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The Physics of Composite and Porous Media

T.J.T. Spanos • Norman Udey

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Preface

This book starts with the description of a number of two-component problems in composite media. Seismic wave propagation in two-component composite elastic media, seismic wave propagation in fluid-filled porous media and two-phase flow in a rigid porous media may all be solved by the same volume averaging techniques and physical arguments. Here, *physical argument* refers to the constraints that basic laws of physics (conservation of mass, Newton's laws, conservation of energy, the principle of equivalence, etc.) must hold at all scales. While these constraints may seem trivially obvious, it is observed that they are too often violated in models of porous media used by engineers and groundwater hydrologists.

An interesting observation was made once the equations for these two-component systems were constructed. The equations of motion that describe seismic wave propagation in a porous medium predict an additional wave process, that is, a wave process composed of incompressible elastic deformations of the matrix coupled to the incompressible motions of the fluid moving through the matrix, much like blood moving through the veins of a body. Furthermore, if the matrix is highly stressed, this highly non-linear wave may extract mechanical energy from the stress field of the matrix. Also, the equations that describe multiphase flow through porous media predict two instability processes when a low viscosity fluid displaces a high viscosity fluid. The first instability process is viscous fingering, in which the front becomes very sharp and then the low viscosity fluid channels through the high viscosity fluid along channels called *viscous fingers*; the size of these channels may be specified from a stability analysis. The second instability process is one where a connate saturation of the displacing fluid is present in the porous medium; the front may initially broaden in an unstable fashion and then each saturation contour propagates at a constant speed described by a wave equation very similar to the wave equations that described the propagation of porosity–pressure waves. A fascinating experimental observation is then made: a low viscosity fluid is injected into a porous medium containing a high viscosity fluid (e.g. heavy oil) with a connate saturation of the displacing fluid (e.g. water). If that displacement is done under steady-state conditions, the injected fluid will channel through the displaced fluid, forming viscous fingers. However, if the displacement is done using porosity–pressure wave propagation, then dispersion (separation of the front and the saturation contours propagating as waves) will always dominate.

It is this coupling that leads to the next theoretical development. To physically describe this behaviour requires the solution of a three-body problem. Of course, the most simplistic approach would be to construct the equations of motion for the components and

look at their interactions. This approach is severely flawed. The origin of this flaw may be seen by considering another two-component problem, miscible flow in a porous medium where the components mix at two scales: the molecular scale (diffusion) and the pore scale (mechanical mixing). When this problem is constructed, both the concept of the component fluids and their volume fractions lose physical meaning. This leads to the understanding that both the component velocities and volume fractions only appeared to be thermodynamic variables in the previous two-component problems because they were proportional to the actual thermodynamic variables. This same observation is then made in the case of the three-body problem by a process of elimination. What is discovered is that if there are three components there are four equations of motion. These four equations describe one in-phase motion and three out-of-phase motions. Here, the components may never be considered independently or in pairs. Without this conclusion the three-body problem cannot be solved and Onsager's relation cannot be constructed. As soon as the three-body problem is solved, the n-body problem is obvious.

This is in fact similar to an n-body solution I obtained in 1973 in the context of charged spinning masses in a stationary electromagnetic vacuum field in general relativity.

One of the most important points in this book is to illustrate specific calculations and show how simplifying assumptions may be applied to numerical calculations. Sadly, Norman passed away on 11 November 2015, almost a year and a half before the completion of this book. His continued work in this area would have greatly improved the examples in this book. However, hopefully it is a good starting point for students who wish to study this subject area.

This book was written in its entirety at Wavefront Technology Solutions, a publicly traded company with head offices in Edmonton, Alberta, Canada. Most of this book is based on research into patented technologies funded by Wavefront Technology Solutions, Inc. (Wavefront). The foundations upon which this book is written are based on the book *The Thermophysics of Porous Media*, published by Chapman & Hall/CRC Press Monographs and Surveys in Pure and Applied Mathematics. The origins of this research began with funding at the Physics Department at the University of Alberta from the Alberta Oil Sands Technology and Research Authority (AOSTRA) in the late 1970s and early 1980s.

