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Introduction

The relatively new scientific field of Geological Fluid Mechanics is concerned with applying the principles of fluid mechanics to the geological sciences. It is characterized by close interaction between carefully conceived laboratory measurements on geological flows and theoretical analyses that interpret the results in terms of basic physical principles. It was given this name by Herbert Huppert in Cambridge, one of its leading practitioners in a company that includes Andrew Woods, also in Cambridge, George Veronis at Yale, Stewart Turner at ANU, Canberra, and many other technically powerful and imaginative scientists. This present book concentrates on the part of Geological Fluid Mechanics that involves the flow of passive and reacting fluids through porous or fractured geological media. In our planet, both hot and cold aqueous fluids have flowed or seeped through sand and fractured rocks for eons, modifying their composition by dissolution, chemical reaction and deposition. Great crystalline formations and mineral deposits were formed by nature during that time and modifications continue naturally. The study of these processes was always an interesting intellectual challenge, but one of no particular urgency. Yet within a couple of lifetimes the pace of change has exploded as a result of human activity.

The contamination of our aquifers, and in turn the rivers and estuaries into which the groundwater flows, is the result of both deliberate and inadvertent injection of a variety of human, agricultural and industrial wastes, but our knowledge of the extent of these changes is meager. How long does it take for the contaminants to build up, where do they go and, if we remove the source, how long will it take for the contamination to flush out? What happens to the effluents from coal mines and paper mills, that are dumped into streams? Nuclear power plants help to satisfy our gluttonous appetite for energy without generating the primary greenhouse gas, carbon dioxide, but the bargain is Faustian – high-level, long-lived radioactive wastes are being stored on site at the nuclear power plants that generated them.

The long-term disposal of these wastes requires that they be removed from human contact for times much longer than all of human history.

Geological fluid dynamics is concerned with how these natural systems work, with their patterns of flow and chemical reaction in a variety of geological media, whether sandy aquifers, layered sediments or mosaics of fractured rocks. The first geological fluid dynamicist was probably Henry Darcy (1803–58), although he certainly did not think of himself as such. A very accomplished hydraulic engineer, he worked on the Dijon water supply for a number of years, and towards the end of his life, he and two assistants conducted a series of hydraulic experiments on the flow of water through a vertical column partially filled with siliceous sand from the Saone River and a flow of water from the Dijon hospital water supply. The volume flux of water was measured in a gauging station, the pressure difference across the sand bed was measured by using two mercury U-tube manometers, and he found a very accurate linear relation between the two. His work was published as an appendix to his extensive report (Darcy, 1856) on the public fountains of the city of Dijon.

Darcy's study exemplifies the three essential ingredients in the scientific exploration of the nature of this world about us. The explorer needs to have (i) a detailed and soundly based understanding of the basic rules, the "laws of nature" under which the flows operate, (ii) a continuing contact with physical reality and familiarity with the results of whatever careful experiments, observations and detailed measurements that have been made on these flows, and (iii) the ability to put the two together. Darcy obviously knew a lot about hydraulics, he performed the experiment himself and he made the critical quantitative connection between flow rate and pressure gradient.

In more recent times and on a larger scale we can discern these same three attributes that have guided the remarkable progress during the past 50 years of our sister science, Meteorology. The "laws of nature" that govern the motion and properties of the atmosphere are essentially the same as those outlined in the next chapter of this book, the conservation laws of thermodynamics, of Newtonian continuum dynamics, of chemical reactions, etc., supplemented in the atmosphere by the laws of radiation. The "physical reality" is the atmosphere itself, in constant motion and burdened by its increasing load of carbon dioxide and other greenhouse gases. Measurements of atmospheric pressure and temperature have been made for over 200 years, but the pace increased in the 1970s when the Global Atmospheric Research Program (GARP) stimulated a vast increase in the systematic observation, measurement and monitoring of the atmosphere that continues today. This in turn provided a strong stimulus to the development of "super-computers" that were needed to handle the new floods of data and the numerical models of large-scale atmospheric motions being developed by Jules Charney and others. New techniques were developed at the National Center for Atmospheric Research in Boulder, Colorado, for airborne measurements while remote sensing systems such as the atmospheric radar of David Atlas at NASA were becoming able to scan for clouds, rain and atmospheric motions over larger and larger volumes of the atmosphere. Today, on the evening TV weather report we see marvelous real-time, data-based computer simulations of local and regional weather that are vivid, ongoing and generally accurate. We receive warnings of rain tomorrow and impending dangers such as hurricanes a thousand miles away.

