Chapter 2 Rock-Fabric Classification

2.1 Introduction

The goal of reservoir characterization is to describe the spatial distribution of petrophysical parameters such as porosity, permeability, and saturation. In Chapter 1 we showed that porosity, permeability, and fluid saturations are linked through pore size. In this chapter we will expand simple pore size to pore-size distribution, that is, the spatial distribution of pore sizes within the rock, and show how pore-size distribution can be linked to rock fabrics. Wireline logs, core analyses, production data, pressure buildups, and tracer tests provide quantitative measurements of petrophysical parameters in the vicinity of the wellbore, but they generally provide only one-dimensional spatial information. Therefore, wellbore data must be integrated with geologic models to display the petrophysical properties in three-dimensional space. Studies that relate rock fabric to pore-size distribution, and thus to petrophysical properties, are key to quantification of geologic models in numerical terms for input into computer simulators (Fig. 1).

![Fig. 2.1. Integration of spatial geologic data with numerical engineering data through rock-fabric studies](image-url)
Geologic models are generally based on observations that are interpreted in terms of depositional models and sequences. In the subsurface, cores, wireline logs, and seismic data are the main sources of information for these interpretations. Engineering models are based on wireline log calculations and average rock properties from core analyses. Numerical engineering data and interpretive geologic data are linked by rock fabrics because the pore structure is fundamental to petrophysical properties, and the pore structure is the result of spatially distributed depositional and diagenetic processes.

The purpose of this chapter is to define important geologic parameters to be described and mapped to allow accurate petrophysical quantification of carbonate geologic models by (1) describing the relationship between carbonate rock fabrics and petrophysical properties and (2) presenting a generic petrophysical classification of carbonate pore space.

2.2 Pore Space Terminology and Classification

Pore space must be defined and classified in terms of rock fabrics and petrophysical properties in order to integrate geological and engineering information. Archie (1952) made the first attempt at relating rock fabrics to petrophysical rock properties in carbonate rocks. The Archie classification focuses on estimating porosity but is also useful for approximating permeability and capillary properties. Archie (1952) recognized that not all the pore space can be observed using a 10 power microscope and that the surface texture of the broken rock reflected the amount of matrix porosity. Therefore, pore space is divided into matrix and visible porosity (Fig. 2). Chalky texture indicates a matrix porosity of about 15 percent, sucrosic texture indicates a matrix porosity of about 7 percent, and compact texture indicates matrix porosity of about 2 percent. Visible pore space is described according to pore size; A for no visible pore space and B, C, and D for increasing pore sizes from pinpoint to larger than cutting size. Porosity/permeability trends and capillary pressure characteristics are also related to these textures.

Although the Archie method is still useful for estimating petrophysical properties, relating these descriptions to geologic models is difficult because the descriptions cannot be defined in depositional or diagenetic terms. A principal difficulty is that no provision is made for distinguishing between visible interparticle pore space and other types of visible pore space such as moldic pores. Research on carbonate pore space (Murray 1960; Choquette and Pray 1970; Lucia 1983) has shown the importance of relating pore space to depositional and diagenetic fabrics and of distinguishing between
interparticle (intergrain and intercrystal) and other types of pore space. Recognition of the importance of these factors prompted modification of Archie’s classification.

**Fig. 2.2.** Petrophysical classification of carbonate pore types used in this report (Lucia 1983) compared with Archie’s original classification (1952) and the fabric selectivity concept of Choquette and Pray (1970)

The petrophysical classification of carbonate porosity presented by Lucia (1983, 1995) emphasizes petrophysical aspects of carbonate pore space, as does the Archie classification. However, by comparing rock fabric descriptions with laboratory measurements of porosity, permeability, capillarity, and Archie $m$ values, Lucia (1983) showed that the most useful division of pore types was between pore space located between grains or crystals, called interparticle porosity, and all other pore space, called vuggy porosity (Fig. 2). Vuggy pore space is further subdivided by Lucia (1983) into two groups based on how the vugs are interconnected: (1) vugs that are interconnected only through the interparticle pore network are termed separate vugs and (2) vugs that form an interconnected pore system are termed touching vugs.

Choquette and Pray (1970) discussed the geologic concepts surrounding carbonate pore space and presented a classification that is widely used. They emphasize the importance of pore space genesis, and the divisions in their
classification are genetic and not petrophysical. They divide all carbonate pore space into two classes: fabric selective and nonfabric selective (Fig. 2). Moldic and intraparticle pore types are classified as fabric selective porosity by Choquette and Pray (1970) and grouped with interparticle and intercrystalline pores. However, Lucia (1983) demonstrated that moldic and intraparticle pores have a different effect on petrophysical properties than do interparticle and intercrystalline pores and, thus should be grouped separately. Pore-type terms used in this classification are listed in Figure 3 and compared with those suggested by Choquette and Pray. Although most of the terms

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<tr>
<th>Term</th>
<th>Abbreviations</th>
<th>Lucia</th>
<th>Choquette and Pray (1970)</th>
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<td>Interparticle</td>
<td></td>
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<tr>
<td>Fracture</td>
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<td>Solution-enlarged fracture</td>
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<td>SF</td>
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<td>Fenestral</td>
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*Channel.

Fig. 2.3. Pore-type terminology used in this report compared with terminology of Choquette and Pray (1970)

defined by Choquette and Pray are also used here, interparticle and vug porosity have different definitions. Lucia (1983) demonstrated that pore spaces located both between grains (intragrain porosity) and between crystals (intercrystal porosity) are petrophysically similar, and a term is need to identify these petrophysically similar pore types. The term “interparticle” was selected because of its broad connotation. The classification of Choquette and Pray (1970) does not have a term that encompasses these two petrophysically similar pore types. In their classification, the term “interparticle” is used instead of “intragrain.”
Vuggy porosity, as defined by Lucia (1983), is pore space that is within grains or crystals or that is significantly larger than grains or crystals; that is, pore space that is not interparticle. Vugs are commonly present as dissolved grains, fossil chambers, fractures, and large irregular cavities. Although fractures may not be formed by depositional or diagenetic processes, fracture porosity is included because it defines a unique type of porosity in carbonate reservoir rocks. This definition of vug deviates from the restrictive definition of vugs used by Choquette and Pray (1970) as nondescript, nonfabric selective pores, but it is consistent with the Archie terminology and with the widespread and less restrictive use in the oil industry of the term “vuggy porosity” to refer to visible pore space in carbonate rocks.

