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REVIEWS

Flow and Reactions in Permeable Rocks. By O. M. PHILLIPS. Cambridge University Press, 1991. 285 pp. £40.

Generations of graduate students with an interest in oceanography have gleaned part of their subject from the author's famous book *The Dynamics of the Upper Oceans* (reviewed by J. W. Miles in *J. Fluid Mech.* vol. 29, 1967, pp. 822–825, and, on the appearance of the second edition, in vol. 88, 1978, pp. 793–796). Those with catholic reading tastes also will have read, and been enlightened by, *The Last Chance Energy Book*. The present book, which is on yet another subject, may prove to be as influential as the first-mentioned book, and is written with the same scintillating style used in these earlier books and in the numerous innovative research papers that have flowed from the author's pen for almost forty years.

The last decade or so has seen considerable excitement develop in aspects of geology that have become more quantitative, and many new intellectually challenging research areas are beginning to emerge. There are now several groups around the world investigating fluid mechanical aspects of the multi-disciplinary problems in igneous (or hard rock) geology. The aim of this book is to build a foundation for part of the fluid mechanical investigations suggested by sedimentary (or soft rock) geology. Thus, as the title indicates, the book deals with flows (generally of water and often with dissolved salts) through porous media and presents many explanations of different natural phenomena. One chapter is devoted primarily to the chemical reactions that can take place as the fluid slowly winds its way through the rock matrix. In the preface Phillips writes that the book 'is intended primarily for geologists'. I believe that its appeal will be very much wider than this. While the book is orientated towards sedimentary geology, there are really very few places where a prior knowledge of geology is needed to follow the text. In addition, flow through porous media is of central importance to areas of petroleum, mining, groundwater and chemical engineering. The clarity and sparkle of the presentation are such that this book deserves to become one of the standard texts in these areas.

After a very short introductory chapter, the second chapter commences with a qualitative description of permeable rocks and displays nine fine-scale photographs of various rocks from around the world. The remainder of this chapter and half of the next chapter present a gradual and comprehensive analytical development of the concepts needed to analyse flow in a permeable medium. The description carefully and incisively develops the relevant approximations without being either long-winded or boring at any point. The reader is shown the central importance of Darcy's law and the (different) forced advection-diffusion equations for temperature and concentration. This material can be read with pleasure by anyone who is interested in the foundations of the subject.

The governing equations are first used to examine effects due to spatial variations in permeability within the medium. Streamlines converge towards a region of excess permeability, and the flow strength thus increases within the more permeable medium. Exact solutions are presented for isothermal flow past an isolated spherical region, for which the degree of convergence, or focusing, as Phillips calls it, can be up to a factor of three, and for a two-dimensional elliptical crack for which the focusing can be extremely large for a long thin crack lying in the direction of the flow. These exact solutions act as a foundation for approximate solutions that determine the focusing of flow within a continuous aquifer with either an embedded thin lens of different permeability, or a series of thin lenses. By such focusing, fluid with a vertical concentration gradient can be drawn into a predominantly horizontal lens within which the concentration gradients are greatly enhanced, and mixing is induced. When the fluid eventually emerges from the lens, the concentration gradient can be significantly altered from its upstream value.

The fourth chapter deals with the transport of dissolved chemicals that change concentration due to either precipitation or dissolution as they flow through the permeable matrix. The controlling factors in such flows are the fluid mechanical processes of advection and diffusion, which specify the rate at which reactants can be supplied to the reaction sites, and the chemical processes, which specify the rates of reaction. Many fluid dynamicisits may find the material of this chapter the furthest from their experience. Indeed, I feel that it might have been better were this chapter to have followed some of the later ones, after many of the more familiar and relevant concepts had been developed. Standard phase diagrams relating temperature to concentration of saturated solutions at thermodynamic equilibrium are described along with three different reaction types. The evolving concentrations are governed by forced advection-diffusion equations with the forcing reflecting the details of these phase diagrams and reaction types. Phillips discusses scale analyses that yield relationships for typical length and time scales over which reactions take place. But, as is so often the case in geology, these can vary by many orders of magnitude from one situation to another. A comprehensive analysis is given of the flow of fluid across a sharp boundary separating one region of constant permeability and mineralogy from another. A reaction front can form and propagate as a travelling wave away from the boundary, developing a concentration profile which evolves both with distance normal to the boundary and with time. Additional processes occur if there is a gradient of concentration in the interstitial fluid, and this leads to situations called gradient reactions, which are also analysed. The remainder of the chapter considers the consequences of such flows in various geometries and with various permeability variations. One section investigates the dissolution or precipitation of a salt, such as calcium carbonate, due to nonlinear mixing between seawater seeping into the rock matrix from an adjacent ocean and interstitial fresh water, both of which are saturated in the salt. Another section considers effects due to gradual temporal changes in permeability as a result of the chemical reactions between interstitial fluid and host matrix. This is the only section, as far as I can find, where temporal variations in permeability are considered, though this is an important effect and will no doubt be the source of many research problems in the future.

