

An Overview: Special Issue on “The Slow Subsurface Fluid Flow Processes (Part I): Theory, Model, and Physical Properties Estimation”

Tomochika TOKUNAGA¹, Hiromi HONDA², Osam SANO³,
Masao SORAI⁴, Toshifumi MATSUOKA⁵, Kazuyoshi HOSHI⁶,
Masaya YASUHARA⁴, Tomio INAZAKI⁷, Hitoshi MIKADA⁵
and Hitoshi KOIDE⁴

I. Importance of “slow” subsurface fluid flow processes

Subsurface fluid flow processes have been studied for over 150 years, starting from securing water resources for drinking and agricultural purposes, salt production from brines, and exploration and production of energy resources such as petroleum and natural gas. Infiltration theory based on Darcy’s law (Darcy, 1856) has been used in analyses. Hubbert (1956) conducted a thorough review of this equation and showed that it can be understood as a microscopic momentum equation averaged over macroscopic scales, even though the equation was originally developed as an empirical one. Hubbert (1956) also stated that Darcy’s law can be used under the condition that viscous resistance is dominant compared to inertial resistance. The laminar flow condition is met with a Reynolds number of 600 to 700 in porous media (Dudgeon, 1966; Kyle and Perrine, 1971); however, according to Hubbert (1956)’s discussion, Darcy’s law does not hold when the Reynolds number is larger than unity in porous media with the reference length set to be the mean diameter of solid grains. The Darcy flux of 1 ($\text{cm}^3/\text{s}/\text{cm}^2$) corresponds to this

condition when the mean grain size of the medium is 10^{-2} cm. Bear (1972) also presented similar results and showed that Darcy’s law is applicable when the Reynolds number is smaller than 1 or 10.

As explained above, subsurface fluid flow is known to be slow. Recently problems related to subsurface fluid flow processes have been increasing, therefore, slow subsurface processes have become more and more important.

Expectations are high today for the appropriate use of stable subsurface environments to solve waste disposal problems. For example, concepts for the geological disposal of radioactive wastes and subsurface sequestration of carbon dioxide (CO_2) have been developed based on the fact that there are places where subsurface fluid flow is extremely slow and that we can expect possible very slow mass transport conditions in the subsurface if we design procedures for disposal/sequestration properly. Also, studies on the petroleum system include migration, accumulation, preservation, and destruction of petroleum and natural gas reservoirs over geological time scales. Here, an extremely slow subsurface fluid flow is the issue.

Land subsidence can also be understood as a

¹ Graduate School of Frontier Sciences, the University of Tokyo, Kashiwa, 277-8563, Japan

² INPEX Corporation, Tokyo, 107-6332, Japan

³ University of Tokyo, Professor Emeritus, Tokyo, 113-0032, Japan

⁴ National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 305-8567, Japan

⁵ Graduate School of Engineering, Kyoto University, Kyoto, 615-8530, Japan

⁶ Japan Petroleum Exploration Co. Ltd., Tokyo, 100-0005, Japan

⁷ Geology and Geotechnical Engineering Research Group, Public Works Research Institute, Tsukuba, 305-8516, Japan

problem caused by slow fluid migration. The main reason for this problem is that elasto-plastic deformation to reduce the thickness of muddy aquitards occurs due to the slow discharge of pore water from the aquitards to neighboring sandy aquifers, which is caused by the abstraction of groundwater. This indicates that understanding the slow fluid flow process is essential to understand the problem.

Fluid flow processes to depths up to 300 to 400 km have also been studied recently, and important results have been published, especially from studies in and around Japan (see Iwamori and Nakamura (2012) and Hasegawa *et al.* (2012)). This is because fluids expelled at depths greater than 100 km are considered to contribute strongly to the generation of magma, development of overpressure and earthquake processes, and to control the behavior of thermal water. Especially in subduction zones, fluid expulsion from subducted slab and subsequent behavior are important for active magmatism, earthquake occurrence, and their uneven spatial distribution. Here, fluid flows through porous media can be used as a model to describe migration processes, and velocity is expected to be very slow. Solid constituents are considered to deform quite easily, hence, discussions should include volumetric and shape changes of both solid and fluid phases, and go beyond the classic theory of fluid flow through porous media. The problem needs consideration of very large ranges of both pressure and temperature, thus detailed evaluations and measurements of physical properties of fluid under a variety of pressure/temperature conditions are necessary for this discussion.

Under the very slow fluid flow regime, coupling processes of solids and fluids may become important for understanding fluid flow and related behavior. For example, instantaneous pore pressure change and subsequent decay can be explained well by the coupling process of solid deformation and fluid flow, which is well known as the theory of poroelasticity. Land subsidence problems are another example of fluid flow-deformation coupling processes. Furthermore, chemical osmosis is reported to be observed in geological formation

(*e.g.*, Neuzil, 2000), which is a two-way coupling process of fluid flow and mass transport. This process might occur in coastal areas once the necessary conditions are met.

