Computational simulation of seepage instability problems in fluid-saturated porous rocks: Potential dynamic mechanisms for controlling mineralisation patterns

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ABSTRACT

Pore-fluid flow associated with seepage instabilities can play an important role in controlling large mineralisation patterns within the upper crust of the Earth. To demonstrate this process, two kinds of seepage instability problems in fluid-saturated porous rocks are considered in this paper. The first kind of seepage instability problem is caused by the temperature-induced buoyancy of pore fluid, so that it can be called the buoyancy-driven seepage instability problem, while the second kind of seepage instability problem is caused by chemical dissolution reactions that are commonly encountered in the upper crust of the Earth, so that it can be called the chemical-dissolution-driven seepage instability problem. After the mathematical governing equations of and computational methods for these two kinds of seepage instability problems are introduced, two numerical examples are used to elucidate how and why these two kinds of seepage instabilities can provide favorable places for the formation of large mineralisation patterns within the upper crust of the Earth. The related computational simulation results have demonstrated that: (1) the convective pore-fluid flow caused by the buoyancy-driven seepage instability not only can dissolve minerals at the lower part of the upper crust, but also can transport the dissolved minerals from the lower part to the upper part of the upper crust, resulting in large mineralisation patterns near the surface of the Earth's upper crust. (2) The chemical-dissolution-driven seepage instability in fluid-saturated porous rock can provide some favorable places, such as finger-like channels created by porosity enhancement in the porous rock, for the formation of large mineralisation patterns within the upper crust of the Earth.

1. Introduction

Pore-fluid flow associated with seepage instabilities can play an important role in controlling large mineralisation patterns within the upper crust of the Earth (Zhao et al., 2008a). Seepage instability refers to the situation where the pore-fluid flow pattern of seepage is suddenly changed from one state into another totally different state. According to this definition, seepage instability can be triggered by an abrupt rock deformation (such as crack initiation) associated with mechanical instability (Zhao et al., 2009), heat transfer associated with thermodynamic instability (Nield and Bejan, 1992; Phillips, 1991; Hayba and Ingebritsen, 1997; Zhao et al., 2008a) and chemical reactions associated with chemical dissolution-front instability (Chadam et al., 1986; Zhao et al., 2008b; Zhao, 2014). Since the time scale of an abrupt rock deformation (such as crack initiation) is much smaller than that of the mineralisation process in an ore-forming system (Zhao et al., 2012), the rock deformation process (including crack initiation and

propagation) can be usually separated from the metallogenic process of the ore-forming system. This means that although the permeability for some kinds of soft rock or easy dissolvable rock (in which the major parts of the rock are dissolvable minerals) is highly sensitive to the rock deformation and chemical reactions (Ingebritsen and Manning, 2010), the time scale of the rock deformation itself is still much smaller than that of the heat conduction process in the thermodynamic system. For example, if an upper crust has a thickness of 10 km and the P-wave speed is 1000 km/s in the soft rock, then the rock deformation time scale of the thermodynamic system is equal to about 0.005 s. However, the heat conduction time scale is equal to about 2.475×10^{14} s, which is equivalent to about 7.79 million years (Zhao et al., 2012). For this reason, the focus of this paper is on the seepage instability associated with thermodynamic and chemical dissolution-front instabilities in fluid-saturated porous rocks, in which the rock deformation can be reasonably neglected.

On the other hand, studies of seepage phenomena in fluid-saturated porous rocks usually need to deal with the following three fundamental issues: (1) seepage probability; (2) the driving force for seepage; and (3) a relationship between porosity and permeability. Since pores and

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particles of a porous rock may have complicated geometries, it is impossible to deal with the seepage (i.e. percolation) probability in porous rock through theoretical analysis. Alternatively, an idealised porous medium, in which pores and particles are assumed to be of regular shapes (such as triangles, squares, circles, hexagon (honeycomb type), spheres and so forth), is usually used in the theoretical analysis of percolation probability in the porous medium (Broadbent and Hammersley, 1957; Stauffer, 1985; Naeem et al., 1998; Grimmett, 1999). Nevertheless, for porous rocks encountered in ore-forming systems within the upper crust of the Earth, there is enough evidence to demonstrate that pore-fluid flow has taken place during the ore-forming processes (Nield and Bejan, 1992; Phillips, 1991; Zhao et al., 2008a,b), so that it is unnecessary to investigate percolation probability in such porous rocks. This means that for porous rocks encountered in ore-forming systems, research attention should be paid to the above-mentioned second and third fundamental issues.

Through several experiments, Darcy found that the driving force of seepage is the pore-fluid pressure gradient in the porous medium (Bear, 1972; Nield and Bejan, 1992; Phillips, 1991; Zhao et al., 2008a). He also found that the magnitude of seepage velocity is directly proportional to the pore-fluid pressure gradient, but the direction of seepage velocity is opposite to the direction of the pore-fluid pressure gradient in the porous medium. This is the foundation of the well-known Darcy's law. Extensive studies have demonstrated that Darcy's law is valid not only for describing liquid (such as water) flow in a porous medium, but also for describing oil flow and gas flow in the porous medium (Schulenberg and Muller, 1987; Miller et al., 1998; Crone et al., 2002; Bergins et al., 2005; Driesner and Geiger, 2007). This implies that Darcy's law is valid not only for describing single-phase flow, but also for describing multiple-phase flow in the porous rock.