2.3 Rock Fabric/Petrophysical Classification

The foundation of the Lucia classification, as well as of the Archie classification, is the concept that pore-size distribution, that is the spatial distribution of pore sizes within the rock, controls permeability and saturation and that pore-size distribution is related to rock fabric. In order to relate carbonate rock fabrics to pore-size distribution, it is important to determine if the pore space belongs to one of the three major pore-type classes, interparticle, separate-vug, or touching-vug. Each class has a different type of pore-size distribution and interconnection. As presented in Chapter 1, the pore size of interparticle pores is controlled by particle size and sorting, and by the volume of interparticle cement; for a given particle size and sorting the interparticle pore size will be reduced in proportion to the volume of cement. The pore size of separate vugs will vary depending upon origin and can vary from large to micro pores within grains.

2.3.1 Classification of Interparticle Pore Space

In the absence of vuggy porosity, pore-size distribution in carbonate rocks can be described in terms of particle size, sorting, and interparticle porosity (Fig. 4). Lucia (1983) showed that particle size can be related to mercury capillary displacement pressure in nonvuggy carbonates with more than 0.1 md permeability, suggesting that particle size describes the size of the largest pores (Fig. 5). Whereas the displacement pressure characterizes the largest pores sizes, the shape of the capillary pressure curve characterizes the smaller pore sizes and is dependent on interparticle porosity (Lucia 1983).
The relationship between displacement pressure and particle size (Fig. 5) is hyperbolic and suggests important particle-size boundaries at 100 and 20 microns. Lucia (1983) demonstrated that three permeability fields can be defined using particle-size boundaries of 100 and 20 microns, a relationship that appears to be limited to particle sizes less than 500 microns (Fig. 6).

These three permeability fields were based on intercrystalline porosity in dolostones primarily. Recent work that includes considerably more limestone fabrics has shown that permeability fields can be better described in geologic terms if sorting as well as particle size is considered. The approach to size and sorting used in this petrophysical classification is similar to the grain/mud-support principle upon which Dunham’s (1962) classification is built. Dunham’s classification, however, is focused on depositional texture, whereas petrophysical classifications are focused on contemporary rock fabrics which include depositional and diagenetic textures. Therefore, minor modifications must be made in Dunham’s classification before it can be applied to a petrophysical classification.

Instead of dividing fabrics into grain support and mud support as in Dunham’s classification, fabrics are divided into grain-dominated and mud-dominated fabrics based on size and sorting of grains and crystals. The volume of interparticle pore space is important because it relates to pore-size distribution.

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**FIG. 2.4.** Geological/petrophysical classification of carbonate interparticle pore space based on size and sorting of grains and crystals. The volume of interparticle pore space is important because it relates to pore-size distribution.
Fig. 2.5. Relationship between mercury displacement pressure and average particle size for nonvuggy carbonate rocks with permeability greater than 0.1 md (Lucia 1983). The displacement pressure is determined by extrapolating the capillary pressure curve to a mercury saturation of zero.

dominated; terms meant to emphasize the fabric elements that control pore size (Fig. 4). The important attributes of grain-dominated fabrics are the presence of open or occluded intergrain porosity and a grain-supported texture. The important attribute of mud-dominated fabrics is that the areas between the grains are filled with mud even if the grains appear to form a supporting framework.

Grainstone is clearly a grain-dominated fabric, but Dunham’s packstone class bridges a boundary between large intergrain pores in grainstone and small interparticle pores in wackestones and mudstones. Some packstones have both intergrain pore space and mud and some have the intergrain spaces filled with mud. The packstone textural class must be divided into two rock-fabric classes: grain-dominated packstones that have intergrain pore space or
cement and mud-dominated packstones that have intergrain spaces filled with mud (Fig. 4).

**Fig. 2.6.** Porosity-air permeability relationship for various particle-size groups in nonvuggy carbonate rocks (Lucia 1983)

### 2.3.2 Classification of Vuggy Pore Space

The addition of vuggy pore space to interparticle pore space alters the petrophysical characteristics by altering the manner in which the pore space is connected, all pore space being connected in some fashion. Separate vugs are defined as pore space that is interconnected only through interparticle pore space. Touching vugs are defined as pore space that forms an interconnected pore system independent of interparticle pore space (Fig. 7).
Separate-Vug Pore Space

Separate-vug pore space is defined as pore space that is 1) either within particles or is significantly larger than the particle size (generally >2x particle size) and 2) interconnected only through interparticle pore space (Fig. 7). Separate vugs are typically fabric-selective in their origin. Intrafossil pore space, such as the living chambers of a gastropod shell; grain molds, such as oomolds or skeletal molds; and intragrain microporosity are examples of intraparticle, fabric-selective separate vugs. Molds of evaporite crystals and fossil-molds found in mud-dominated fabrics are examples of fabric-selective separate vugs that are significantly larger than the particle size. In mud-dominated fabrics, shelter pore space is typically much larger than the particle size and is classified as separate-vug porosity, whereas in grain-dominated fabrics, shelter pore space is related to particle size and is considered intergrain porosity.

In grain-dominated fabrics, crushing of grains with large intragrain pores by overburden pressure may improve the connection between intragrain and intergrain pore space by fracturing the walls of the grains. In the extreme case the grains may be crushed beyond recognition and the distinction between intra- and inter-grain pore space blurred, in which case the grain fragments become particles of diagenetic origin. Similarly, the centers of dolomite crystals may be selectively dissolved and the skeletal dolomite
crystals crushed to form diagenetic particles composed of pieces of dolomite crystals.

Grain-dominated fabrics may contain grains with intragrain microporosity (Pittman 1971, Keith and Pittman, 1983, Moshier et al. 1988). Even though the pore size is small, intragrain microporosity is classified as a type of separate vug because it is located within the particles of the rock. Mud-dominated fabrics may also contain grains with microporosity, but they present no unique petrophysical condition because of the similar pore sizes between the microporosity in the mud matrix and in the grains.

