

An Overview: Special Issue on “The Slow Subsurface Fluid Flow Processes (Part II): Field Examples and Laboratory Experiments”

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I. Introduction

Volume 121, Number 1, of the *Journal of Geography (Chigaku Zasshi)* was a Special Issue dedicated to “The Slow Subsurface Fluid Flow Processes (Part I): Theory, Model, and Physical Properties Estimation.” The current issue is Part II of the Special Issue Series. Here, field examples and laboratory experimental results are presented.

As summarized in the overview of Part I, the theory of subsurface fluid flow has been developed and established based mainly on studies of groundwater flow through aquifers and fluid flow processes through reservoirs in oil and gas fields. On the other hand, extremely slow fluid flow processes have become important to address some topics in the subsurface. For example, a structural closure is crucial for the formation of a petroleum field, and in order for the structural closure to function properly, the existence is required of both geological and/or sedimentological structures to prevent significant leaks of oil and gas, and rocks that are tight enough to act as seal rocks encasing a reservoir in a field. The production of a variety of wastes from a highly developed human society also forces us to study the characteristics of subsurface environments. For example, geological disposal of high-level radioactive waste basically

expects subsurface environments to behave as long-term barriers to avoid unnecessary exposure of human society to radionuclides (*i.e.*, Yoshida, 2012).

Slow fluid flow is also important for understanding geological processes. It is well known that overpressure is often discussed with respect to large-scale thrusting (*e.g.*, Rubey and Hubbert, 1959). The importance of the degree of overpressure on the shape of an accretionary wedge has also been discussed (*e.g.*, Davis *et al.*, 1983). In Part I of this Special Issue, the behavior of geofluids at subduction zones was presented (Iwamori and Nakamura, 2012), and seismological processes along subduction zones (Hasegawa *et al.*, 2012) were studied in relation to the generation and migration of fluids in the deep subsurface. Other examples include significant overpressure generation and related geological phenomena reported off the Mississippi delta (*e.g.*, Flemings *et al.*, 2008), which were explained by the rapid deposition of low permeability muddy sediments.

In Part II of this Special Issue, case studies both from field examples and laboratory studies are presented to show new ideas and highlight remaining issues. The main fields treated in Part II relate to petroleum exploration, evaluation of long-term safety of geological environments, and labo-

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ratory studies on coupled processes.

II. Slow subsurface fluid flow processes and petroleum exploration

A significant amount of research related to subsurface fluid flows has been conducted in the field of energy resources development. In particular, so-called reservoir engineering plays a central role in the development of theories. Muskat (1937) is a benchmark textbook in this field. Combining reservoir engineering and hydrogeological knowledge and petroleum systems concept (*e.g.*, Magoon and Dow, 1994) has resulted in the development of a methodology called basin modeling (*e.g.*, Welte and Yukler, 1981). There has been a quantitative discussion on petroleum field formation processes that take into account those occurring in geologic time scales. For example, Berg (1975) and Schowalter (1979) are good examples of extending capillary pressure concepts developed in the field of reservoir engineering (*e.g.*, Leverett, 1941) to seal potentials of cap rocks and long-term fluid migration in carrier beds. However, the mechanisms for the existence of petroleum fields over geological time scales are not yet fully understood, hence, studies are still necessary to unravel this issue.

Two articles (Nakayama *et al.*, 2013; Honda, 2013) discuss the characteristics of the contact surface between oil/gas and formation water based on petroleum exploration activities abroad. These can be said to be studies on subsurface fluid flow processes and overpressure generation caused by tectonic and sedimentological processes through the distribution of oil and gas in reservoirs. Tsuji *et al.* (2013) describe trap formation of siliceous rocks by diagenesis. This includes changes of pore structures during diagenesis and possible contribution of mass transfer by fluid flow. Hoshi (2013) discusses the formation of sedimentary basins and the development of geological structures based on a detailed analysis of the compaction of sedimentary rocks. Honda *et al.* (2013)'s paper, which is the last paper in this Special Issue, is in memorium of the late Dr. Kinji Magara, who contributed to the field of basin analysis and petroleum system modeling.

The following are summaries of the papers in the category mentioned above.