In terms of dealing with the above-mentioned third fundamental issue, permeability (that is a macroscopic property) depends essentially on the detailed structure of a porous medium including pore and particle shapes, pore size distributions, particle packing ways, pore connectivity and particle components. In theory, permeability should be a function of all these factors. However, in practice, because it is very difficult, if not impossible, to quantitatively measure these factors, it is common to use porosity for approximately representing the detailed structure of a porous medium, so that permeability is described as a function of the porosity only. Due to this approximate treatment, the porosity–permeability relationship is usually dependent on the rock type. Consequently, different porosity–permeability relationships, such as the modified Fair–Hatch (MFH) formula (Bear, 1972; Chadam et al., 1986), the Kozeny–Carman (KC) formula (Carman, 1956) and the Verma–Pruess (VP) formula (Verma and Pruess, 1988), have been used to represent different rock types in reactive transport models for simulating the dependence of permeability on porosity (Lai et al., 2014). Traditionally, the porosity–permeability relationship is determined by laboratory experiments. With the advancement of modern computer technology, it becomes possible nowadays to determine the porosity–permeability relationship through the combined use of the microtomography technique and Lattice–Boltzmann (LB) simulation (Ahrenholz et al., 2008; Liu et al., 2014). However, such an approach is highly dependent on the rock heterogeneity, constituents, sample size, resolution as well as geochemical reactions (Gao et al., 2014, 2015).

The contents of this paper are arranged as follows. In the second section, the first kind of seepage instability problem, which is associated with thermodynamic instability in fluid-saturated porous rocks, is considered. Since the buoyancy of pore fluid is the main driving force, the first kind of seepage instability problem is also called the buoyancy-driven seepage instability problem in fluid-saturated porous rocks. After the mathematical formulas of and numerical procedures for this seepage instability problem are briefly introduced, a numerical example is used to illustrate how the buoyancy-driven seepage instability can affect the mineral precipitation patterns within the upper crust of the Earth. In the third section, the second kind of seepage instability

problem, which is associated with chemical-dissolution front instability in fluid-saturated porous rocks, is considered. Since the chemical dissolution reaction is the main driving force, the second kind of seepage instability problem is also called the chemical-dissolution-driven seepage instability problem in fluid-saturated porous rocks. Similarly, after the mathematical governing equations of and computational methods for the chemical-dissolution-driven seepage instability problem are briefly introduced, a numerical example is employed to elucidate why the chemical-dissolution-driven seepage instability can provide favorable places for the formation of large mineralisation patterns within the upper crust of the Earth. Finally, some conclusions drawn from this study are given in the fourth section.

The main difference between this study and the previous studies is that in the previous studies, the seepage instability associated with thermodynamic and chemical dissolution-front instabilities in fluid-saturated porous rocks is mainly considered from the physical point of view, so that the previous studies are mainly concentrated on why and how such instabilities take place in fluid-saturated porous rocks. In this study, the seepage instability associated with thermodynamic and chemical dissolution-front instabilities in fluid-saturated porous rocks is primarily considered from the mineral exploration point of view, so that this study is primarily concentrated on why and how such instabilities can affect the mineral distribution patterns in the fluid-saturated porous rocks.

2. Seepage instability associated with thermodynamic instability in fluid-saturated porous rocks

For the Earth's upper crust, which is comprised of fluid-saturated porous rocks, the pore-fluid residing in the pores of the porous rocks can be in a rest state if the temperature gradient is smaller than the corresponding critical temperature gradient, while it can be in a convective state if the temperature gradient is greater than the corresponding critical temperature gradient. From the physical point of view, this phenomenon is often called the thermodynamic instability of the system, for which the critical temperature gradient can be determined from the corresponding critical Rayleigh number (Nield and Bejan, 1992; Zhao et al., 2008a). In this situation, the seepage instability takes place because the pore-fluid flow pattern is changed from a rest (i.e. motionless) state into a convective state. Since the temperature gradient within the Earth's upper crust is the driving force to trigger the seepage instability, the corresponding critical temperature gradient of the system can be also used to assess whether or not the seepage instability associated with the thermodynamic instability takes place within fluid-saturated porous rocks.

As shown in Fig. 1, we can suppose that the xoy plane and the origin of the right-angle coordinate system are located on the surface of the Earth, and that the positive direction of the z axis is upward, which is opposite to the direction of the gravity. By using such a right-angle coordinate system, the governing partial differential equations of a seepage instability problem (associated with thermodynamic instability) in fluid-saturated, homogeneous and isotropic porous rocks can be expressed as follows (Nield and Bejan, 1992; Zhao et al., 2008a):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$u = -\frac{k_h}{\mu}\frac{\partial p}{\partial x}, \quad v = -\frac{k_h}{\mu}\frac{\partial p}{\partial y}, \quad w = -\frac{k_h}{\mu}\left(\frac{\partial p}{\partial z} - \rho_f g\right) \tag{2}$$

$$\rho_0 c_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} \right)$$
$$= \lambda_{e0}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{3}$$