Porosity and permeability structures of the Shimanto accretionary prism, Kochi prefecture, southwest Japan

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Abstract: In order to explore the whole variation of the porosity and the permeability structures across the Shimanto accretionary complex, we measured porosity of cored rock samples from early Cretaceous to Miocene Shimanto belt in Kochi prefecture. Obtained results were compared with the porosity data reported for a toe region of the Nankai trough in the ODP-reports. The porosity of the Shimanto rocks is mostly under 5% and it seems there is no systematic variation of the porosity values from place to place in relation to the major structures or the sedimentary ages of the Shimanto belt. Sample of Miocene age of the ODP core at site 808 of the Leg 131 show much higher porosity of about 30% than the same age samples from the Shimanto belt. This remarkable difference of the porosity between the two same-aged samples may be explained with porosity-depth relationship as a result of compaction of the Shimanto belt due to burial to the depth of approximately more than 5km. This estimated depth of the Shimanto belt agrees with the estimated depth reported in the studies of thermal histories of the Shimanto belt. Permeability of the massive rocks is about 10⁻¹⁵ m² under low effective pressure (Pe) and lower than 10⁻¹⁹ m² at high Pe. On the other hand, permeability of fractured rock is about 10⁻¹⁷ m² at the lowest. Although shear zones such as melange units and decollements have been suggested as a main fluid conduit in accretionary prisms, presented study showed relatively impermeable nature of melange rocks. On the other hand, permeability of the fractured rocks was measured to be relatively high, suggesting these fractures as an important conduit for fluid transport processes within accretionary prisms.

1. Introduction
Previous studies of accretionary complexes have argued that shear zones such as mélangé zone, decollements and other thrusts may act as a main fluid conduit within the accretionary prisms (Agar, 1990, Yamano et al., 1992; Hyndman et al., 1995). However, studies of the hydrological properties of rocks such as porosity and permeability have been limited in the toe region of an accretionary prism (Bray and Karig, 1985; Byrne et al., 1993) and it can hardly be said that fluid transport properties of an accretionary prism has been fully solved. Fluid transport properties of an accretionary prism should reflect the state of pore spaces or fracture distributions of the materials within the prism. In order explore the fluid transport properties within an accretionary prism, porosity and permeability variations must be evaluated in the whole structural ranges. In this study, we measured porosity of rocks from the Shimanto belt in Kochi prefecture, under the atmospheric pressure and gas permeability of the Shimanto rocks under high confining
pressure at room temperature.

The study area is located in the Shimanto belt in Kochi prefecture, SW Japan (Fig.1). The Shimanto belt is one of the typical accretionary prisms, and its geological settings have been well studied (e.g. Taira et al., 1988). The Shimanto belt shows an overall younging towards the south or southeast (oceanic side) and is divided by Aki Tectonic Line (A.T.L.) into the “Northern belt” of Cretaceous age and the “Southern belt” of Tertiary age. The southern half of the Shimanto belt is located almost above the seismogenic zone of the Nankai subduction zone. Porosity, permeability and sedimentary age data for rocks from oceanic region are available in the report of the Ocean Drilling Program (ODP, Taylor and Fisher, 1993) (Fig.1).

3. Experimental

Porosity measurement was made on sandstone and mudstone samples collected from the studied area. Porosity values were estimated from the volume of water that replaced the pore space of a sample immersed in water inside a vacuum chamber. Representative samples used for the porosity measurement were used again for permeability measurement after drying them at temperature of about 85 degree for about a week to evaporate the pore water.

For the permeability measurements, a gas-medium triaxial deformation and fluid flow apparatus was used. In this study, nitrogen gas was used as a pore fluid and two methods; constant flow rate method and oscillating pore pressure method (Kranz et al., 1990; Fischer, 1992; Fischer and Paterson, 1992), were used for the measurements. On both methods, confining pressure was changed in a step-wise manner up to 200 MPa and permeability was measured for each step of the pressure changes. In the constant flow rate method, pore pressure of the upstream reservoir was maintained constant at a given value within range of 0.16 to 0.9 MPa above atmospheric pressure while the downstream side was vented to the atmosphere. In the oscillation method, pore pressure was maintained constant at around 20MPa.