II. Contents of this special issue

The special issue of “The Slow Subsurface Fluid Flow Processes” is composed of two sub-issues, *i.e.*, Part 1 and Part 2. Papers in Part 1 include conceptual and theoretical understandings of the slow fluid flow process in the subsurface, a numerical modeling approach to resolving dynamic effects on fluid flow, characterization of fracture system in geological mass, which is fundamental for better understanding subsurface fluid flow processes, methodology and applications of groundwater age and residence time estimation, and discussions on the physical properties of fluids. Here, discussions on the physical properties are more specific to two-phase fluid systems (Sorai and Kouda, 2012; Kunieda *et al.*, 2012). Physical properties of water and solutions under a variety of pressure and temperature conditions are also very important and interesting subjects; however, we would like to leave them to future special issues. Papers in Part 2 are mainly case studies with actual subsurface systems.

The following is a summary of the papers that appear in Part 1 of this special issue.

The multi-phase fluid flow process in the subsurface has been becoming important for geological engineering activities such as CO₂ sequestration, exploration of energy resources, and use of subsurface environments for waste disposal and stockpiling of petroleum and related products. Sorai and Kouda (2012) and Kunieda *et al.* (2012) discuss the physical properties of fluids with reference to a two-phase fluid system. Aichi and Tokunaga (2012) present recent advances in the theoretical development of deformation-fluid flow coupling processes under a two-phase fluid system in porous media. Yamabe and Matsuoka (2012) present their numerical simulation results on the effects of seismic waves on a two-phase fluid flow process. Yoshida (2012) discusses the formation of fracture systems in a crystalline rock mass and evaluations of their long-term stability in Japan.

Sorai and Kouda (2012) review the seal capacity of cap rocks, which is one of the main issues for the practical implementation of CO₂ sequestration in the subsurface. Here, they explain the terminology, experimental procedures, and models presented up until now, related to capillary pressures. Also described is the present status of our understanding of interfacial tension and contact angle, both of which are fundamental properties for evaluating seal capacity. In addition, problems obtaining these physical properties are presented. Both the advantages and disadvantages of the experimental methods proposed until now are summarized, and the authors point out the importance of standardizing the experimental methodology to measure seal pressure. From a comparison of the present status of petroleum exploration and CO₂ sequestration, more data on interfacial tension have been provided and summarized in the field of CO₂ sequestration, while there has been insufficient discussion on seal pressure and contact angle, compared to that in the field of petroleum exploration. The complexity of CO₂ systems in the subsurface due to phase changes, existence of critical point, and tendency of dissolution of CO₂ in water under subsurface conditions are explained. They briefly present their approach to modeling seal pressures and there are great expectations for future results.

Kunieda *et al.* (2012) present their experimental approach to wettability characteristics. Their main topic is contact angle at a microscopic scale. They assess whether contact angle is affected by droplet size. Here, they develop a methodology to measure contact angles smaller than can be done with micrometers, and report experiments on contact angle measurements with a decane-pure water system on a muscovite cleavage surface. Their results suggest that contact angle decreases with decreasing droplet size; therefore, water becomes more wettable with respect to muscovite with decreasing droplet size. They also argue that the conventional Young's equation relating interfacial tension and contact angle does not take into account the dependency of the size of a droplet on contact angle, and suggest that it is better to use the modified Young's equation. This equation ex-

plains the experimental results well. Based on their results, it is suggested that the discussion using contact angle measurements on a macroscopic scale may not represent phenomena at a microscopic scale well, and it is necessary to further discuss multi-phase fluid flow processes in geological formations from a microscopic viewpoint.

Aichi and Tokunaga (2012) review the present status of the theory of coupled processes between deformation and multi-phase fluid flow. In this paper, the authors discuss elastic behavior because the effects of underground use with controlled manner are considered to result in elastic deformation. This paper first describes the coupled process of deformation and single-phase fluid flow, then extends the topic to a multi-phase fluid flow system. The authors point out differences among fluid pressures of each phase, the need to take into account the effects of interfacial tension, and differences in the deformation behavior of pore spaces filled with different fluids, and argue that what is called the "equivalent pore pressure approach" is valid only in special cases, and cannot be applied to the problem in general. They explain that constitutive equations based on thermodynamics and elastic potential theory can be written by introducing Lagrangian porosity and Lagrangian saturation. They also present equations with experimentally measurable parameters. Finally, they show the possible further extension of this approach to the elast-plastic problem with a multi-phase fluid flow.

Yamabe and Matsuoka (2012) conducted a modeling study through numerical simulations of the migration of a droplet of non-wetting phase fluid through a pore throat with seismically induced vibration. Here, they use the Lattice-Boltzmann Method (LBM) to numerically simulate the process that occurs in a single pore throat. They first confirm the effectiveness of LBM for interfacial tension controlled by the Laplace Equation. They construct a spherical droplet in their LBM model as predicted by the Laplace Equation. They apply body force to represent the effects of low-frequency seismic waves on fluid migration, and show that a droplet composed of non-wetting

phase fluid can pass through the pore throat with seismically induced vibration.