Tim Spanos
Norman Udey

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This book contains a great deal of copyrighted material previously published by the authors. This work is being republished in this book with the permission of Elsevier, Wiley, Taylor & Francis, Proceedings of the Royal Society of London, Springer, Canadian Journal of Physics and Wavefront Technology Solutions. A summary of the parts of the book this work appears in and the articles they came from is given below. The section on seismic wave propagation in a composite elastic medium of Chapter 2 contains material from *Transp. Porous Med.* (2009), 79, 135–148. The plots on the reflection transmission problem in Chapter 3 are taken from *Wave Motion* (1992), 16, 1–16. Much of Chapter 4 is based on *Proc. R. Soc. Lond. A* (1993), 443, 247–255. Chapter 5 contains plots from Chapter 1, ‘Relative Permeability’, in M.A.D. Viera, P.N. Sahay, M. Coronado, and A.O. Tapia (eds.), *Mathematical and Numerical Modeling in Porous Media: Applications in Geosciences*, CRC Press, July 24, 2012. Chapter 5 also contains plots from *Can. J. Chem. Eng.* (1985), 63, 735–746. Chapter 6 contains plots from Chapter 16, ‘Coupled Porosity and Saturation Waves In Porous Media’, MAD Viera, PN Sahay, M Coronado, AO Tapia (eds.), *Mathematical and Numerical Modeling in Porous Media: Applications in Geosciences* CRC Press, July 24, 2012 as well material and figures are taken from Wavefront Technology Solutions documents and marketing material. Chapter 7 contains material and plots from *Transp. Porous Med.* (1993), 10, 1–41. Chapter 11 contains material and plots from *Proc. R. Soc. Lond. A* (1999), 455, 3565–3587; plots from *Can. J. Phys.* (1999), 77, 473–470; and plots from *Transp. Porous Med.* (1999), 35, 37–47.

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Norman Udey received his PhD in the thermodynamics of mixtures in general relativity and a special certificate in computing science (specialization in software design), both at the University of Alberta. Following this degree, Norman received an AOSTRA postdoctoral fellowship working with Tim Spanos. After this fellowship ended, he worked as a research associate in seismology for four years. Norman then spent the next six and a half years in industry as a systems analyst and software developer. In 2001 he came to work for Wavefront on the physical processes and applications related to the patents held by Wavefront until the time of his passing in 2015.

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Introduction

BACKGROUND

Composite media are composed of structure and materials mixed at various scales. Some examples of composite media are most structures in the Earth's interior, granular media at the Earth's surface, plant materials such as wood, animal material such as bone, building material such as concrete and modern materials made with carbon fibre.

The theory of porous and composite media is an area of research that has been studied by engineers, geologists, geophysicists and applied mathematicians for many decades. Many unphysical models have been used for a very long time. Some of these models have been useful in the study of quasi-static processes. In the study of multiphase flow, Muskat proposed a model using equations analogous to Darcy's equation (Muskat 1937, 1949). These equations are still in use by some petroleum engineers today but have no relationship to physical reality. These equations model the highly non-linear processes of multiphase flow in porous media by separate linear equations, thus completely ignoring the dynamic interactions of the fluids. Furthermore, the dynamic pressure difference between the fluids is modelled by a zeroth order constraint, leading to a theory that is physically self-contradictory (see Chapter 5). In the study of miscible flow associated with groundwater contaminants, geologists and engineers have used the convection diffusion equation (which they sometimes call the *advection diffusion equation*) (Perkins and Johnston 1963). This is an equation that was constructed to describe molecular diffusion with phases mixing at only one scale, the molecular scale. Many authors have recognized this failure and have proposed alternatives (e.g. Koch and Brady 1987; Quintard and Whitaker 1994). The most common explanation for deviations from convection diffusion models is heterogeneities and fractures. As is shown in this book, if miscible phases are mixed at various scales, as in the case of a porous medium, then the theory describing the fluid motions is given by coupled Fokker-Planck equations. Furthermore, diffusion processes can be an order of magnitude or more larger than that predicted by the convection diffusion equation, which is consistent with observations.

In the case of deformations of porous media, the theory most commonly used by engineers is the Biot-Gassmann theory (Gassmann 1951; Biot 1956; Biot and Willis 1957).

In spite of all of its flaws, this theory has been quite useful to civil engineers as well as some other areas of engineering. The main flaw with this theory is that as it is constructed it is unphysical. The main advantage of this theory is that in the static limit the equations are of the correct form and can be made into a physical theory (in the case of statics) by reinterpreting the variables (see de la Cruz et al. 1993). Thus, experimentalists have been able to construct many relationships between theory and experiment in static experiments. The original construction of this theory gives the elastic matrix a preferential roll by describing it in the context of equilibrium thermodynamics. The fluid is then introduced as an external constraint through Darcy's equation, which is self-contradictory since fluid flow involves non-equilibrium thermodynamics and the components are coupled. Another serious error is that the role of porosity is not accounted for. This is not a serious error for statics; as is shown by de la Cruz et al. (1993), the Biot strain may be reinterpreted to include the role of porosity and it then becomes consistent with equilibrium thermodynamics. However, it cannot be generalized to describe dynamic processes because it is not consistent with non-equilibrium thermodynamics. The procedure to make the Biot-Gassmann theory into a physical theory for two-component dynamic processes would be to follow through the construction given in this book and introduce porosity changes at the outset. In its present form, this theory describes motions that do not conserve mass and violate Newton's third law. As a result, it is also not possible to construct physical boundary conditions for this theory (see Chapter 3, 'Boundary Conditions' section).

Other descriptions of porous media have been constructed in the context of thermodynamic interactions in the Earth's lithosphere (Steefel et al. 2005). In this theory porosity changes may occur due to deformations, chemical reactions or thermal processes (Connolly 1997). As is the case for the theory presented in this book, these descriptions predict the propagation of porosity waves in the earth (Malvoisin et al. 2015).