**Touching-Vug Pore Space**

Touching-vug pore systems are defined as pore space that (1) is significantly larger than the particle size and (2) forms an interconnected pore system of significant extent (Fig. 7). Touching vugs are typically nonfabric selective in origin. Cavernous, collapse breccia, fracture, and solution-enlarged fracture pore types commonly form an interconnected pore system on a reservoir scale and are typical touching-vug pore types. Fenestral pore space is commonly connected on a reservoir scale and is grouped with touching vugs because the pore size is not related to particle size or sorting (Major et al. 1990).

Fracture porosity is included as a touching-vug pore type because fracture porosity is an important contributor to permeability in many carbonate reservoirs and, therefore, must be included in any petrophysical classification of pore space. Although fracturing is often considered to be of tectonic origin, and thus not a part of carbonate geology, diagenetic processes common to carbonate reservoirs, such as karsting (Kerans 1989), can produce extensive fracture porosity. The focus of this classification is on petrophysical properties rather than genesis, and must include fracture porosity as a pore type irrespective of its origin.

**2.4 Rock-Fabric/Petrophysical Relationships**

**2.4.1 Interparticle Porosity/Permeability Relationships**

**Limestone Rock Fabrics**

Examples of limestone rock fabrics with little vuggy pore space are illustrated in Figure 8. In grainstone fabrics (Fig. 8 A, B), the pore-size distribution is controlled by grain size and sorting and by the volume of intergrain cement, which is reflected in the amount of interparticle porosity.
Fig. 2.8. Examples of nonvuggy limestone rock fabrics. (a) Grainstone. (b) Grainstone with some separate-vug pore space. (c) Grain-dominated packstone. (d) Large grain grain-dominated packstone. (e) Mud-dominated packstone. (f) Mud-dominated packstone with some separate-vug pore space. (g) Wackestone with microporosity. (h) Scanning electron microscope photo of microporosity in a wackestone.
In grain-dominated packstones the pore-size distribution is controlled by grain size, intergrain cement, and the size and porosity of the intergrain micrite (Fig. 8 C, D). In mud-dominated packstones, wackestones, and mudstones (Fig. 8 E, F, G), the size of the micrite particles and the amount of interparticle porosity in the mud controls the pore-size distribution. The small pore size is often referred to as microporosity and is visible with a scanning electron microscope (SEM) (Fig. 8H).

Figure 9a illustrates a cross plot between air permeability and intergrain porosity for grainstones. The data are from Choquette and Steinem’s (1985) publication on the Ste. Genevieve oolite (Mississippian) and from Lucia et
al.’s (2001) publication on the Arab D (Jurassic). The grain size of the oolites ranges from 500 to 200 microns. The points on this graph are concentrated within the >100 micron permeability field. Within the grainstone field the pore size and permeability are reduced in proportion to the decrease in intergrain porosity resulting from cementation and compaction.

Figure 9b illustrates a cross plot of porosity and interparticle porosity for grain-dominated packstones. The data are from Lucia et al. (2001), Lucia and Conti (1987), and Cruz (1997). Data from the Ghawar field (Lucia et al., 2001) plot within the 20-micron to 100-micron permeability field. The fabric is a peloid grain-dominated packstone with a grain size of 150 microns to 300 microns. The volume of intergrain lime mud varies from a few percent to 40 percent of bulk volume. Data reported by Lucia and Conti (1987) from a core of Wolfcamp age in West Texas plot on the boundary between 100- to 20-micron and the <20-micron permeability fields, and are described as a fine-grained grain-dominated packstone with a grain size of 80-100 microns. Data reported by Cruz (1997) for a Cretaceous reservoir, offshore Brazil, are described as an ooid-oncoid grain-dominated packstone. The ooids are 400 microns in diameter, the oncoids 1-2 mm in diameter, and the intergrain lime mud is composed of 5-micron particles. Data from this fabric scatter about the upper limit of the 100-micron to 20-micron permeability field because of the large size of the oncoids. The grain size and volume of intergrain lime mud vary considerably within grain-dominated packstone fabrics and control the location of the data within the 100-micron to 20-micron field. Within the grain-dominated-packstone field the pore size and permeability are reduced in proportion to the decrease in interparticle porosity resulting from cementation and compaction.

Figure 9c illustrates a cross plot between air permeability and interparticle porosity from wackestones, mudstones, and mud-dominated packstones from Arab D reservoirs (Lucia et al. 2001) and unpublished data from Middle East Cretaceous reservoirs. The textures range from mudstone with an average crystal size of about 5 microns to mud-dominated packstone with peloids ranging in size from 80 microns to 300 microns. The data are concentrated in the <20 micron permeability field. The mudstones define the lower limit of this field whereas the mud-dominated packstones define the upper limit. Within the mud-dominated field the pore size and permeability are reduced in proportion to the decrease in interparticle porosity resulting from cementation and compaction.

Figure 9d illustrates a cross plot between air permeability and total porosity for North Sea coccolith chalk (Scholle 1977). The average size of the coccoliths is about 1 micron. The data points plot below the <20-micron
permeability field because the particle size is less than 5 microns, resulting in a much smaller pore size.

Figure 10 illustrates all the data for limestones compared with the permeability fields. Grainstone and mud-dominated wackestones and mud-

![Fig. 2.10. Composite porosity-air permeability cross plot for nonvuggy limestone fabrics compared with the three permeability fields illustrated in Fig. 2.6. The chalk data suggest that an additional porosity-permeability field should be added](image)

stones define reasonably well constrained permeability fields. Grain-dominated packstone fabrics plot at an intermediate location between grainstones and mud-dominated limestones. They overlap with the grainstone field when the grain size is larger than about 500 microns. Grain-dominated packstones tend to overlap with the mud-dominated field when the grains are less than 100 microns and where the distinction between grain-dominated and mud-dominated packstone is not clear. The deep sea chalks plot below the mud-dominated fabrics and define a separate porosity-permeability field.

Despite the considerable scatter in the data, grainstone, grain-dominated packstone, and mud-dominated fabrics are reasonably well constrained to the three permeability fields. Whereas grain size and sorting define the permeability fields, the interparticle porosity defines the permeability within
the field because pore size is related to the volume of interparticle pore space as well as particle size and sorting. Systematic changes in intergrain porosity by cementation, compaction, and dissolution processes will produce systematic changes in the pore-size distribution and result in systematic changes in permeability. Therefore, permeability in limestones with little vuggy porosity is a function of interparticle porosity, grain size, and sorting.