In contrast, the quantitative base of data in the geological sciences is much more sparse. It is probably safe to assert that more atmospheric measurements are made every day, than have been made on geological flows in all of recorded history. Subterranean flow measurements are difficult and expensive to acquire by drilling and the data are sometimes classified for commercial reasons. The medium is solid, often hard, opaque, and complex in structure and composition. Seismic techniques are able to delineate internal structures, but most of the information that we have still comes from surface exposures and patterns of seepage. As a result of all these factors, the quantitative measurements that we do have are extremely valuable but still severely limited in number and scope. Particularly notable are the recent measurement programs on the dispersal of tagged fluids in aquifers, conducted mainly by the US and state Geological Surveys and their analogs in Europe. These have generated a leap forward in our understanding of the structure of the variations in permeability in sandy substrates and the spatially random flow field that percolates through them.

The relative paucity of field data on geological flows presents a mis-match with the power and sophistication of modern digital computers. With few exceptions, numerical simulations of geological flows have little measured data input, or quantitative comparison between the computer output and field measurements. Parameters can be chosen without observational or experimental basis, but simply to make the output "seem reasonable," i.e. to be in accord with preconceptions. Though often presented as factual, and generating their own air of reality, these simulations are often quite misleading, and no more than digitally precise renditions of a mostly imaginary world. There is little doubt that a more fruitful approach would include the development of relatively simple models with several essential ingredients: (i) the powerful but often neglected physical constraints such as minimum dissipation, (ii) the use of measured parameters, (iii) the pertinent physical and chemical balances involved and (iv) the flexibility for application to a variety of possible structural configurations. The results must then be evaluated critically by comparison with whatever laboratory or field data that does exist.

In the next chapter of this book, the general geometrical characteristics of permeable media are described, together with the basic physical and chemical balances that underlie the developments that follow. Two important general theorems concerning uniqueness and minimum dissipation, dating from the nineteenth century and often overlooked, provide useful insights into the structure of constant density flows in complex regions with variable matrix permeability. The first part of Chapter 3 is a brief summary of some "classical" porous media flows, the basic concepts of groundwater age and the various time scales for aquifer flows. Recent measurements have shown that the spatially random, horizontally isotropic permeability structure of a nominally uniform sandy aquifer is associated with highly *anisotropic* dispersive characteristics of dissolved contaminants. Dissolved solutes in fracture–matrix media disperse rapidly in the longitudinal direction, but much more slowly in transverse directions. These findings can be understood best in terms of the minimum dissipation constraint. Unsteady flows are also of interest. Pressure pulses from explosions and seismic eruptions spread rapidly at acoustic speeds, but the residual pressure then relaxes diffusively as interstitial gas and liquids present flow out of fractured porous rock in seeps or geysers, at a rate that diminishes in time.

Chapter 4 describes the nature of buoyancy-driven flows from convection plumes to freshwater wedges and gravity currents. These flows are qualitatively different from uniform-density flows and characteristically possess circulation in the transport velocity field. In a given geological structure, the flow patterns are no longer unique, which raises the possibility of instability and spontaneous evolution of one flow pattern into another. The archetypical thermal instability is associated with the name of Rayleigh (1916) and, since then, many variations of the basic theme have been discovered that depend on the different rates of diffusion of heat and dissolved salts in permeable media. These instability processes have been found in laboratory measurements, in contemporary natural flows and their traces left in ancient rocks.

Chapter 5 synthesizes these flow patterns with the patterns of reaction, deposition and dissolution that the flow produces when the interstitial fluids and the matrix interact chemically. There are three dominant flow-mediated reaction scenarios, reaction fronts, gradient reactions and mixing zones, each of which has characteristic patterns of occurrence. In many geological scenarios, the rates of reaction may be limited by the rate at which the flow can deliver dissolved solutes to the reaction site. When dissolved contaminants in a surface aquifer are absorbed into, or react with, the enclosing matrix, a patch of contaminant moves considerably more slowly than does the interstitial fluid, centimeters per day, perhaps. An extreme situation is found when the reaction involves replacement and the solutions are dilute compared with the mass per unit volume of the solid reactant. The propagation speed of a reaction front may be smaller than the interstitial fluid velocity by *many* orders of magnitude, possibly being only a few centimeters per millennium. Application of these concepts and results can illuminate not only the formation of mineral deposits in paleogeologic time, but also also the accumulation, transport and dispersal of dissolved contaminants in present-day aquifers.