Nakayama *et al.* (2013) gave a detailed description of the distributions of oil and natural gas in multiple reservoir layers at the U Field, offshore Malaysia, and the contact surface between oil/gas and formation water. Based on these data, the authors discuss the possible mechanism for the formation of the nested distribution of contact surfaces. It is well known that oil/gas columns in petroleum fields tend to be thicker as the reservoir becomes deeper in multiple reservoir settings. However, one of the reservoirs in the U Field showed a thinner oil/gas column in one of the three reservoirs forming a nested distribution. Taking into account differences in overpressures in each reservoir, it was possible to explain the distribution of the contact surface based on the classic concept of the seal capacity, *i.e.*, seal potential based on the concept of the capillary pressure of cap rocks. The distribution observed was interpreted to be for a transient situation during dissipation of overpressures generated by Quaternary tectonic activities. From this interpretation, it is expected that the contact surface between oil/gas and formation water can be deeper for limbs of an anticline under a tectonic and hydrological setting such as the U Field discussed in the article. The implications of this interpretation for petroleum exploration activities are described.

Honda (2013) discuss subsurface fluid behavior based on detailed geological information obtained from gas exploration and the shape of the inclined gas-water contact surface in the Peciko gas field, Mahakam delta, Indonesia. This paper discusses how to recognize the contact surface between oil/gas and formation water in reservoirs. Then, it is argued that information related to fluid flow velocity can be obtained from the shape of the contact surface and application of Darcy's law. A detailed discussion is presented based on the spatial distribution of a gas-water contact surface in a gas zone named MF8-FS88, which is interpreted to be a continuous gas zone. The contact surface is shown to be inclined, and average flow velocity is estimated based on the inclination angle. The average hydraulic gradients between boreholes is esti-

mated and their values for different directions are discussed with its relation to sedimentation processes in the delta. It is concluded that the hydraulic gradient is small in the direction of river channels and is large in the direction perpendicular to the channels, which is consistent with the connectivity of high-permeability formations formed by sand layers deposited along the river channels.

Tsuji *et al.* (2013) describe changes of pore structures and related physical properties during diagenetic processes of siliceous rocks, and discuss the importance of the changes on petroleum migration and accumulation. Details of changes of mineral phases and internal structures caused by burial diagenesis are shown based on data obtained from Miocene siliceous rocks in Japan and Miocene Monterey Formation in the United States. Siliceous sediments change mineral phases from opal A to opal CT, and finally to quartz by burial diagenesis. Phase transformation occurs due to dissolution and re-precipitation, and results in changes of porosity and pore structure, which are important characteristics of rocks for fluid flow. In this article, there is a detailed discussion especially on the transformation from opal CT to quartz. Pores with larger diameters tend to be increased by the transformation from opal CT to quartz if siliceous rocks include smaller amounts of clay minerals, and permeability increases because of an increase of pores with larger diameters. However, it is pointed out that a permeability increase is not observed for siliceous rocks including larger amounts of clay minerals. The existence of clay minerals also affects the temperature of mineral transformation. In addition, the effects of the chemical composition of pore water on diagenetic processes and the importance of diagenesis on fracture formation are discussed. The variety of traps observed in the field are explained based on physical property changes caused by diagenesis, and the migration and accumulation of petroleum are analyzed for several fields. These results are compared with geochemical data and it is shown that geochemical data support the authors' interpretation.

Hoshi (2013) discusses compaction and regional

tectonic activities based on porosity reduction with depth in a sedimentary basin. The Niigata sedimentary basin was chosen as the study area, and compaction curves obtained from acoustic logging data were used to classify three different patterns, *i.e.*, those showing that compaction occurs slowly, those rapidly, and those somewhere in between. The classification is shown to correspond to the locations of boreholes. Here, local differences of compaction trends cannot be explained by overpressure generation caused by delayed pore fluid release, and they are interpreted to be caused by different thermal gradients both at present and in the past, which affected mineral diagenesis, dissolution, and re-crystallization. Besides, different depositional rates are considered to be another principal reason. Based on standard compaction trends for three different regions and a comparison between standard trends and measured trend for each borehole, the amount of erosion and maximum burial depth is estimated. Spatial distribution of the amount of erosion is presented near the Araya anticline, which is situated close to the epicenter of the Chuetsu earthquake, and the relationship between accumulated displacements due to tectonic activities and estimated amount of erosion is discussed. Discussions in this paper make it possible to analyze detailed relationships among geological history, dewatering, and related fluid migration in the area, and it is expected that a similar approach can be used not only for energy resource exploration but also for evaluating the long-term stability of the geosphere.