**Dolostone Rock Fabrics**

Examples of dolostone rock fabrics with little vuggy porosity are illustrated in Figure 11. Dolomitization can change the rock fabric significantly. Limestones fabrics can usually be distinguished with little difficulty. If the rock has been dolomitized, however, the overprint of dolomite crystals often obscures the precursor limestone fabric. Precursor fabrics in fine-crystalline dolostones are easily recognizable. However, as the crystal size increases, the precursor fabrics become progressively more difficult to determine.

Dolomite crystals (defined as particles in this classification) commonly range in size from several microns to >200 microns. Micrite particles are usually <20 microns in size. Thus, dolomitization of a mud-dominated carbonate fabric can result in an increase in particle size from <20 microns to >200 microns and the increase in dolomite crystal size results in a proportional increase in pore size (Fig. 11 E-H). The cross-plot of interparticle-porosity and permeability (Fig. 12a) illustrates the principle that, in mud-dominated fabrics, permeability increases as dolomite crystal size, and resulting pore size, increases. Finely crystalline (average 15 microns) mud-dominated dolostones from Farmer and Taylor Link fields (Lucia and Kerans 1992) in the Permian Basin and from Choquette and Steiner (1985) plot within the <20 micron permeability field. Medium crystalline (average 50 microns) mud-dominated dolostones from the Dune field, Permian Basin (Bebout et al. 1987) plot within the 100- to 20-micron permeability field. Large crystalline dolostones from the Haradh sector of the Ghawar field (Lucia et al. 2001) and large crystalline mud-dominated dolostones from Andrews South Devonian field, Permian Basin (Lucia 1962), plot in the >100-micron permeability field.

Grainstones are usually composed of grains much larger than the dolomite crystal size (Fig. 11 A,B) so that dolomitization does not have a significant effect on the pore-size distribution. This principle is illustrated in Figure 12b, where interparticle porosity and permeability measurements from dolomitized grainstones are cross plotted. The grain size of the dolograinstones is 200 microns. The finely crystalline dolograinstone from Taylor Link field, Permian Basin, the medium crystalline dolograinstone
Fig. 2.11. Examples of nonvuggy dolostone fabrics. (a) Medium crystalline ooid dolograinstone. (b) Large crystalline dolograinstone. (c) Fine peloid medium crystalline grain-dominated dolopackstone with poikilotopic anhydrite (white). (d) Peloid medium crystalline grain-dominated dolopackstone with poikilotopic anhydrite (white). (e) Fine crystalline dolowackestone. (f) Medium crystalline dolowackestone. (g) Large crystalline dolowackestone. (h) Large crystalline dolostone
Fig. 2.12. Porosity-air permeability cross plots of nonvuggy dolostone fabrics compared with the three permeability fields illustrated in Fig. 6. (a) Mud-dominated dolostones with dolomite crystal sizes ranging from 10 to 500 microns. (b) Dolograinstones (average grain size is 200 microns) with dolomite crystal sizes ranging from 15 to 150 microns. (c) Grain-dominated dolopackstones with fine to medium dolomite crystal sizes from Dune field, Permian Basin, and the large crystalline dolograinstone from an outcrop on the Algerita Escarpment, New Mexico, all plot within the >100-micron permeability field.

Interparticle porosity and permeability measurements from fine to medium crystalline grain-dominated dolopackstones are crossplotted in Figure 12c. The average grain size is 200 microns. The samples are from the Seminole San Andres Unit (Wang et al. 1998) and the Dune (Grayburg) field (Bebout et al. 1987), Permian Basin. The data plot in the 100- to 20-micron permeability field.

Figure 13 illustrates all dolomite data compared with permeability fields. Dolograinstones and large crystal dolostones constitute the >100-micron permeability field. Grains are very difficult to recognize in dolostones with >100 micron crystal size. However, because all large crystalline dolostones plot in the >100 micron permeability field, the precursor fabric makes little
difference petrophysically. Fine and medium crystalline grain-dominated dolopackstones and medium crystalline mud-dominated dolostones constitute the 100- to 20-micron permeability field. Fine crystalline mud-dominated dolostones constitute the <20-micron field.

Fig. 2.13. Composite porosity-air permeability cross plot for nonvuggy dolostone fabrics compared with the three permeability fields illustrated in Fig. 6

The dolostone permeability fields are defined by dolomite crystal size as well as by grain size and sorting of the precursor limestone. Within the field, pore size and permeability are defined by interparticle porosity. Systematic changes in intergrain and intercrystal porosity by dolomite cementation and by burial compaction will systematically change the pore-size distribution, resulting in a systematic change in permeability. Therefore, interparticle porosity defines the permeability within the permeability field defined by dolomite crystal size, grain size, and sorting.

**Limestone and Dolomite Comparison**

Data from limestone and dolomite rock fabrics are combined into one porosity-permeability cross plot in Fig. 14. The permeability fields are referred to as rock-fabric petrophysical class 1, class 2, and class 3. The class fields are similar to the original permeability fields, but the upper limit of the >100 micron permeability field and the lower limit of the <20 micron field
Three rock fabrics that make up the class 1 field are: (1) grainstones, (2) dolomitized grainstones, and (3) large crystalline dolostones, which may be dolograinstones, grain-dominated dolopackstones or mud-dominated dolostones. In general, grain size and crystal size increase from right to left across this field from 100 microns to 500 microns. The upper particle size limit of 500 microns is not well defined. An upper limit to this permeability field is imposed because as the particle size increases the slope of the porosity-permeability transform approaches infinity and porosity has little relationship to permeability.

Three rock fabrics make up the class 2 field: (1) grain-dominated packstones, (2) fine to medium crystalline grain-dominated dolopackstones, and (3) medium crystalline mud-dominated dolostones. Grain size of the grain-dominated packstones/dolopackstones ranges from 400 to 80 microns. Crystal sizes in the mud-dominated dolostones range from 20 to 100 microns.

Two rock fabrics make up the class 3 field: (1) mud-dominated fabrics (mud-dominated packstone, wackestone, and mudstone) and (2) fine crystalline mud-dominated dolostones. Thin section observations suggest that permeability increases as the grain content increases within this field.
Permeability Estimation

Transforms between permeability and interparticle porosity can be defined for each of the three petrophysical classes. Reduced major axis (RMA) transforms, calculated based on data presented by Lucia (1999), are presented below for each petrophysical class (Fig. 14). Although the new data presented in Fig. 14 suggest slightly different transforms, the original transforms are still useful.