Some other dynamic descriptions of composite materials are made in describing a broad range of processes (Brennen 2005), including landslides (Straub 1997), volcanic activity (McTigue 1986; Natale 1998), fluidized beds (Harris and Crighton 1994), shock waves in porous media (Spiegelman 1993a, 1993b), earthquake interactions (Lemoine et al. 2001), earthquake fluid-level interactions in general (Montgomery and Manga 2003), allowing for viscoplastic behaviour of rocks (Connolly and Podladchikov 2015), etc.

THEORY

This book studies the form that physical equations take when materials are mixed at various scales. As a starting point, the following definitions of scale will be used:

Microscale (molecular scale)

Physical interactions described in terms of molecular dynamics.

Mixing of the phases is described by molecular diffusion.

Macroscale (pore scale)

Physical processes described in terms of continuum equations.

Fluid motions: Navier–Stokes equation.

Solid motions: Elasticity equation, plus frictional sliding of grains, etc.

Miscible fluid interactions: Convection diffusion equation, chemical potential, mass fractions of the component fluid phases.

The component phases for simple motions are described by linear equations, which interact according to prescribed boundary conditions or chemical mixing.

Megascale (laboratory scale)

The component fluid and solid phases cannot be described independently. At this scale, the averaged behaviour of the component phases and their interactions is being described. The phases at this scale are described by a non-linear classical field theory, which accounts for both molecular scale interactions of the phases and the macroscale interactions.

Mesoscale (intermediate scale)

At this scale, the description of the motions is too close to the scale of the structure for a continuum theory to be constructed. For example, acoustic wave propagation would need to be described in terms of scattering theory.

Gigascale (crustal scale)

Any scale larger than the megascale where additional structure has been introduced.

When macroscopic mixtures are observed at the megascale, one type of process that occurs is channelling, where the majority of a flow occurs along pathways, such as in landslides, when the majority of the flow occurs along narrow pathways, or in porous media, where the displacing fluid channels through the displaced fluid. Another observation, which is a process that will be discussed in this book, is the case where the flow occurs uniformly (i.e. the components interact uniformly at the macroscale), which in the case of the displacement of one phase by another is referred to as *dispersion*. So one of the points to be discussed is the conditions under which these different flow processes occur.

In order to gain additional understanding of the problem that must be addressed in going up in scale, consider the following thought experiment. Consider cubic membranes the size of the small squares shown in Figure 1.1 containing a fluid.

Assume the membranes in the upper half with the light grey colour contain water and the membranes in the lower half with the darker grey colour contain glycerine. In the first experiment, allow all of the membranes to dissolve and wait until the fluids are completely mixed at the molecular scale, as shown in Figure 1.2.

Here, it is observed that the fluids mix with each other at the molecular scale.

The thermodynamic description is given by the chemical potential and the mass fractions of the fluids. Here the mixing occurs at the molecular scale and the energy involved is the chemical energy. This process involves only molecular-scale thermodynamics.

FIGURE 1.1 Fluid is contained in membranes the size of the small squares shown. The upper membranes contain water and the lower ones contain glycerine. The smallest scale at which the motions may be described is the scale of the four large squares.

FIGURE 1.2 When the membranes dissolve, the fluids mix at the molecular scale. The mixing is described by the chemical potential and the mass fractions of the fluids.

Now assume that the membranes all remain intact and the fluids are mixed by moving the membranes around in a semi-random manner, as shown in Figure 1.3.

Now, before analysing this experiment, perform another one in which the membranes are moved around in orderly fashion, as shown in Figure 1.4.

In the last two experiments, mixing occurs at macroscale, which could be referred to as the *pore scale*, and the results are observed at a much larger scale.

The mixing that occurs in the last two experiments has absolutely nothing to do with molecular-scale thermodynamics. The mixing occurs though mechanical energy

FIGURE 1.3 The membranes are moved around randomly so that approximately the same number of membranes containing each liquid are in each of the large squares.

FIGURE 1.4 The membranes are moved around systematically so that they alternate along each line and column in each of the large squares.

at the scale of the membranes, and the fluids can be described independently by their volume fractions. Furthermore, their volume fractions are mixed differently in Figures 1.3 and 1.4. If the thermodynamics is now considered at the scale of the larger cubes shown by the white lines, then the mixing is described by the volume fractions and an order potential (see Chapter 4). If these processes are now generalized to consider the dynamic mixing of the phases, then saturation (the volume fractions of the fluids) becomes a dynamic variable.