Yoshida (2012) discusses the formation processes of a fracture system and its temporal changes in crystalline rock masses in Japan. Here, previous research results both abroad and in Japan are summarized, and the author states that these studies are oriented more to characterizing the present status of fluid conductive fractures. He also mentions that geochemical processes such as water-rock interaction are necessary to better understand long-term processes occurring in rock masses, in addition to the characterization of structural features of the fractures. Then, it will be possible to evaluate temporal changes of fracture properties and fluid flow patterns through fractured rock masses. The author conducted a comparative study on fracture systems of granitic rock masses of different ages, and shows that the fundamental patterns and intensities of the fractures were formed at relatively early stages of the rock mass formation process, *i.e.*, during cooling and uplifting stages. This result suggests the long-term stability of the fracture network existing at present. The author noted that changes of hydraulic and geochemical conditions caused by human activities should be taken into account for detailed discussions of engineering usage of subsurface environments, in addition to the knowledge presented in this paper based on geological and geochemical investigations.

Approaches based on age and residence time estimates of subsurface fluid and analyses of dissolved components to estimate the origins of the fluid can be a powerful tool.

Mahara and Ohta (2012) review studies on residence time estimations and estimations of the origins of subsurface fluids based on dissolved noble gas and long-lived radionuclides. They present the fundamentals of residence time estimations and their applications in detail, in particular an approach based on dissolved helium. The approaches presented in this paper can be used to directly prove the existence of extremely slow fluid flow processes in the subsurface, in addition to estimating the residence time of fluids. The authors also explain that it is possible to discriminate sub-

surface fluid flow regimes and the origin of water when one uses the techniques properly. How to estimate recharge temperature is explained and the paleo-climate based on recharge temperature is also discussed. These approaches can be used in the study of migration processes of fluids in the deep subsurface.

Large-scale behavior of fluids in subduction zones in general is related to volcanic activities and earthquake occurrences. Iwamori and Nakamura (2012) and Hasegawa *et al.* (2012) discuss the generation of slab-derived fluids, migration of fluids through the wedge mantle to the crust, and relationship between fluid behavior and earthquake mechanisms.

Iwamori and Nakamura (2012) explain the behavior of water in the subducting plate, especially behavior after water was brought into the deep subsurface, based on theory, models, and observations. The water is considered to be taken to depths greater than 100 km as hydrous minerals, then expelled by dehydration reactions and provided to the deep subsurface as a fluid phase. Depending on the thermal structure of the mantle wedge, it is possible to expect fluid expulsion at further depths. The mechanisms of fluid migration are at least partly constrained by observations including those on seismic velocity structures of the upper-most part of mantle. Based on an estimation of fluid fraction and on the fluid flow model, a vertical upward migration of slab-derived fluids through the mantle wedge can be expected, and geochemical data such as the spatial distribution of isotope composition are consistent with the expected vertical upward migration processes. As described above, fluid flow processes at present can be explained consistently by theory, seismic observations, and geochemical data analysis; however, there is still a need to improve resolution and reliability. The authors explain the importance of new observations, improvement of the physical models, and integrated interpretations in order to further our understanding of deep fluid flow processes and their consequences.

Hasegawa *et al.* (2012) review the present understanding of the mechanisms of earthquake processes based mainly on seismic observations

with special reference to subsurface fluids. They discuss several different earthquakes, *i.e.*, intra-slab earthquakes, plate-boundary earthquakes, and inland earthquakes. Overpressure development due to dehydration in the slab may result in a reduction of effective normal stress, and this might be a possible cause of intra-slab earthquakes. This interpretation is supported by the correspondence between hypocenter positions with the expected locations of dehydration based on temperature, pressure, and mineralogy information. The asperity model of earthquake generation at the plate-boundary is explained. Differences in seismic velocities are observed between the wedge mantle just above the asperity and that above the non-asperity, and this can be interpreted by differences in the migration of slab-derived water to the wedge mantle and by the spatial distribution of overpressures along plate boundaries. The relationships between the supply of magma and slab-derived fluids and the occurrence of inland earthquakes are also inferred. It is explained that the concentrated supply of fluid from the mantle wedge to the lower crust reduces the strength of the lower crust, making it one of the causes of inland earthquakes. It should be noted that the paper suggests the need to improve the asperity model based on our recent understanding of the behavior of asperities, such as the simultaneous slip of several asperities and possible dynamic slippage in a region where a “stable slip” has been expected based on studies after the March 11, 2011 Tohoku Earthquake.

As we can see from the above, problems related to slow fluid flow processes in the subsurface can be very broad both in space and time; therefore, it is not easy to view them systematically. On the other hand, if the main fluid flow processes can be understood through the theory of infiltration, then it is expected that exchanges of ideas and understandings achieved by different research disciplines can become a reality if we can successfully summarize and present the spatial and temporal distributions of hydraulic properties, *i.e.*, permeability, storage capacities, physical properties of the fluids with reference to broad temperature/pressure conditions, and driving forces of fluid flow.

Besides, we have high hopes that the further development and improvement of geophysical, geochemical, and geological approaches, modeling, and measurements of variables such as temperature, fluid pressure, chemical compositions, and stress, will be pursued to better understand subsurface processes related to slow fluid flow.

Finally, we would like to express our gratitude to those who reviewed and improved the papers in this special issue.

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