Class 1  \[ k = \left(45.35 \times 10^8\right) \phi_{ip}^{8.537} \]

Class 2  \[ k = \left(2.040 \times 10^6\right) \phi_{ip}^{6.38} \]

Class 3  \[ k = \left(2.884 \times 10^3\right) \phi_{ip}^{4.275} \]

where \( k \) is permeability in md and \( \phi_{ip} \) is porosity as a fraction.

Although eight rock fabrics are divided into three petrophysical classes, in nature there is no sharp boundary between the rock fabrics. Instead, there is a continuum of grain size and sorting from mudstone to grainstone, as reflected in the proportion of mud to grains and in grain size (Fig. 15a). Similarly, there is a continuum of dolomite crystal size from 5 μm to 500 μm in mud-dominated dolostones (Fig. 15b). Therefore, there is also a complete continuum of porosity-permeability transforms within the petrophysical class fields.

To model such a continuum the boundaries of each petrophysical class are assigned a value (0.5, 1.5, 2.5, and 4) (Fig. 15c) and porosity-permeability transforms generated. These transforms, together with the three petrophysical-class transforms, were used to develop an equation relating permeability and interparticle porosity to a continuum of petrophysical classes using multiple linear regressions. The continuum of petrophysical classes is called rock-fabric numbers (rfn). The resulting global transform is given below (Lucia et al. 2001; Jennings and Lucia 2003).

\[ \log(k) = (A - B\log(rfn)) + ((C - D\log(rfn))\log(\phi_{ip})) \]

where \( A = 9.7982, B = 12.0838, C = 8.6711, D = 8.2965 \) and \( rfn \) is the rock fabric number ranging from 0.5 – 4, and \( \phi_{ip} \) is the fractional interparticle porosity.

Mud-dominated limestones and fine crystalline mud-dominated dolostones occupy rfn’s from 4 to 2.5 (Fig. 15c). The rfn decreases with
Fig. 2.15. Continuum of rock fabrics and associated porosity-permeability transforms. (a) Fabric continuum in nonvuggy limestone. (b) Fabric continuum in nonvuggy dolostone. (c) Rock-fabric numbers ranging from 0.5 - 4 defined by class-average and class-boundary porosity-permeability transforms.
increasing dolomite crystal size from 5 to 20 microns in mud-dominated dolostones and with increasing grains in mud-dominated limestones. Grain-dominated packstones, fine-to-medium crystalline grain-dominated dolopackstones, and medium crystalline mud-dominated dolostones occupy rfn’s from 2.5 to 1.5 (Fig. 15c). The rfn’s decrease with increasing dolomite crystal size from 20 to 100 microns in mud-dominated dolostones and with increasing grain size and decreasing amounts of intergrain micrite. Grainstones, dolograinstones, and large crystalline dolomites occupy rfn’s 1.5 to 0.5 (Fig. 15c). The rfn’s decrease with increasing grain size and dolomite crystal size from 100 microns to 500 microns.

As discussed in Chapter 1, Pittman (1992) and Winland (Kolodzie 1980) have published petrophysical relationships between interparticle porosity, permeability, and capillary pressure, principally for siliciclastics, but applied to carbonates as well. They conclude that pore-throat size measured at 35% mercury saturation gives the best relationship to porosity and permeability, and Pittman’s equation (1992) is presented below.

\[
\log(R35) = 0.255 + 0.565\log(k) - 0.523\log(\phi)
\]

where R35 is the pore-throat size calculated at 35% mercury saturation, k is permeability in md, and \( \phi \) is porosity. Because the published data are from siliciclastics, porosity is best considered as interparticle porosity.

The above equation is plotted in Figure 16 and compared with the petrophysical-class fields described in this report. It is apparent that Pittman’s relationship between pore-throat size, porosity, and permeability does not conform to the petrophysical classes defined in this classification. It is also apparent that, within a petrophysical class, pore-throat size decreases as interparticle porosity decreases. The eight basic rock fabrics defined here are constrained to specific petrophysical-class fields and not to a specific pore-throat size. Therefore, there is no direct link between pore size and rock fabrics in carbonate rocks.

### 2.4.2 Rock-Fabric/Porosity/Water Saturation Relationships

As stated in Chapter 1, fluid saturations are related to pore-throat size and capillary pressure (reservoir height). Several methods have been proposed for relating pore size, water saturation and reservoir height (Leverett 1941; Aufricht et al. 1957; Heseldin 1974; Alger et al. 1989). These methods equate pore size with the ratio of permeability and porosity (\( k/\phi \)) and attempt to average the capillary pressure curves into one relationship by using \( k/\phi \) as normalizing parameter. The Leverett “J” function is a common method of
Fig. 2.16. Comparison of petrophysical-class fields and pore-throat sizes versus interparticle porosity and permeability

averaging capillary pressure data. A common form of the J function is given below.

\[ J(S_w) = \left( \frac{P_c}{\sigma} \right) \left( \frac{k}{\phi} \right)^{1/2} \]

where \( P_c \) = capillary pressure in psia, \( \sigma \) = interfacial tension in dynes/cm, \( k \) = permeability in md, and \( \phi \) = fractional porosity.

The Leverett J function relates water saturation to capillary pressure, which is a function of reservoir height, and \((k/\phi)^{1/2}\), which is a function of pore size. Figure 16 suggests that pore size can be related to petrophysical class and interparticle porosity as well as to \((k/\phi)^{1/2}\). Therefore, changes in interparticle porosity within each petrophysical field represent a change in pore size, and water saturation should be related to reservoir height (H), porosity (\( \phi \)), and petrophysical class (PC).
These equations are not suitable for carbonates with large volumes of vuggy porosity, such as moldic grainstones or grain-dominated fabrics with extensive intragrain microporosity.

To quantify the saturation characteristics of the three petrophysical classes, a suite of capillary pressure curves was collected from each petrophysical class with varying values for porosity. The data includes limestones and dolostones. Curves for each class were grouped into porosity bins, and average porosity was calculated. Mercury saturation values were averaged for each injection pressure, and plots of reservoir height (capillary pressure), mercury saturation, and porosity were constructed for each class. Injection pressure was converted to reservoir height using generic values and the equations described in Chapter 1. Equations relating water saturation to porosity and reservoir height were developed using a multiple linear regression with the log of water saturation as the dependent variable and the logs of capillary pressure and porosity as independent variables. The water saturation described by these equations is the initial, or original, water saturation assuming a reservoir in drainage, not imbibition, mode.

