIGURE 1.8   The categories "homogeneous−inhomogeneous" and "isotropic−anisotropic" after Gassmann (1964).

from a sandstone layer may be homogeneous, whereas a sandstone bed with variation of grain size, shale content, etc. is heterogeneous. The scale is also fundamental for anisotropy. A typical example is a laminated sand; it may be that the individual small layers are isotropic, but a section as resolved by an electrical logging tool "sees" an anisotropy (macroscopic anisotropy, see Section 8.6).