In general the phases involved may be gasses, liquids or solids and not only can they flow but wave propagation such as seismic waves may be observed. So the next matter

to be discussed is how these processes may be described. This work starts with the construction of the equations describing the behaviour of a number of physical processes in multicomponent systems. For example, the steady-state flow of a fluid through a homogeneous porous matrix may be described by Darcy's equation. This result may be established through fairly straightforward experimental procedures (see Chapter 5). This result may also be established starting with the well-known equations describing the fluid flow and boundary conditions at the pore scale and then going up in scale using volume averaging (Anderson and Jackson 1967; Slattery 1967; Whitaker 1967; Newman 1969). This example is very important in that it establishes a relationship between theory and experiment. In fact, physical theory is a description of experimental observations or a prediction of experimental results subject to the constraints of the assumptions made in the construction of the theory. Each equation in a physical theory is a description of an experiment or a set of experiments. For example, consider the following equation when describing a compression associated with a porous medium.

$$\eta - \eta_o = \delta_s \nabla \cdot \vec{u}_s - \delta_f \nabla \cdot \vec{u}_f \quad (1.1)$$

Here, the left-hand side of this equation describes the change in the volume fraction of space occupied by the fluid (the porosity). The right-hand side describes a dimensionless physical parameter times the dilatational motion of the solid minus another dimensionless physical parameter times the dilatational motion of the fluid. This equation describes how porosity changes when a porous medium is compressed under static conditions. The associated experiments may be done in an infinite number of different ways depending on how the fluid pressure is constrained during the compression (see Hickey 1994). Any two of these experiments uniquely specify the values of the parameters δ_s and δ_f . Those values are the same no matter which experiments are chosen (Hickey 1994; Hickey et al. 1995). That is in fact a requirement for a quantity to be a physical parameter, for example, viscosity, bulk modulus and shear modulus are physical parameters because they may be related to experimental observations in the same fashion and are uniquely determined.

The special case where both components are elastic solids is considered in Chapter 2.

Here, Equation 1.1 is a static equation and the experiments discussed above are static experiments. However, this book is about dynamic processes, so the concept of statics will be discarded at this point except as a point of comparison. An example of a dynamic dilation is a seismic P wave. So in order to describe a dilatational seismic wave, the dynamic equation associated with changes in porosity is

$$\frac{\partial \eta}{\partial t} = \delta_s \nabla \cdot \vec{v}_s - \delta_f \nabla \cdot \vec{v}_f \quad (1.2)$$

So the obvious question to be asked is, 'What is the difference between δ_s and δ_f in Equations 1.1 and 1.2?' The answer is that different processes are being described in the two cases. There is nothing new about this observation. For example, if a bulk

modulus is measured, it is necessary to specify the physical conditions under which it was measured in order to get a unique result. For example, isothermal or adiabatic measurements will yield different results. In the case of Equation 1.1, δ_s and δ_f may be specified by drained and undrained compression experiments (Zimmerman 1991) or from any of a continuous family of compression experiments in between these two extremes (Hickey et al. 1995). This result is of zeroth order in bulk modulus experiments (see Chapter 3).

$$\delta_s = (1 - \eta_o) \frac{(K_s - K_{ud})(K_s - K_d)}{(K_s - K_f)[K_s - (1 - \eta_o)K_d]} \quad (1.3)$$

$$\delta_f = \eta_o \frac{K_s(K_{ud} - K_f) - (1 - \eta_o)K_d(K_s - K_f)}{(K_s - K_f)[K_s - (1 - \eta_o)K_d]} \quad (1.4)$$

Here, K_s is the solid bulk modulus, K_f is the fluid bulk modulus, K_{ud} is the undrained bulk modulus (no fluid motion is allowed in or out of the matrix during the compression) and K_d is the drained bulk modulus (the fluid is allowed to escape and the fluid pressure remains constant during the compression). Equation 1.2, however, also includes local fluid flow associated with the dilatational motion, which is affected by the solid shear modulus, the shear viscosity of the fluid and the bulk viscosity of the fluid. This causes a correction to Equations 1.3 and 1.4 in the form of a dynamic term of the order of $1/K$ (i.e. δ_s and δ_f have values close to those in Equation 1.1 but deviate slightly due to dynamics of fluid flow associated with seismic compressions) (see Chapter 3).

$$\delta_s = (1 - \eta_o) \frac{(K_s - K_{ud})(K_s - K_d)}{(K_s - K_f)[K_s - (1 - \eta_o)K_d]} + \frac{\Xi(\mu_s, \mu_f, \xi_f)}{[K_s - (1 - \eta_o)K_d]} \quad (1.5)$$

$$\delta_f = \eta_o \frac{K_s(K_{ud} - K_f) - (1 - \eta_o)K_d(K_s - K_f)}{(K_s - K_f)[K_s - (1 - \eta_o)K_d]} + \frac{\Theta(\mu_s, \mu_f, \xi_f)}{[K_s - (1 - \eta_o)K_d]} \quad (1.6)$$

where μ_s , μ_f , ξ_f are the solid shear modulus, the fluid shear viscosity and the fluid bulk viscosity, respectively. However, now things begin to change: upon constructing a complete set of physical equations (Equations 3.67 to 3.73) for the dynamics of a fluid-filled porous medium, the equations now predict another wave process. As it turns out, this predicted wave process is fairly easy to observe in a laboratory. What is predicted is that there is a limit at which the fluid behaves in an almost incompressible fashion. In this limit, fluid flow is coupled to elastic deformations of the matrix, and the fluid moves through the porous medium like blood through the veins of a body. This differs completely from the flow associated with seismic compressions, which predicts local and compressional flow, in which the porous medium returns to its original configuration after the wave passes. It also differs from the steady-state flow described by Darcy's equation, where the matrix simply acts as an external constraint on the motion of the fluid. Since this is a different physical process and involves almost no compression of the fluid, δ_s and