The resulting equations are listed below and illustrated in Figure 17.

\[
Sw_i = f(H, \phi, PC)
\]

Class 1: \( Sw_i = 0.02219 \times H^{-0.316} \times \phi^{-1.745} \)

Class 2: \( Sw_i = 0.1404 \times H^{-0.407} \times \phi^{-1.440} \)

Class 3: \( Sw_i = 0.6110 \times H^{-0.505} \times \phi^{-1.210} \)

where \( Sw_i \) is the initial fractional water saturation, \( H \) is reservoir height in feet, and \( \phi \) is fractional porosity (mostly interparticle). Reservoir height can be converted to capillary pressure by \( CP = H/0.7888 \).

A fourth equation developed for rfn-4 fabrics using data from the Cretaceous Shuaiba formation in the Middle East is presented below.

\[
\text{Rfn 4 } Sw_i = 5 \times H^{-0.7} \times \phi^{-1.0}
\]

The relationship between porosity, initial water saturation and petrophysical class can be demonstrated by selecting a reservoir height of 500 ft (equates to a mercury capillary pressure of about 650 psia) and plotting saturation against porosity for each petrophysical class. The results (Fig. 18) show that, in carbonates with little vuggy porosity, a plot of porosity versus water saturation can separate the three petrophysical classes into saturation
2.4 Rock-Fabric/Petrophysical Relationships

Fig. 2.17. Initial water saturation models based on capillary pressure data for specific petrophysical classes. (a) Class 1 saturation model based on data from dolograinstones. (b) Class 2 saturation model based on data from medium crystalline dolowackestones. (c) Class 3 saturation model based on data from fine crystalline dolowackestones. (d) Class 4 saturation model based on data from microcrystalline mudstones and wackestones from Shuaiba reservoirs in the Middle East.

fields similar to permeability fields. This observation confirms the premise that both permeability and fluid saturations are controlled by pore-size distribution and that pore-size distribution can be described by rock fabric descriptions and porosity in carbonates with little vuggy porosity.

2.4.3 Rock-Fabric/Petrophysical Classes

Three rock fabric groups define the three petrophysical classes. Figure 19 illustrates the relationship between rock fabric and petrophysical classes. Grainstones, dolograinstones, and large crystalline dolostones all have similar petrophysical properties that are characterized by petrophysical class 1. Grain-dominated packstones, fine and medium crystalline grain-dominated
Fig. 2.18. Cross plot of porosity and water saturation for the three rock-fabric petrophysical classes at a reservoir height of 150 m (500 ft). Water saturation (1-Hg saturation) and porosity values are taken from capillary pressure curves illustrated in Fig. 2.17

Fig. 2.19. A block diagram illustrating the relationship between rock fabrics and petrophysical classes. There are three rock fabrics in class 1, three rock fabrics in class 2, and two rock fabrics in class 3
dolopackstones, and medium crystalline mud-dominated dolostones all have similar petrophysical properties that are characterized by petrophysical class 2. Mud-dominated limestones (mud-dominated packstone, wackestone, and mudstone) and fine crystalline mud-dominated dolostones all have similar petrophysical properties that are characterized by petrophysical class 3. The equations relating porosity, permeability, water saturation, and reservoir height (capillary pressure) are summarized below.

**Class 1**

\[
k = \left(45.35 \times 10^8 \right) \phi_p^{8.537}
\]

\[
S_{wi} = 0.02219 \times H^{-0.316} \times \phi^{-1.745}
\]

**Class 2**

\[
k = \left(2.040 \times 10^6 \right) \phi_p^{6.38}
\]

\[
S_{wi} = 0.1404 \times H^{-0.407} \times \phi^{-1.440}
\]

**Class 3**

\[
k = \left(2.884 \times 10^3 \right) \phi_p^{4.275}
\]

\[
S_{wi} = 0.6110 \times H^{-0.505} \times \phi^{-1.210}
\]

Global permeability transform

\[
\text{Log}(k) = \left( A - B \text{Log}(rfn) \right) + \left( C - D \text{Log}(rfn) \right) \text{Log}(\phi_p)
\]

### 2.4.4 Petrophysics of Separate-Vug Pore Space

The addition of separate-vug porosity to interparticle porosity alters the petrophysical characteristics by altering the manner in which pore space is connected, all pore space being connected at some level. Examples of separate-vug pore space are illustrated in Figure 20. Separate vugs are not connected to each other. They are connected only through the interparticle pore space and, although the addition of separate vugs increases total porosity, it does not significantly increase permeability (Lucia 1983). Figure 21a illustrates this principle. Permeability of a moldic grainstone is less than would be expected if all the total porosity were interparticle and, at constant porosity, permeability increases with decreasing separate-vug porosity (Lucia and Conti 1987). The same is true for a large crystalline dolowackestone (Fig. 21b) in that the data plot to the left of the class 1 field in proportion to the separate-vug porosity (Lucia 1983). The same principle is illustrated by
Fig. 2.20. Examples of separate-vug pore types. (a) Oomolds in oomoldic grainstone. (b) Oomolds and intergrain pore space in a grainstone. (c) Intrafossil pore space in a fusulinid grain-dominated packstone. (d) Intrafossil pore space in a foram with a large opening to interparticle pore space. (e) Skeletal grain molds in moldic skeletal grainstone. (f) Grain molds in a wackestone. (g) Ooid grainstone with intragrain microporosity. (h) Scanning electron photomicrograph of intragrain microporosity showing micropores in a 5-micron rhombic calcite matrix.
Fig. 2.21. Cross plot illustrating the effect of separate-vug porosity on air permeability. (a) Grainstones with separate-vug porosity in the form of grain molds plot to the right of the grainstone field in proportion to the volume of separate-vug porosity. (b) Grainstones with intrafossil and intragrain microporosity plot in the class 2 field when plotted against total porosity. (c) Dolograinstones with intragrain microporosity plot in the class 2 field. (d) Grainstones with intragrain microporosity plot in the class 3 field.