III. Long-term stability of subsurface environments and slow fluid flow processes

Recently, evaluations of the long-term stability of subsurface environments have become important because possible subsurface use for waste disposal, *i.e.*, high-level radioactive wastes, carbon dioxide, etc., has been becoming an issue. To discuss the stability, long-term subsurface fluid flow and related mass transport processes need to be analyzed in detail. For example, SKB (2011) presented studies related to site selection for the disposal of spent fuels from nuclear power plants in

Sweden, and explained details of techniques, methodologies, and strategies for the study. In Part I of this Special Issue, Mahara and Ohta (2012) showed the use of isotopic information for estimating groundwater residence time, and this methodology is considered to be very informative. In this Issue, Hasegawa *et al.* (2013) present an example of the application of this technique for analyzing a hydrogeological system near a coastal area of Japan. Characterizing the fractured system, both fracture distribution and hydraulic conductivity distribution, is crucial for understanding subsurface fluid behavior. The cubic law is known to be applied to a single fracture (*e.g.*, Witherspoon *et al.*, 1980), and fluid flux through a single fracture is proportional to the hydraulic gradient under the condition of a linear and laminar flow regime. However, it is not easy to identify the continuity of connected fractures and how the fracture system contributes to regional fluid flow. Kubo *et al.* (2013) present an example of a study related to fracture distribution and its relation to fluid flows in the Mizunami area, Japan.

Earthquakes and their effects on fluid behavior are also important for the long-term stability of the subsurface environment. Koizumi (2013) summarizes the present status of research related to groundwater fluctuation caused by earthquakes.

The following are brief summaries of each paper in this category.

Hasegawa *et al.* (2013) present the results of applying a groundwater residence time analysis at a coastal area to discuss long-term groundwater behavior. In this study, a 500-m deep borehole was drilled and both geological and hydrogeological studies were conducted. In addition, groundwater residence times were estimated using ^{14}C , ^{36}Cl , and ^4He . A study based on stable isotopic ratios of chlorine ($\delta^{37}\text{Cl}$) was also performed. It is shown that groundwater in the Hayama Group, lower geological body in the area, is considered to remain for a long period, while that in the Miura Group, upper geological body, showed a relatively active fluid flow situation. Stable isotopic ratios of chlorine suggest that advection is dominant in the Miura Group, while diffusion is dominant in the Hayama Group, which is consistent with the

results obtained from groundwater residence time information. Applying multiple methodologies for the study efficiently shows the reliability and appropriateness of the results, hence, it is important for understanding groundwater behavior.

Kubo *et al.* (2013) studied a method to estimate the spatial distribution of hydraulic conductivity of fractured rock masses using geostatistics and numerical simulations. Obtaining the hydraulic conductivity distribution is of primary importance for evaluating groundwater flow processes using a numerical simulation technique. In this study, a three-dimensional fracture distribution model is established using a geostatistical approach with fracture data obtained from boreholes in the Tono area, Gifu Prefecture, Japan. Then, connected fractures are extracted from the fracture distribution model, and the relationship between fracture area and hydraulic conductivity is proposed from a comparison of the locations of connected fractures and hydraulic test results in boreholes. Because scattering was rather large, a final estimation of the spatial distribution of hydraulic conductivity was obtained through a further statistical analysis taking into account the variability observed in the relationship. A numerical simulation of groundwater flow in the area is carried out using the equivalent porous medium approach with the spatial distribution of estimated hydraulic conductivity, and the appropriateness of the simulation results are discussed by comparing calculated results with previous research results.

Koizumi (2013) present groundwater pressure changes in confined aquifers caused by earthquakes. The need to understand the effects of well bore storage is shown in this paper to correctly understand measured data. Then, the theoretical background to pore pressure changes caused by crustal deformation is explained based on the theory of poroelasticity. The possibility of water level changes caused by vertical tectonic movements is also mentioned. In addition, the effects of dynamic deformation on groundwater pressure change is discussed. Examples such as pore pressure changes caused by dynamic volumetric strains, changes of hydraulic parameters caused by dynamic deformation, and effects of liquefac-

tion are presented. Temporal changes of the permeability of an active fault are shown, in which the duration of the recovery of hydraulic properties of the fault is described. Further studies are necessary to better understand fluid behavior caused by earthquake activities, even though simple relationships may be difficult to obtain because the observed groundwater pressure changes are controlled by a variety of conditions and factors as explained in this paper.