δ_f must have values that are obtained from an experiment that describes the associated motions (see Chapter 3).

$$\delta_s = (1 - \eta_o) \frac{(K_s - K_d)}{[K_s - (1 - \eta_o)K_d]} + \frac{A(\mu_s, \mu_f)}{K_d} \quad (1.7)$$

$$\delta_f = \eta_o \frac{(1 - \eta_o)K_d}{[K_s - (1 - \eta_o)K_d]} + \frac{B(\mu_s, \mu_f)}{K_d} \quad (1.8)$$

Here, a drained dilatational motion of the solid is described, which causes deformations of the matrix without solid compressions and is coupled to fluid flow. In this limit the undrained bulk modulus does not contribute. Here, it is important that the dilatational motions occur at the rate specified by the wave process. In the context of the thermodynamics, it is observed that the values of δ_s and δ_f are constrained by Onsager's relations (see Chapter 4). At this point it is useful to observe a result obtained prior to the analysis of the thermodynamics (Hickey 1990). He observed that the equations of motion gave unphysical results unless δ_s and δ_f were constrained to specific values (Figure 1.5).

Here, it may now be observed that the upper right-hand corner of the shaded area yields values for δ_s and δ_f that describe static compressions and slight deviations from those values describe seismic waves. The lower left-hand corner yields the values for porosity waves. The equation referred to as Equation 50 in this plot is

$$\frac{\delta_s}{\delta_f} = \frac{K_s}{K_f} \quad (1.9)$$

FIGURE 1.5 The values of the δ 's for which the equations of motion give physical results for the first P wave are given by the shaded region of this plot.

Another difference between the porosity-pressure waves and the seismic waves is that the seismic waves are non-linear and the porosity-pressure waves are highly non-linear. This becomes an important point when the matrix is highly stressed as is the case for the Earth's tectonic stress field. In this case, if irreversible motions of the matrix are triggered as the porosity-pressure waves pass, then these waves may extract mechanical energy from the stress field of the matrix. If this energy is less than the energy lost to viscous dissipation, then the wave propagates further than it would have without this extracted mechanical energy. If this extracted mechanical energy is equivalent to the energy lost to viscous dissipation, then the porosity-pressure waves propagate as solitons. If this extracted mechanical energy is greater than the energy lost to viscous dissipation at some position, then the porosity-pressure waves may induce rock bursts or seismic events. In all cases a redistribution of the fluid and fluid pressure occurs, which causes porosity pressure diffusion to occur after the wave passes. This may be observed experimentally in Figure 3.11, where these processes have been slowed by using glycerine as the pore fluid.

In Chapter 4, the equilibrium thermodynamics of porous media is described. Thus, constraints obtained in this chapter are only strictly true for static experiments or dynamic motions of perfectly elastic materials. So a slight correction should be expected for near-equilibrium dynamic processes. This chapter illustrates that in the case of static deformations porosity change may be incorporated into the strains. This is the transformation that when incorporated into the Biot strains allowed that theory to be consistent with physical theory in the static limit (see de la Cruz et. al. 1993). As well, reciprocity is introduced and constraints are placed on δ_s and δ_f by the Onsager relations subject to equilibrium thermodynamics.

In Chapter 5, the case of two immiscible fluid phases in a rigid porous matrix is considered. It is observed that for the interaction of the two fluid phases, saturation (the volume fraction of a fluid phase) plays a role similar to the role played by porosity in the interaction between a single fluid and the solid.

$$\frac{\partial \eta_1}{\partial t} = \delta_2 \nabla \cdot \mathbf{v}_2 - \delta_1 \nabla \cdot \mathbf{v}_1 \quad (1.10)$$

A new wave process is predicted and observed, the propagation of saturation waves. These waves are straightforward to observe experimentally and they are observed to be strongly coupled to porosity waves. Porosity waves are observed to suppress viscous fingering and enhance sweep efficiency. This chapter explores the conditions under which viscous fingering or dispersion becomes the dominant flow process when an adverse mobility ratio is present. In addition, the stability of steam–water front and the effect of phase transitions on the stability of the front are considered. An analysis of the coupling between porosity waves and saturation waves (dispersion) using simplifying assumptions is discussed in Chapter 6. However, in later chapters, it is observed that the construction up to that point in the book is limited to two-component models mixed only at the macroscale. For more complex systems the concept of volume averaging as a physical tool must be discarded. Upon taking the equations of motion for the component phases in a three-component system (a solid matrix and two fluids) and the volume fractions expressed by the porosity

and saturation equations, it is observed that solutions of the porosity and saturation wave equations are only possible in the limit where the waves are decoupled. This is interesting because simple experiments illustrate that they are in general strongly coupled. Another clue comes from the thermodynamics in that it is not possible to construct Onsager's relations from the equations of motion for the three-component phases and the equations for porosity and saturation. Yet another clue comes from the equations for miscible flow when the phases are mixed at various scales; here the concepts of component velocities and volume fractions lose physical meaning.