Data from an Eocene grainstone described by Budd (2002). Interparticle porosity is estimated from thin section by detailed point counts. The data plots in the class 1 field when interparticle porosity is used and in the class 2 field when total porosity is used (Fig. 21c). In this example, total porosity includes intrafossil, intragrain microporosity, and intergrain pore types. An ooid grainstone from a Cretaceous reservoir, offshore Brazil (Cruz 1997) is composed of some intergrain porosity and considerable intragrain microporosity (Fig. 21d). The data plot in the class 3 field and below because intergrain porosity is very low.

Initial water saturation in carbonates with separate vugs depends upon the interparticle pore size and, in grain-dominated fabrics, the size of the pores connecting the separate-vug and interparticle pore space. The pores in intragrain microporosity are small, and the connection to interparticle pore
space is always through microporosity. Grain molds and intrafossil vugs are usually large and the connection depends upon the size of the pore space in the rim surrounding the grain mold or fossil chamber. Pore spaces within gastropods and forams are usually large and have some large openings to the intergrain pore space. Grain molds, such as oomolds, are normally rimmed by microporosity, unless the grains have been dolomitized, in which case the rimming pore size will depend upon the dolomite crystal size. Overburden crushing of grains can produce microfractures that enhance the connection between grain molds and interparticle pores.

An example drainage capillary pressure curve from an oomoldic limestone (Fig. 22a) shows that the pores connecting the grain molds to the

---

**Fig. 2.22.** Capillary pressure curves illustrating the effect of separate vugs on capillary properties. (a) High-porosity, low-permeability oomoldic grainstone with little intergrain pore space. Most of the curve reflects entry into the large oomolds through micro pores lining the oomolds. (b) High-porosity, low-permeability ooid grainstone with intragrain microporosity. Most of the curve reflects entry into the micropores located within the grains. (c) Grainstone with a high intergrain porosity
2.4 Rock-Fabric/Petrophysical Relationships

interparticle pores are very small. However, once a capillary pressure (reservoir height) is obtained that will force oil into the molds, the molds rapidly become oil saturated. Within the transition zone the oil will be concentrated in the interparticle pores and grain molds with water saturation concentrated in the small connecting pores.

The distribution of initial water saturation in intragrain microporosity is different because of small pore sizes. Example capillary pressure curves from grainstones with significant amounts of intragrain microporosity (Fig. 22b) show that considerable amounts of water can be trapped water within the grains by capillary forces within the transition zone. Initial oil saturation is concentrated in the intergrain pore spaces, and water is concentrated in the intragrain microporosity. Within the transition zone, this fabric will be characterized by high initial water saturation trapped by capillary forces within the grains and producible hydrocarbons in the intergrain porosity. This results in the possibility of having water-free production in an interval that calculates high water saturation (Pittman 1971; Dixon and Marek 1990).

An example capillary pressure curve from a grainstone with intergrain porosity, intragrain microporosity, and crushed intrafossil pores shows little effect of the intrafossil porosity on initial water saturation because it is connected to the intergrain pores by microfractures and large openings typical of gastropods and forams. The water is trapped primarily in the intragrain microporosity (Fig. 22c).

2.4.5 Petrophysics of Touching-Vug Pore Space

Examples of touching-vug pore types are illustrated in Figure 23 and have little relationship to rock fabrics. Touching vugs can increase permeability well above what would be expected from the interparticle pore system. Lucia (1983) illustrated this fact by comparing a plot of fracture permeability versus fracture porosity to the three petrophysical fields (Fig. 24). This graph shows that permeability in touching-vug pore systems cannot be characterized by rock fabrics or petrophysical classes.

Estimating the permeability of touching-vug systems is difficult because the pores are often larger than the well bore. The best information about flow properties comes from production data. In general, core measurements are not meaningful because of the large size of most touching-vug systems. The core analysis of the cavernous core from northern Michigan (Fig. 23A) reports a permeability < 0.1 md, which is clearly not a useful value. However, the permeability of small touching-vug fabrics composed of microfractures and grain molds can be measured by routine methods. Porosity-permeability cross-plots from two microfracture fabrics are illustrated in
Fig. 2.23. Touching-vug pore types: (a) Cavernous pore space in a Niagaran reef, northern Michigan. (b) Cavernous pore space in Miami oolite, Florida. (c) Solution-enlarged fractures with saddle dolomite, Ellenburger, West Texas. (d) Solution-enlarged fracture, Permian, West Texas. (e) Fenestral pore space, Permian, West Texas. (f) Microfractures connecting grain molds in a wackestone, Cretaceous, Qatar. (g) Microfracturing and collapse of a fusumold, Permian, West Texas.
Figure 25 and suggest a permeability enhancement of 5x to 10x over what would be expected from a simple interparticle pore system (Lucia and Ruppel 1996).

![Theoretical fracture air permeability-porosity relationship compared to the rock-fabric/petrophysical porosity, permeability fields (Lucia 1983). W = fracture width, Z = fracture spacing](image)

**Fig. 2.24.** Theoretical fracture air permeability-porosity relationship compared to the rock-fabric/petrophysical porosity, permeability fields (Lucia 1983). W = fracture width, Z = fracture spacing

![Illustrations of permeability enhancement due to microfractures. (a) A factor of 5 permeability enhancement due to microfracturing of a mud-dominated limestone. (b) A factor of 5 permeability enhancement in a class 2 medium crystalline dolowackestone due to microfractures connecting fusumolds](image)

**Fig. 2.25.** Illustrations of permeability enhancement due to microfractures. (a) A factor of 5 permeability enhancement due to microfracturing of a mud-dominated limestone. (b) A factor of 5 permeability enhancement in a class 2 medium crystalline dolowackestone due to microfractures connecting fusumolds
There is no hard data on saturation characteristics of large touching vugs. It is thought that large touching vugs most likely have initial water saturations near zero. The initial water saturation of the microfracture fabrics, however, is probably similar to matrix saturation values because the microfractures occupy a small percentage of the pore volume.

2.5 Summary

The goal of reservoir characterization is to describe the spatial distribution of petrophysical parameters such as porosity, permeability, and saturation. In Chapter 1 we showed that permeability and water saturation are controlled by pore size. The rock fabric approach presented here is based on the premise that pore size and pore-size distribution can be expressed in terms of particle size, sorting, interparticle porosity, and separate vug porosity. Therefore, pore-size distribution is related to rock fabric, a product of geologic processes. Thus, rock fabric integrates geologic interpretation with engineering numerical measurements.