2

The basic principles

2.1 Pores and fractures

The geological materials with which we are concerned usually lie at one extreme of the range of "porous media" encountered in nature and technology. The porosity, the volume fraction of connected voids that allow fluid movement, may be as large as 0.3 or 0.4 in a well-sorted sandbank or as small as 1% in natural calcite (Pryor, 1973). The skeletal remains of corals that abound in tropical reefs contain myriad interstices on scales of up to a centimeter or so and may have a similarly large porosity; Figure 2.1 shows a sample from Bermuda at approximately half-scale. This kind of structure containing fluid conduits as well as more numerous smaller pores is at the high-porosity extreme of those generally encountered. Compaction by overlying sediments, the infilling of interstices by finer grains, and the precipitation of cements from solution can reduce the porosity by an order of magnitude and reduce the permeability, as we shall see, by three orders of magnitude or more.

Many large pores are also apparent in dolomite from the Latemar Massif in northern Italy (Figure 2.2). Calcium ions from the original calcite mineral have been replaced by magnesium, generating dolomite. The specific volume of the dolomite produced in the reaction is less by 3–13% than that of the original calcite, so that as the reaction proceeded, the porosity increased.

Networks of small cracks or fractures allow fluid percolation even when the matrix itself is relatively impermeable. Seepage from fractures can often be discerned in roadside rock exposures. Figure 2.3 illustrates a smaller-scale network in a sandstone cleavage plane, made visible by stain. Stained fluid moves relatively rapidly through the fracture network but spreads laterally into the matrix blocks only slowly. Note the progression of wider, older stains passing through the whole sample, from which spring shorter, narrower and newer branches.

Fault systems also provide conduits for fluid motion. Even a cursory glance at many field exposures often reveals layers of quartz or other minerals apparently

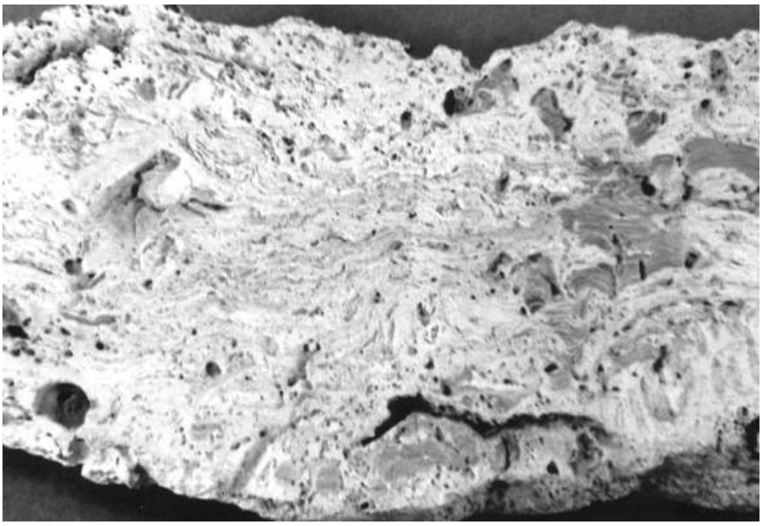

Figure 2.1. An extremely porous limestone from a Bermuda coral reef, approximately half-scale, containing shell fragments and many interstices with scales of up to a centimeter or so, courtesy of Professor L. Hardie.

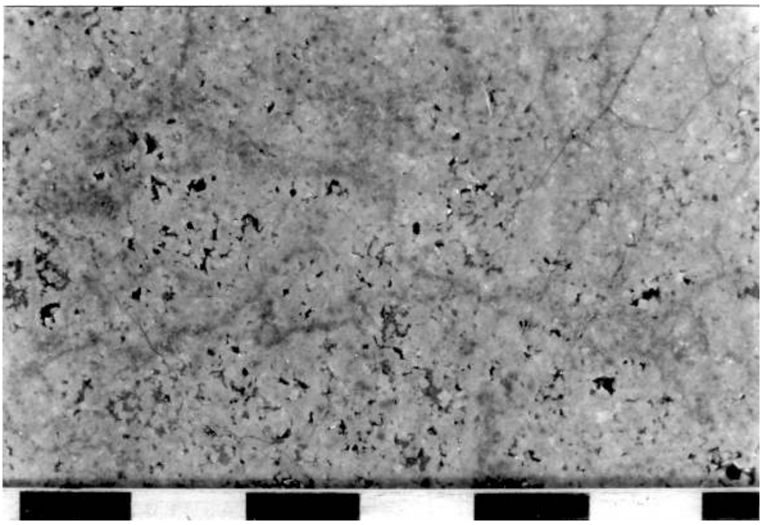

Figure 2.2. Pores in dolomite from the Latemar Massif in northern Italy. The blocks in the scale are 1 cm long. (Photograph courtesy of Dr. E. N. Wilson.)