Chapter 5, entitled 'Instabilities', commences with a beautifully clear, brief exposition of the classical linear stability problem for a porous medium heated from below and also obtains results for a porous layer at an angle to the horizontal. The effects of different boundary conditions are discussed along with comparisons between the theoretical predictions and experimental results. The first section ends by noting that if the saturated interstitial fluid has an equilibrium saturation density that increases with increasing temperature, the porous layer is unconditionally stable whenever it is heated from below. The next section determines the local linear stability criteria, relevant in the limit of negligible diffusive effects, when there are (unsaturated) fields of both temperature and concentration continuously distributed throughout the layer. The investigation of effects due to the (different) diffusivities of heat and composition in a porous medium requires incorporation of the fact that, although heat is diffused through the whole medium, concentration can only be diffused through the vacant pores (through which both fields are advected). Thus the value of the (generally small) porosity multiplies the coefficient of molecular diffusion of concentration, which increases the influence of concentration. A brief example is given of a hot saline lagoon above a permeable substrate saturated with initially cooler and salt-free water. Double-diffusive fingering within the substrate will develop, which transfers salt to the underlying medium and allows geochemical alteration to occur. Phillips suggests that this process has been operative in the huge Permean Basin of western Texas and New Mexico which is the source of much natural gas, oil and potassium carbonate, or potash. The chapter ends with a nicely balanced, though brief, account of the now famous Saffman–Taylor instability. It could not have been easy for Phillips to have decided how much to write on this topic because it has blossomed so much over the last decade and attracted a large number of contributions from physicists and mathematicians as well as from fluid dynamicists. I was disappointed, however, that there was no mention of the concepts and techniques of diffusion-limited aggregation (DLA; *Aggregation and Fractal Aggregates*, by R. Jullien & R. Botet, World Scientific, 1987) which has recently given rise to a series of interesting calculations in this area. In addition, I feel confident that the techniques of DLA could be used to good effect in the study of many of the other situations considered in the book.

The sixth chapter extends the investigation of earlier chapters to determine the form of various pressure-driven flows. In a long thin aquifer lying between two impermeable regions the use of a technique akin to that used in lubrication theory leads to a simple second-order partial differential equation. If the aquifer is leaky the equation incorporates a forcing term which accounts for the flow through to the surrounding permeable regions. A few special solutions are obtained in addition to some limiting solutions for elongated lenses and conduits of slowly varying thickness. For flow in a general permeable medium, however, a fully numerical solution is needed; and Phillips presents a rather detailed three-page description of how to carry out such numerical calculations. Such detail seems somewhat out of place to me in a book devoted mainly to analytical investigations. Thermal effects are considered next and, as might be anticipated, a series of boundary-layer calculations for flow in long thin layers is presented. There follows an interesting section on the trapping of fluids in topographical bends of an aquifer. Phillips investigates the conditions under which a light pool of hydrocarbons, for example, can remain trapped, rather than being flushed out, above a flowing heavier fluid and below a locally domed top of an aquifer. The chapter ends with a section on the form of mineralization that can accompany such flows. There is a rather vague description of the previous numerical calculations of others without really any specific application of the powerful analytical solutions and approximations determined in this book. Instead Phillips discusses some of the geochemical data which have been used to explain the distribution of lead–zinc and other ore deposits in the Mississippi Valley. He concludes by stating that 'These individual studies ... give tantalizing glimpses of the insights that are beginning to be developed' (p. 219). More is awaited.

In my opinion, the final chapter, which considers effects due to thermal convection, is the most beautifully crafted chapter of all. It sets the scene by describing the observed vertical temperature gradient in the ocean, and a significant part of the chapter investigates the effect of this gradient on adjacent, permeable sloping strata. In particular, Phillips evaluates the static temperature distribution, augmented by a background geothermal gradient, in a submerged permeable bank surrounded by either thermally stratified or isothermal water. The resultant flow at low Rayleigh numbers in a reef is then calculated, followed by a section on buoyant plumes at high Rayleigh numbers. The next section presents numerical calculations for motions at moderate Rayleigh numbers, and thus bridges the analytical results of the two previous sections. The final six pages uses this material to present an explanation of paleoconvection and the formation of a dolomite suite in Northern Italy. Specifically, Phillips argues that convection of 10^3 km^3 of sea water through porous rock by a plume originating at 300 °C at a volcanic hot spot will transport the 2 km^3 of magnesium needed to convert in 10^6 years calcium carbonate into the amount of dolomite which is observed.