In Chapter 7 it is shown that the equations of immiscible flow may be rewritten in the form of miscible flow with negligible molecular diffusion when surface tension is taken to be zero. In this limiting case, it is shown that such flow may be described by a Fokker–Planck equation. In Chapter 8 the equations of miscible flow in porous media may be formally constructed in terms of momentum fluxes and mass fractions. The resulting description is expressed in terms of two coupled Fokker–Planck equations, and it is shown that, in the limiting case where molecular diffusion becomes negligible, one of these equations becomes identical to the Fokker–Planck equation obtained in Chapter 7 and the other Fokker–Planck equation vanishes.

In Chapter 9, the non-equilibrium thermodynamics of porous media (or in general multicomponent systems mixed at various scales) is constructed. This description is required to be expressed in terms of mass fractions and momentum fluxes.

In Chapter 10, the equations of motion for a three-phase system are constructed. It is observed that there is an additional degree of freedom that was not present in the case of the construction in terms of the component phases using volume averaging and the volume fractions (porosity and saturation) obtained from dilatational experiments. This occurs because the interactions of the three phases yield four momentum fluxes. Thus, an additional degree of freedom is obtained, which allows for the construction of Onsager's relations. In the special case where the phases are only mixed at the macroscale, these momentums and mass fractions may be rewritten in terms of the component phases and volume fractions (the porosity and saturation). Thus, the system of equations may also be cast in this form with one more equation than was obtained from volume averaging and dilatational experiments. Here, the three phases cannot be observed independently at the megascale, and their interactions yield one in-phase momentum flux and three out-of-phase momentum fluxes. Thus, four momentum equations are required to specify Newton's second law at the megascale. Once this three-body problem is solved, then the generalization to n -bodies is trivial.

Chapter 11 presents a Lorentz invariant thermal lattice gas computation. Here, particles are placed on a lattice and the motion of one lattice unit per time step is defined as the speed of light. The lattice points are used as a bookkeeper, much like the centre of a volume averaging sphere, the difference being that unlike volume averaging, where a volume average is ascribed to every point in space, the lattice points define a discrete space–time. Thus, here the particles are allowed to populate a discretized space–time that is equivalent to all particles and their properties in a volume of space being ascribed to a point in that volume, the lattice point. Unlike early models where the particles were constrained to move on the

lattice (e.g. Frisch et al. 1986), the particle motions are independent of the lattice in this computation. As a result, there is no exclusion principle (i.e. any number of particles may occupy the volume ascribed to a given lattice site). It is shown that the energy momentum tensor and relativistic Boltzmann equation can be derived from the collision and propagation rules. Thus, as in all other constructions in this book the objective is to go from the fundamental to the applied. The physics should arise naturally from the particle behaviour. The next step is to compare this computation to a more simplistic one that models non-relativistic elastic collisions. When this is done, it is observed that, if the average particle velocity is less than 0.1 times the speed of light, the two computational models are indistinguishable. As well, the possibility of a particle propagating at greater than the speed of light in the non-relativistic model is so rare (maybe once in an hour or so of computation) that such events may be simply discarded without affecting the results.

In thermal lattice gas computations, flow conditions and the boundary conditions are extremely important because of the thermal nature of the computation. In order to mimic a pressure gradient when modelling fluid flow, momentum is added to each particle at each iteration. This introduces a problem because energy is being added to the system and thus the temperature is increased. However, temperature may be kept constant by introducing a thermodynamic boundary condition. This allows models of Poiseuille flow to be constructed. Turbulence, relativistic shock waves, etc., are straightforward to construct but are not presented here. Next, the thermodynamic boundary condition is introduced randomly throughout the medium and Darcy flow is observed. Future constructions that readers are encouraged to consider are non-ideal gas behaviour and phase transitions.