deposited along fractures in a larger matrix. Figure 2.4 shows a mosaic of small scale fractures that have served as pathways for fluid motion until becoming filled by deposition from the infiltrating solution, with subsequent fractures appearing later.

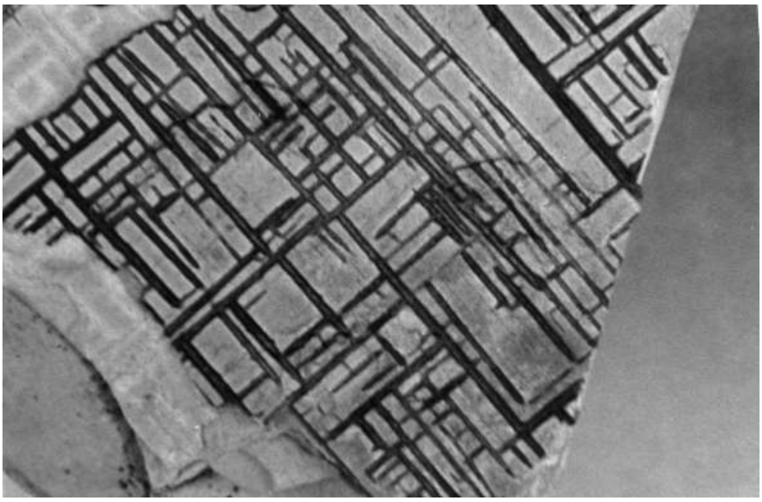

Figure 2.3. A network of plane fractures provided pathways for the flow of dyed fluid in a sandstone cleavage plane, which then diffused into the matrix blocks, courtesy of Professor L. Hardie. Approximately full scale.

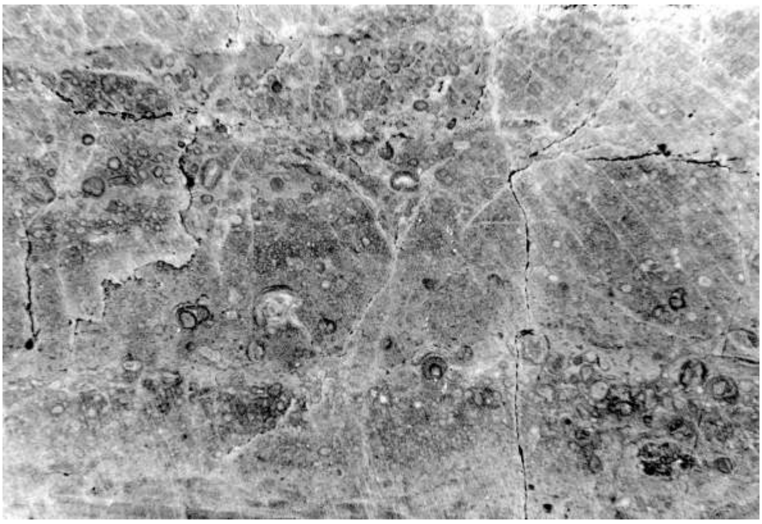

Figure 2.4. In this calcite block, previous fractures have been filled with dolomite, while more recent fractures remain partially open.

2.2 Geometrical characteristics

2.2.1 Porosity

A number of geometrical length scales are pertinent to flow through permeable rocks and aquifer matrices. In aqueous solutions, the intermolecular or inter-ionic distances are of order 10^{-9} m, while the scale of the smallest interstices of hydrological interest is possibly 1000 times larger, i.e. 1 micron or more. As a result, the fluid can be regarded as a continuum whose motion through the passages of the medium can be described in terms of the concepts and equations of continuum fluid mechanics. The photographs of the previous section indicate that in porous limestone or partly cemented sandstone, the characteristic diameter δ_0 of the orifices or interstices may be as large as 10^{-4}–10^{-3} m, with a relative few even larger. In sand, the distance between the individual flow paths, the diameter of the interstices and the grain size are all comparable. In more consolidated rocks and granites, however, the size of the interstices is characteristically much smaller than the microscale distance l_0 between them. Media may also be extensively fractured on scales from 10^{-2} to 10 m (see Figure 2.3) and such fracture networks are potentially important flow conduits. Sedimentary deposits are frequently bedded, with local variations in physical properties such as the porosity and permeability occurring over vertical scales that are large compared with the grain size but small compared with the overall thickness of the bed. Finally, there are the macroscopic length scales h, which specify the thickness (or smallest dimension) of the porous bed as a whole, and l, its lateral extent.