As is inevitable for an introductory book of this size, each reader will be able to suggest additional topics that might have been included. I am surprised that there is no mention of effects due to random distributions of permeability (King, P. R. *Transport in Porous Media* vol. 4, 1989, pp. 37–58). It is also a pity that Phillips did not include a chapter on the currently hot topic of compaction (Stevenson & Scott, *Ann. Rev. Fluid Mech.* vol. 23, 1991, pp. 305–339) whereby melt is squeezed out of a compressible rock matrix by the weight of overlying rock. Such a chapter would have enlarged upon effects due to changes in permeability of the host matrix as well as showing that many of the concepts introduced by Phillips have application to larger scales and also to igneous geology. A lucid critique of this area by a powerful fluid dynamicist would be read avidly by many geologists and geophysicists.

The typographical preparation and proof-reading seem to have been carefully carried out. I found only one obvious error. In Section 6.6 the angle ϕ is used in the text, while it is depicted as θ in figure 6.20; and ϕ is a bad symbol anyway for an angle in a book devoted to investigating the effects of porosity denoted throughout by ϕ. There is also a joke included. After 109 pages of sophisticated applied mathematics, which includes the vectorial representation of the Navier–Stokes equations, the tensorial representation of the permeability, elliptic coordinates and so on, Phillips needs to introduce $\boldsymbol{u}.\boldsymbol{\nabla} T$ in the text, which is amusingly footnoted as: 'This is read u-dot-grad-T'!

In summary, this is an extremely well-written and thought-provoking book, which contains many results not previously published. It is likely to have considerable influence on future research. I cannot imagine that anyone will really be disappointed with the material covered. But it places considerable onus on Phillips, and his colleagues, to use the firm mathematical foundation he has laid to build a fine, scintillating edifice for the physical and chemical effects of flow through porous sedimentary rocks.

HERBERT E. HUPPERT

Plasma Loops in the Solar Corona. By R. J. BRAY, L. E. CRAM, C. J. DURRANT AND R. E. LOUGHHEAD. Cambridge University Press, 1991. 498 pp. £70.

Imagine flying in an airplane at night, while a lightning storm rages below. Looking out the window, you might see clouds here and there light up as they release electrical energy. Extreme UV and X-ray telescopes observing the sun see an analogous phenomenon. Against a dark background (the photosphere emits little in these ranges) there appear numerous bright sources, generally in the shape of arcs or loops. Unlike our terrestrial electrical storms, however, these solar X-ray sources arise from the release of magnetic energy.

The strong magnetic field in the solar atmosphere (corona) is responsible for the loop structures seen in observations. Most of the magnetic flux emerging from the photosphere forms the 'closed corona'; field lines reach heights up to 10^5 km before plunging back down to the surface. In the 'open corona' field lines connect to the interplanetary field. Temperatures are not so extreme here, and so regions with open field lines appear on X-ray photographs as dark areas, or 'coronal holes'. While plasma is trapped in the closed corona, it flows outwards along the open field lines to form the solar wind.

The coronal plasma is highly magnetized: particles, heat, etc. travel much more easily along field lines than across field lines. Temperature differences arise much more easily across lines than along lines. If we observe the sun at a wavelength sensitive to a small range of temperatures, we tend to see entire closed field lines radiating at that temperature. A bundle of neighbouring field lines sharing a similar temperature will then be observed as a loop. Loops are the basic building block of the closed corona, and are of crucial importance in the understanding of flares and coronal heating.

Astrophysicists find solar coronal loops interesting (and troublesome) because they can be observed in detail. A wide variety of stars emit X-rays and other indicators of coronal activity which presumably come from plasma loops. Accretion disks may well have atmospheres filled with plasma loops, and astrophysical jets share some similar structural features.

These authors have in the past contributed several books on different aspects of solar physics, including sunspots, the chromosphere, and the solar granulation. This book extends this series by providing a thorough guide to the observed properties of solar loops. It starts with a historical introduction covering loop and prominence observations. Eclipse observations of loops date back as far as 1239; careful astronomical studies date from the mid-19th century. The historical account of more recent developments provides a useful introduction to the observations described in later chapters. Chapters 2–4 cover cool loops (temperatures under 10^6 K), hot loops (over 10^6 K), and loops associated with flares. The chapters end with detailed summaries and tables of physical data, with the useful feature that each line of data is indexed to the relevant section.

The final two chapters discuss theory, with particular emphasis on the dominating influence of the magnetic field. Chapter 5 gives an overview of MHD theory in the context of the special conditions found in the corona. Three basic conditions should be immediately stated. First, the coronal plasma has a conductivity similar to that of copper, but the magnetic Reynolds numbers can be as high as 10^{13} because of the large lengthscales involved (the radius of a hot loop can be several times that of the Earth). Second, magnetic forces dominate over gravitational and pressure forces. Third, the endpoints of field lines are anchored (line-tied) in dense photospheric material. Forces generated within the loop are too weak to have much influence at the photosphere, so the photosphere (or for some purposes the chromosphere) provides natural boundary conditions for the loop.