EXPERIMENTAL RESULTS (LABORATORY AND FIELD)

Porosity and saturation waves have been observed in laboratory experiments (e.g. Wang et al. 1998; Davidson et al. 1999; Zschuppe 2002). In the early experiments it was observed that the tighter the sand pack and the more highly stressed it was, the better the flow enhancement. These media were encased in materials like concrete, steel and Plexiglas. Any contact with materials like rubber or neoprene was shown to damp out the porosity waves. Using pressure measurements it was observed that wave motions occurred in the porous medium moving about 40 times slower than a P wave. These waves attenuated due to viscous dissipation, and the higher the viscosity of the fluid, the more quickly the waves attenuated. Also it was observed that the higher the fluid viscosity, the slower the waves propagated. These waves could be generated by either a sudden increase or a sudden decrease in pressure. For a one-darcy permeability and a 30% porosity, with silica sand and water, the effectiveness of the pressure pulses could be tuned such that the most effective pulses have a rise time of about 1/10th of a second followed by a relaxation time back to the original pressure of about 1 second. The most effective laboratory pulser was constructed using two solenoids, one producing the sudden pressure increase and the other venting back to the original pressure (see Chapter 3). Other laboratory experiments have demonstrated that porosity waves may be used to suppress viscous fingering and enhance the distribution of injected fluids through dispersion. This may be done by pulsing in a lower viscosity fluid such as a surfactant and causing it to spread throughout the medium or by

injecting a high viscosity fluid such as a polymer and then pulsing a low viscosity fluid through it, causing the high viscosity fluid to spread through the medium (see Chapter 5). These experiments clearly illustrate that porosity waves enhance flow in porous media and strongly couple with saturation waves to make dispersion the dominant displacement process when a lower viscosity fluid is used to displace a higher viscosity fluid.

Many field applications have been developed to remediate environmental contaminants, to enhance oil recovery and to improve production in older wells (e.g. Dusseault et al. 1999a, 1999b, 2000, 2002; Samaroo 1999; Spanos et al. 2003). These processes may also be used to disperse chemicals into an inhomogeneous porous medium. This has proven to be a useful method of environmental remediation. Some of the environmental clean-ups this process has been applied to are gas stations where tanks have leaked, trichloroethylene remediation processes involving the dispersion of nano-iron particles, creosote removal using surfactants, light non-aqueous phase liquid recovery levels have been observed to be increased by more than 250% over standard injection processes (Environmental Technology Verification program, Government of Canada licence #ETV 00012, March 28, 2001) (Grey et al. 2001), and many other environmental projects involving the injection of chemicals to neutralize groundwater contaminants. Oil field applications involve enhanced oil recovery and workovers to re-establish flow to older wells. In the case of workovers, water, chemicals or acids are injected uniformly into the formation surrounding the well to re-establish the original permeability reduced by plugging of flow paths during production. Without pulsing, the injected fluids tend to flow into the formation along high permeability pathways, bypassing the blockages. This was illustrated in one case by a successful acid workover in a well in which two previous acid workovers without pulsing had failed. Of course, this is only one example, but this technology has now been in commercial use around the world for 19 years with no technical failures. The original application of this technology and its primary use was to enhance oil recovery. Many years ago, oil was produced using the reservoir's existing pressure to cause flow from a production well. This was called *primary production*. Once the reservoir pressure dropped, water was injected into the formation in injection wells in an attempt to re-establish reservoir pressure. This was called *secondary production*. Of course, the injected water channelled through the formation to the production wells, with usually 70%–80% of the original oil in place still in the reservoir. Therefore, other injection technologies were then employed involving various chemicals (surfactants, polymers, supercritical CO₂, etc.); this was called *tertiary recovery*. Of course it was eventually recognized that much of the production done during primary and secondary recovery was damaging the reservoir and making tertiary processes less effective. This led to the terminology of *enhanced oil recovery*, which may be implemented at any stage of the production in an attempt to maximize the recovery of oil. This has made reservoir modelling an important tool in planning the production technologies to be used in reservoirs.

OTHER OBSERVATIONS

The following observations are consistent with the predictions of the theory presented here, but only anecdotal correlations have been made at this stage. This appears to be a fruitful area for future research.

The very first constructions of the porosity wave were made in 1993. It was noticed at that time two earthquake pairs had been observed at CICESE in Mexico. In one case, the second earthquake occurred at exactly the time that the porosity wave would have arrived. In the second case, the second earthquake occurred about 30 seconds after it would have passed. Since that time many anecdotal observations have been made of earthquake interactions. However, the following discussion relates only to published observations of earthquakes.

Earthquakes appear to affect fluid motions. In the United States, water level fluctuations were recorded in 716 wells after the Alaska earthquake of magnitude of 8.5 in 1964. (Note that the Alaska earthquake was the largest earthquake in the Northern Hemisphere in the previous century.) It is well documented that the Alaska earthquake also had effects on water level recorders in many other countries around the world. This is of course consistent with the soliton predictions of this theory, where fluid is moved great distances by extracting mechanical energy from the Earth's tectonic stress field. Similar observations were made following the Japan earthquake in 2011. There have also been many observations of both increases and decreases in pressure and flow rate in the earth at distances several hundred kilometres from earthquake epicentres (Roeloffs 1988). Changes in oil production, induced seismicity, changes in the height of water wells, etc., have all been observed. It has been observed that the Landers earthquake triggered earthquake swarms more than 1280 km away in Yellowstone National Park (USA), as well as other jolts near Mammoth Lake, California, and Yucca Mountain, Nevada (Hauksson et al. 1993). In the Yellowstone National Park area, geyser activity and micro-earthquake swarms increased after the Denali Fault earthquake (Alaska) on November 2, 2002 (Husen et al. 2004). The park is about 3100 km distant from the Denali fault epicentre.