IV. Laboratory experiments for discussing coupled processes

As already mentioned in the overview of Part I, coupled processes may become important for understanding fluid flow and related behavior. As shown in Koizumi (2013), pore pressure change and its dissipation due to earthquakes can sometimes be explained by coupled processes of deformation and fluid flow. Different phenomena compared to quasi-static processes are expected to be observed by dynamic deformation such as the propagation of seismic waves. In this Issue, Nishiyama *et al.* (2013) describe a detailed laboratory study on the behavior of rock specimens under dynamic deformation. The authors further discuss the possibility of estimating flow-related physical properties from the dynamic behavior of rock.

Chemical osmosis is another example of coupled subsurface processes. Under a condition where chemical osmosis plays a role, a two-way coupling process of fluid flow and mass transport should be taken into account. Takeda *et al.* (2013) describe the present understanding of this phenomenon, and show that chemical osmosis can occur for a certain rock type by laboratory experiments. They further argue the possible importance of chemical osmosis by showing a theoretical analysis for ideal geological processes.

Summaries of these two papers are as follows.

Nishiyama *et al.* (2013) studied the applicability of the Biot-Squirt model with both laboratory experiments and theoretical considerations. The Biot-Squirt model explains the dispersion of elastic waves due to pore fluid behavior in rock. It suggests that observations of the dispersion of elastic waves can be used to estimate the hy-

draulic properties of rocks, hence, they can be an important approach for studying subsurface fluid flows. Nishiyama *et al.* (2013) first evaluate whether the experimental conditions were appropriate to obtain reliable results for this study, then measure the frequency dependency of phase velocities of sedimentary and granitic rocks under dry and water-saturated conditions. Based on their measurements, measured frequency dependency is found to be strongly affected by the behavior of pore water. Experimental results are discussed using the standard linear solid model, the one-dimensional Biot model, and the Biot-Squirt model, which includes multi-dimensional pore fluid behavior. They conclude that the Biot-Squirt model using the Squirt flow length obtained from a representative pore diameter of the sample can better explain frequency dependency. The relationship between frequency dependency and permeability of rocks is discussed, and it is concluded that differentiating rocks having higher hydraulic conductivity and those having lower hydraulic conductivity can be achieved by measuring frequency dependency.

Takeda *et al.* (2013) summarize the present status of the chemical osmotic process in a subsurface setting, and propose a method to obtain the necessary parameters for quantitatively evaluating chemical osmosis in rock. The parameters necessary to discuss chemical osmosis include those for osmosis, diffusion, and fluid flow. Using the apparatus proposed, they successfully obtained the parameters from the same specimen. They further discuss the effects and implications of chemical osmosis by developing a dimensionless analytical model and by conducting parameter studies for several boundary conditions expected in the subsurface. Their analysis shows that an interpretation based only on hydraulic potential can be erroneous, for example, by estimating too large a flux or the wrong fluid flow direction. This result should be applied to evaluating groundwater flow-related processes under the condition that clayey sedimentary rocks exist and water bodies with different concentrations juxtapose, such as coastal settings.

V. Summary

The papers in this Issue show that both careful data acquisition and analysis, and flexible conceptual approaches are necessary to study slow subsurface fluid flow processes. At the same time, the wealth of knowledge in research fields such as petroleum engineering and hydrogeology is fundamentally important. Besides, approaches based on a fundamental theoretical analysis are indispensable. Research fields related to slow fluid flow are quite wide, hence, achievements in one field can provide hints for solving problems in other fields. Through this Special Issue, the editors hope readers will sense the width of the interests involved in slow fluid flow processes and find similarities in both conceptual approaches and methodologies adopted. Further studies will make it possible for us to better understand invisible subsurface processes, and hopefully, a new Special Issue on this topic will appear in the near future in *Journal of Geography (Chigaku Zasshi)*.

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