Line-tying distinguishes the corona from open magnetic systems like the solar wind or systems where magnetic lines can close upon themselves like tokamaks. The effects of line-tying bear upon many aspects of MHD theory. The photosphere is constantly moving due to the solar convection. As a consequence field lines tied into it jiggle and braid about each other. The loop is thus like a wave cavity driven at the two ends. The book discusses equilibrium, stability and wave theory under such conditions, as well as the thermal structure of loops.

Chapter 6 provides a more general viewpoint, first relating coronal loops to magnetic structures in other parts of the sun: convection zone, photosphere and chromosphere. A brief section on field topology follows. The magnetic field topology within a loop will be quite complex if endpoint motions braid the field lines. Eugene Parker, in 1972, stimulated much interest in complex field topologies by suggesting that they are incapable of settling to a smooth equilibrium: in a process he called topological dissipation, the field develops sharp gradients, leading to the release of magnetic energy in impulsive reconnection events. The book ends with a detailed introduction to plasma loops on other stars.

In any science as complex as solar physics, there will be many areas of controversy. These authors generally succeed in providing fair statements of differing ideas and viewpoints with little negative editorial comment. This is probably the best way to proceed, but the drawback is that readers will miss some of the vigour of current debates.

The book separates into an observational part and a theoretical part; I would have enjoyed seeing a jointly written final chapter where theory and observation confront each other. Apart from that, however, I found the book a well-written, comprehensive, and carefully organized account of the current understanding of coronal loops. It will be a very useful reference.

M. A. BERGER

Debris Flow. By T. TAKAHASHI. Balkema, 1991. 165 pp. £29.

Debris flows occasionally arise in mountainous regions under heavy rainfall conditions and then constitute a threat to the communities, causing extensive damage to properties and claiming many lives. This monograph is probably the first to treat comprehensively the mechanism of debris flows from their onset to deposition. Its purpose is to provide a detailed phenomenological description of events, to present reasonably detailed physical models for this description and test these with detailed measurements of flow data in the laboratory and the field.

Chapter 1 summarizes the nature of debris flow as it is observed in some (e.g. Japanese) mountain torrents; it is descriptive and primarily aims at a first understanding of the processes of these fluids. This contrasts with Chapter 2, in which a detailed understanding of the mechanics of the flow of a layer of a binary particle–fluid mixture is developed. After a brief presentation of the constituent momentum equations, constitutive models for a granular material, with interstitial fluid under rapid shearing are discussed and Bagnold's concepts of inertia and macroviscous regimes are introduced. Steady stony debris flow is discussed for these two limiting cases as is immature debris flow (of a layer of pure liquid above a gravel–fluid mixture layer) and turbulent mud flow. The focus is always to arrive at reasonably tractable formulae for, say, the transverse distributions of particle concentration and streamwise velocity and comparison of these with measured counterparts.

Chapter 3, entitled 'Processes of occurrence, development and declination' first treats steady conditions of a system of sediment water layers and discusses their 'stability' on the basis of a cohesive Coulomb yield criterion. Then, the formation of hydrographs and their deformation is discussed. Reading is unfortunately rather heavy going, as concepts are somewhat hidden and only briefly touched upon, and equations are often stated but neither deduced nor properly explained, let alone references being quoted (see e.g. pp. 76–77). In a similar spirit debris flow due to landslide dam failure and its description by the kinematic wave theory is also treated.

Chapter 4 on the 'Characteristics of fully developed flow' discusses quasi-steady flow and the shape of the snout, touches briefly upon the phenomenon of roll waves, and gives a fairly detailed account of accumulation of large boulders at the front, of inverse grading (transportation of huge stones on the debris flow surface) and of debris flow around bends. Finally, in Chapter 5 processes of deposition of sediment are treated and models for the stoppage of the flow and the distribution of the debris in the deposition zone are presented.

The book provides a broad overview of the basic underlying processes, presents mechanical models for them, simplifies these often in order to arrive at explicit expressions for measurable quantities and presents wherever possible a comparison with experimental findings. To my non-native English tongue it reads smoothly, and I discovered only a few misprints. Figures are well designed and their captions and/or description appropriate. Nevertheless I generally missed a careful, clear presentation of the models when they were introduced and would at least have expected specific references stated instead. As a result the monograph will enable researchers and specialists in the field to find recent advances collected and coherently written in one place; it is most likely not ideally suited for those who want to learn the subject and, most unfortunately, does not lead the reader to see the weaknesses of the presented theoretical concepts that would facilitate his own progress in the subject.

K. Hutter