In order to relate the overall flow behavior to the average geometrical characteristics of the rocks, we must consider carefully certain statistical aspects of the microscopic flow through individual pores or regions of inhomogeneity, as in Section 2.10 below. Our primary concerns are with flow patterns and velocities, with the transports of heat and chemical solutes on the scale of structural variations or on the macroscopic length scale h of the structure itself. Immense simplifications are possible when the microscale l_0 is sufficiently small compared with h that we can find an intermediate local scale, the matrix averaging scale l_{AV}, that is large compared with the grain or matrix block size l_0 yet small compared with the scale h of the flow patterns that we wish to resolve. Thus we require that

$$\delta_0 \le l_0 \ll l_{AV} \ll h, \tag{2.1}$$

where, as a rule of thumb, the $\ll$ inequality signs can be interpreted to mean "is less by a factor of at least 10 than." Within a given stratum, properties of the medium and characteristics of the flow through it, when averaged over the volume l_{AV}^3 are expected to vary smoothly from one averaging volume to the next. When the system is viewed on a macroscopic scale, it can again be regarded as a continuum, with the "point" properties being, in fact, local averages of this kind, functions of three spatial coordinates (x, y, z) and possibly time t.

When the locally averaged properties of the medium are independent of the position of the averaging volume, the medium is said to be homogeneous. If all locally averaged properties are independent of direction, the medium is described as locally isotropic. A well-mixed sand bed may be, on this averaging scale, both homogeneous and locally isotropic. As mentioned previously, however, sediments are frequently deposited in such a way that the fabric preserves a record in its layering of the vertical direction, though there may be no differences discernible in the two orthogonal horizontal directions. Seasonal variations in sedimentation rate may produce, on a microscopic scale, a stack of horizontal laminations that, on a macroscopic scale, lead to different percolation characteristics along and across the laminations. Similarly, when elongated or plate-shaped sedimenting particles tend to settle horizontally, the resulting fabric will preserve a record of the vertical direction at the time of deposition. In general, when the medium has one preferred direction but its properties are independent of rotation about that direction, it can be described as locally axi-symmetrical. In spite of these caveats, a uniform sandbank does provide the basic prototype of a classic hydrodynamical porous medium, whose essential geometry, involving a three-dimensional web of minute intersecting fluid pathways, is found in many porous rocks and other geologic media at different scales and with different detailed topologies. It is convenient to call these “sandbank-type” media to distinguish them from the fracture–matrix media described later, which obey the same basic conservation laws but whose geometry gives them quite different flow characteristics.

An important characteristic of a porous rock is the void fraction. The total void fraction ϕ_T is that fraction of the total averaging volume represented by the interstices; the solids occupy a fraction $1 - \phi_T$ of the whole. This can be measured by an examination of randomly taken thin sections; since a volumetric sample can be considered to be a stack of plane slices, the ratio of void area to total area in a typical thin section is equal to the ratio of void volume to total volume, ϕ_T. Similarly, along a sampling line the average ratio of total length of the line segments in voids to total line length is also ϕ_T. However, not all of the void spaces may be active in fluid flow through the medium. Isolated cavities or “dead end” tubes can contribute to ϕ_T but do not provide microscopic pathways to fluid motion. A more significant measure for our purposes is the connected porosity ϕ, in which only those voids that provide connections among the averaging volumes are considered. In general, this quantity cannot be estimated from thin-section examination without some additional information or assumption about the structure of the fabric, but it can be measured by comparison of the mass of saturated and dried samples or, as we shall see in the next section, by fluid observations. In this book, the term “porosity” refers to the connected porosity, since this is the property of interest in fluid motion, though in the petroleum industry it is commonly used as a synonym for “void fraction.”

Clearly, $\phi \leq \phi_T < 1$. At one extreme, in a material with the geometry of Swiss cheese, such as pumice, all the voids are isolated so that $\phi = 0$ while ϕ_T may