4. Results

Shimanto belt is characterized by the overall younging of sedimentary age toward south (ocean side) and thrusts that divide Shimanto belt into several units. As shown in Fig.2, however, porosity of the measured core samples from the Shimanto belt shows no remarkable relationship with these macroscopic structures. The porosity of the Shimanto rocks is measured to be extremely low, mostly less than 5% (Fig. 2). Previously reported porosity of the core samples of ODP Leg 131 at site 808 is mostly at more than 40% near the seafloor and decreases with depth or with sedimentary age down to 28% at about 1km depth (Taylor and Fisher, 1993). Here, note that samples from the southern toe of Muroto Peninsula are in the same sedimentary age (Miocene) with the samples reported in ODP Leg131 from the deepest portion of the site 808 core (e.g. Olafsson, 1993, Soh et al., 1993). Porosity of these samples show about 30% difference. Permeability of the massive rocks are about $10^{-15}$ m$^2$ under low effective pressure (Pe) and lower than $10^{-19}$ m$^2$ at high Pe. On the other hand, permeability of fractured rock are about $10^{-17}$ m$^2$ at
5. Discussion

Porosity value of the Shimanto rocks are mostly less than 5% except for the rocks of Shijujiyama formation (15 – 25%), and no systematic change of the value related with the thrusts or sedimentary age of the Shimanto belt was observed (Fig.2). Comparison of the porosity between the Shimanto belt and the ODP borehole data showed that rocks with the same sedimentary age have extremely different porosity or permeability in the accretionary prism. The porosity-depth relationship of rocks compiled by Bray and Karig (1985) for sedimentary basin and accretionary complex regions in the world shows that porosity decreases with depth for both regions. According to this relationship, the porosity of the accreted sediments becomes lower to 5% at the depth of more than 5km. This relationship suggests the maximum burial depth of the Shimanto belt, which has low porosity less than 5%, to be deeper than 5km.

Bray and Karig (1985) proposed that porosity decreases systematically with depth faster in accretionary prisms than in normally consolidating basinal sections because of the additional tectonic stresses resulting from plate convergence. This implies that the tectonic deformation is one of the mechanisms of porosity reduction in the accretionary prisms. According to Bray and Karig(1985), the difference of porosity between the accreted sediments and normally consolidated basinal sediments is about 5 - 10% at the depth deeper than 5km. Tectonic stresses associated with accretion should contribute to the porosity reduction of the Shimanto rocks to some extent at the depth deeper than 5km.

Sedimentary rocks found in the outcrops of the Shimanto belt are mostly well lithified. This intense lithification seems to be due not only to compaction but also to cementation processes. Cementation should have been one of the mechanisms of the porosity reduction for sedimentary rocks in the Shimanto accretionary prism.

Several papers have reported on the thermal histories of the Shimanto belt using methods of fluid inclusions (Sakaguchi, 1999), vitrinite reflectance (Yanase, 1996) or fission-track analysis (Tagami et al., 1995). They have estimated the maximum temperature of the Shimanto belt, and figured out the maximum burial depth of the Shimanto belt with the maximum temperature and the geothermal gradient data. Most of these studies agree that the maximum burial depth of the northern belt was 10-12km and that the southern belt was 6-10km. These values can be regarded as consistent with the estimated depth conditions in this study from the porosity-depth relationship.

6. Conclusions

Porosity of rock samples from the Shimanto belt is measured mostly to be less than 5%, and no systematic change of the the value can be recognized related to the thrusts or sedimentary age of the Shimanto belt. Sample of Miocene age of the ODP core at site 808 of the Leg 131 shows much higher porosity of about 30% than the same age samples from the Shimanto belt. This
A remarkable difference of the porosity between the two same-aged samples may be explained with porosity-depth relationship as a result of compaction of the Shimanto belt due to burial to the depth of approximately more than 5km. This estimated depth of the Shimanto belt agrees with the estimated depth reported in the studies of thermal histories of the Shimanto belt.

Permeability of the massive rocks is about $10^{-15}$ m$^2$ under low effective pressure (Pe) and lower than $10^{-19}$ m$^2$ under high Pe. On the other hand, the permeability of the fractured rocks is about $10^{-17}$ m$^2$ at lowest. Although shear zones such as melange units and decollements have been suggested main fluid confuits in accretionary prisms, presented study showed relatively impermeable nature of melange rocks. On the other hand, the permeability values of the fractured rocks were measured to be high, suggesting that fractures would play an important role in fluid transport processes within accretionary prisms.

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Fig. 1 Shimanto belt in Kochi Prefecture and study areas of this study. ODP sites are shown as solid circles.
Fig. 2: Porosity of the Shimanto rocks plotted against sedimentary age. Data from the ODP core at site 808 (Taylor and Fisher, 1993) are also shown for comparison.

Fig. 3: Permeability of Shimanto sandstones and mudstones. (a) Massive sandstone and mudstone from coherent unit of the Northern Belt, (b) massive sandstone and mudstone from melange unit of the Northern Belt, (c) massive sandstone from coherent unit of the Southern Belt, and (d) pelitic matrix part of melange zone and fracture developed sandstone samples.