Dogo Hot Spring, situated in Matsuyama City, Ehime Prefecture, Japan, has had groundwater level or discharge at the spring decrease four times during the past eight or nine Nankai earthquakes. These are large interplate earthquakes that occur in the western part of the Nankai Trough at intervals of 100–200 years (Satoshi and Koizumi 2007).

Associated with the 2004 earthquake off the west coast of northern Sumatra, changes in groundwater levels were observed at many observation stations in Japan that were more than 5000 km from the hypocentre (Kitagawa et al. 2006). At 38 of the 45 observation stations, there were changes in groundwater levels. At the 10 observation stations in which the Ishii-type borehole strain instruments were established, changes in crustal strains were also observed. A major part of the changes in crustal strains and groundwater levels or pressures were dynamic oscillations due to a seismic wave.

Distant as well as local earthquakes have induced groundwater-level changes persisting for days to weeks at Long Valley Caldera, California (Roeloffs et al. 2003).

Water-level/pressure data recorded at a dense network of 16 wells of depths ranging from 23 to 201 m within 400 m of the Tono Mine in Gifu Prefecture, central Japan, have been studied in search of possible earthquake-related changes (King et al. 1999).

The post-seismic change in the groundwater level following the 1999 ($M_w = 7.5$) Chi-Chi earthquake in central Taiwan was recorded by a network of 70 evenly distributed

hydrological stations over a large alluvial fan near the epicentre. Four types of post-seismic responses were distinguished (Wang et al. 2004).

The 2008 Wenchuan earthquake occurred at the border of the Indo-Australian Plate and the Eurasian Plate. Following the earthquake, persistent changes in groundwater level were observed in more than 60 monitoring wells in Taiwan located at the boundary between the Eurasian Plate and the Philippine Sea Plate (Lee et al. 2012).

This only represents a very small sample of the observations of fluid level changes that have been observed following earthquakes. Fluid level changes have also been correlated as a precursor to earthquake activity (Roeloffs 1988) indicating the possibility of earthquake interactions (i.e. one earthquake being a trigger for a subsequent earthquake) (Xiaolong 2011).

Based on physical theory (Spanos 2002; also see Chapter 4), a tsunami-like process (a soliton) is predicted to propagate through the Earth's crust with a range of speeds from 100 to about 300 m/sec depending on the crustal properties and the wavelength of the solitary wave. In a study looking to see if earthquake interactions could be occurring at this speed, Rashid (2006) found 232 sources for possible single or multiple earthquake interactions that fit with this prediction. These observations are for the year 2003 and for earthquake sources over a magnitude of 4.3. Note that these are only earthquakes that would be triggered immediately after the solitary wave passes; as noted above, fluid level changes before many earthquakes are observed long before the main earthquake is triggered. Another interesting result that came from this study was that apparent earthquake interactions in the Himalayas did not fit with this theory. Upon closer inspection they appeared to be interacting vertically at the speed of a Stoneley wave. In Chapters 2 and 3 it is shown that when a medium is heterogeneous (its properties changing with depth) these surface waves (in homogeneous media) may propagate as highly non-linear body waves. This is of course only one possible explanation of these interactions and much more research is required before a definitive explanation may be given. However, this illustrates that often the most interesting experimental results are those that do not fit with expectations.

Following the loading of reservoirs, micro-seismic activity has been observed to diffuse outward from the reservoir with a diffusion constant of about $10^5 \text{ cm}^2/\text{sec}$ (Talwani and Acree 1985). Geilikman et al. (1993) have shown that this is the same diffusion constant predicted by the porosity-pressure diffusion process described in this book.

A similar pressure diffusion process may be observed in the lab by suddenly opening a flow valve (i.e. suddenly changing the pressure) at one end of a porous medium and then observing the pressure changes across the porous medium as it evolves to Darcy flow (see Chapter 3). This process may be made much easier to observe by using a high viscosity fluid such glycerine, thus slowing the process.

SUMMARY

Dynamic fluid motions have been observed after earthquakes over thousands of kilometres. Pressure diffusion has been observed to cause micro-seismic activity after the loading of man-made reservoirs. Oil production and chemical injection has been observed to be able to be controlled by the pulsing of fluids. These observations have been made in commercial enhanced oil recovery processes and environmental remediation. Laboratory experiments

have led to insight into the dynamic processes at work. In the following chapters the underlying physical description of the processes responsible for these observations at the various scales are investigated. The correlations of the theory discussed in this book to enhanced oil recovery and environmental remediation have been firmly established. However, applications to larger-scale geophysical observations are anecdotal at present.

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