To determine the relationships between rock fabric and petrophysical parameters it is necessary to define and classify pore space as it exists today in terms of petrophysical properties. This is best accomplished by dividing pore space into pore space located between grains or crystals, called interparticle porosity, and all other pore space, called vuggy porosity. Vuggy pore space is further subdivided into two groups based on how the vugs are interconnected: (1) vugs that are interconnected only through the interparticle pore network are termed separate vugs and (2) vugs that are in direct contact with each other are termed touching vugs.

The petrophysical properties of interparticle porosity are related to particle size, sorting and interparticle porosity. Grain size and sorting of grains and micrite is based on Dunham’s classification, modified to make it compatible with petrophysical considerations. Instead of dividing fabrics into grain support and mud support, fabrics are divided into grain-dominated and mud-dominated. The important attributes of grain-dominated fabrics are the presence of open or occluded intergrain porosity and a grain-supported texture. The important attribute of mud-dominated fabrics is that the volume between the grains is filled with mud even if the grains appear to form a supporting framework.

Grainstone is clearly a grain-dominated fabric, but Dunham’s packstone class bridges an important petrophysical boundary. Some packstones, as we see them now, have intergrain pore space, and some have the intergrain spaces filled with mud. Therefore, the packstone textural class must be
divided into two rock-fabric classes: grain-dominated packstones that have intergrain pore space or cement as well as intergrain mud, and mud-dominated packstones where the intergrain spaces are filled with mud.

The important fabric elements to recognize for petrophysical classification of dolomites are precursor grain size and sorting, dolomite crystal size, and intergrain/intercrystal porosity. Important dolomite crystal size boundaries are 20 and 100 microns. Dolomite crystal size has little effect on the petrophysical properties of grain-dominated dolostones. The petrophysical properties of mud-dominated dolostones, however, are significantly improved when the dolomite crystal size is >20 microns.

Permeability and saturation characteristics of interparticle porosity can be grouped into three rock-fabric/petrophysical classes. Class 1 is composed of grainstones, dolograinstones, and large crystalline dolostones. Class 2 is composed of grain-dominated packstones, fine to medium crystalline grain-dominated dolopackstones, and medium crystalline mud-dominated dolostones. Class 3 is composed of mud-dominated limestone and fine crystalline mud-dominated dolostones.

Generic permeability transforms and initial water saturation, porosity, reservoir-height equations for each rock-fabric/petrophysical class are presented below. The $S_{wi}$ equations are valid only when little vuggy porosity is present.

Class 1 - Grainstones, dolograinstones, and large crystalline dolostones.

\[
k = \left(45.35 \times 10^8 \right) \phi_p^{8.537}
\]

\[
S_{wi} = 0.02219 \times H^{-0.316} \times \phi^{-1.745}
\]

Class 2 - Grain-dominated packstones, fine and medium crystalline grain-dominated dolopackstones, and medium crystal mud-dominated dolostones.

\[
k = \left(2.040 \times 10^6 \right) \phi_p^{6.38}
\]

\[
S_{wi} = 0.1404 \times H^{-0.407} \times \phi^{-1.440}
\]

Class 3 - Mud-dominated limestones and fine crystalline mud-dominated dolostones.

\[
k = \left(2.884 \times 10^3 \right) \phi_p^{4.275}
\]

\[
S_{wi} = 0.6110 \times H^{-0.505} \times \phi^{-1.210}
\]
The three permeability transforms together with transforms describing the boundary of the petrophysical classes are combined into a global porosity-permeability transform presented below. Petrophysical class is replaced with a continuum of rock-fabric numbers (rfn).

\[
\log(k) = (A - B\log(rfn)) + ((C - D\log(rfn))\log(\phi_p))
\]

where \(A = 9.7982, B = 12.0838, C = 8.6711, D = 8.2965\) and \(rfn\) is the rock fabric number ranging from 0.5 – 4, and \(\phi_p\) is the fractional interparticle porosity.

The addition of separate-vug porosity to interparticle porosity increases total porosity but does not significantly increase permeability. Therefore, it is important to determine interparticle porosity by subtracting separate-vug porosity from total porosity and using interparticle porosity to estimate permeability. The effect of separate vugs on permeability and initial water saturation depends upon the size of the pores connecting the intra- and intergrain pore space.

Large separate vugs are normally filled with hydrocarbons above the transition zone. Intragrain microporosity will contain significant amounts of capillary-bound water within the transition zone, resulting in water-free production of hydrocarbons from intervals with high initial water saturations. The transition zone for grainstones with large volumes of separate vugs will be greater than that expected for a nonvuggy grainstone.

Touching-vug pore systems cannot be related to porosity but are related to the geometry of fracture pore space, large vugs, and collapse breccia. These pore systems are normally larger than the well bore and cannot be adequately studied using cores. Small touching-vug systems formed by microfractures and grain dissolution connecting grain molds can be characterized by core measurements. These systems enhance permeability 5x to 10x over that expected from matrix permeability.

The key to constructing a geologic model that can be quantified in petrophysical terms is to select facies or units that have unique petrophysical qualities for mapping. In non-touching vug reservoirs (matrix reservoirs), the most important fabric elements to describe and map are 1) grain size and sorting using the modified Dunham classification, 2) dolomite crystal size using 20 and 100 microns as size boundaries, 3) interparticle porosity, 4) separate-vug type with special attention to intragrain microporosity, and 5) separate-vug porosity.

In touching-vug reservoirs, characterizing the pore system is difficult because the pore system is not related to a precursor depositional fabric but is usually wholly diagenetic in nature. Whereas it may conform to bedding, as
in the case of evaporite collapse brecciation and associated fractures, it more often cuts across strata. However, recognition of the presence of a touching-vug pore system is paramount because it may dominate the flow characteristics of the reservoir.

Three basic steps in predicting the spatial distribution of petrophysical properties are 1) developing predictable models relating rock fabrics to petrophysical properties as described in this chapter, 2) describing the one-dimensional distribution of rock fabrics and petrophysical properties from core and wireline log data, and 3) extrapolating this information in three dimensions using geologic processes and stratigraphic principles. In the next chapter we will discuss describing rock fabrics and petrophysical properties in one dimension using core and wireline log data.

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