Existence of stagnant fresh groundwater and diffusion-limited chloride migration in a sub-sea formation at Yatsushiro Bay, Japan

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Abstract We attempted to evaluate long-term behaviour of saline groundwater by analysing chloride concentration and chlorine isotopic ratios of porewaters obtained from the sub-sea formation at Yatsushiro Bay, southwest Japan. Chloride concentrations and stable chlorine isotopic ratios were measured on 13 porewater samples. Porewaters with chloride concentrations higher than 16 400 mg/L are found at depths shallower than 1.5 metres below sea floor (m b.s.f.). Chloride concentrations decrease downwards gradually, and become lower than 250 mg/L below 7.7 m b.s.f. The stable chlorine isotopic ratios show a minimum value of –1.27 ‰ at 5.5 m b.s.f., and those from other depths show minor fluctuation, from –0.45‰ to 0.11‰. From these results, diffusion is considered to be the dominant process for the transport of chloride at the location studied.

Key words seawater intrusion; diffusion; stable chlorine isotope; groundwater

INTRODUCTION

Understanding the mechanism of solute transport has become an important issue for studies on water and mass movement in the coastal area. Previous research results on the porewater chemistry of coastal sub-sea formations (e.g. Hathaway *et al.*, 1979; Groen *et al.*, 2000) have shown the existence of fresh to brackish porewaters. It has been suggested that the low permeability clayey formations that were deposited by transgression after the last glacial maximum, significantly delay the intrusion of sea-water into lower formations, so contributing to this occurrence (Groen *et al.*, 2000). Kooi *et al.* (2000) conducted numerical experiments and showed that the low permeability material controls the patterns of seawater intrusion into the sub-sea formation.

In this study, we tried to evaluate the physical mechanism of seawater intrusion into the sub-sea formation where marine clay is deposited, through drilling, porewater sampling, and analysing chlorine isotopic ratios. Chlorine isotopic ratios are used as a measure for evaluating the mechanism because differences in diffusion coefficients of chlorine isotopes caused by the difference in molecular mass create isotope fractionation (Senftle & Bracken, 1955; Desaulniers *et al.*, 1986; Kaufmann *et al.*, 1988; Eggenkamp *et al.*, 1994) but fractionations are not caused by hydrodynamic dispersion processes (Fig. 1). Thus, fractionation of the chlorine isotopic ratio caused by diffusion process can be measurable and be useful as direct evidence of diffusion.

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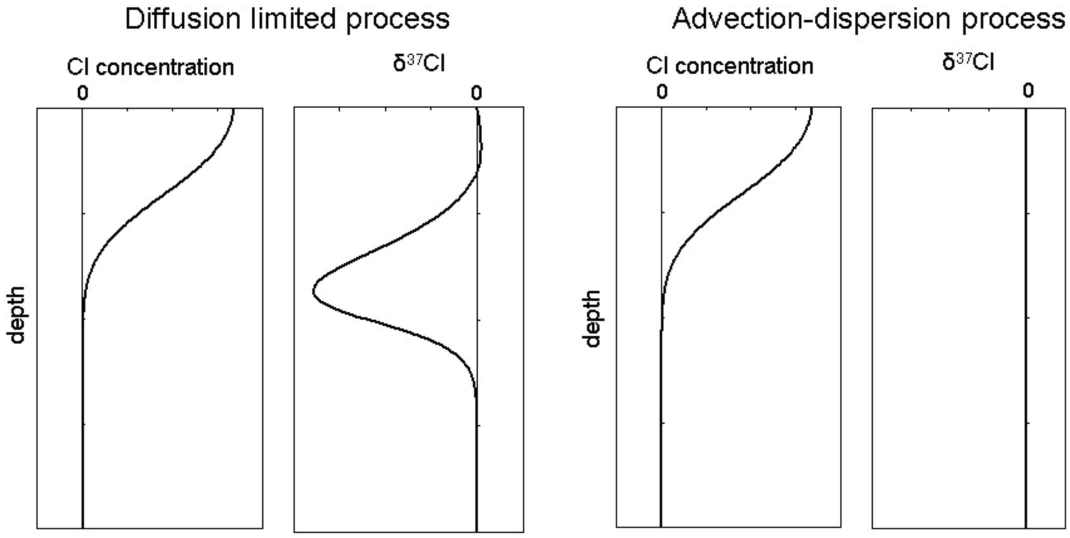

Fig. 1 Conceptual diagrams showing different profiles formed by the diffusion-limited process (left) and the advection–dispersion process (right). Note that chloride concentrations show very similar profile shapes while stable chlorine isotopic ratios show distinct differences. This diagram was constructed by a sedimentation–diffusion coupling model after Kimura (2006).

DATA OBTAINED

We drilled a 50-m borehole and took continuous sub-sea core samples where the average water depth is about 3 m, offshore of Eino-o, Kumamoto Prefecture, Japan (Fig. 2). At the study site, tuff breccia of late Pliocene to early Pleistocene is present from 3.8 m below sea floor (m b.s.f.) to the bottom of the borehole (50 m). Marine clay deposited after the last glacial maximum covers the tuff breccia. Porewaters were extracted from core samples both using a squeezing method for the rock cores and a centrifuge method for the marine clay. Then, we measured chloride concentrations and stable chlorine isotropic ratios on 13 porewater samples to construct these profiles.

DISCUSSION AND CONCLUSIONS

Figure 3 shows the results obtained. Porewaters with chloride concentrations higher than 16 400 mg/L are found at depths shallower than 1.5 m b.s.f. Chloride concentrations decrease downwards gradually, and to lower than 250 mg/L below 7.7 m b.s.f., showing an apparent diffusion profile. This result clearly shows the existence of fresh groundwater in the sub-sea formation at the location studied. The stable chlorine isotopic ratios show a minimum value of –1.27‰ at 5.5 m b.s.f., and those from other depths show minor fluctuation, from –0.45‰ to 0.11‰. Also, the profile of the stable chlorine isotopic ratios shows a very similar shape to that shown in Fig. 1. From these results, diffusion is considered to be the dominant process for the transport of chloride. Thus, fresh groundwater below 7.7 m b.s.f. is considered to be stagnant fresh groundwater, the existence of which has been controlled by the deposition of the low

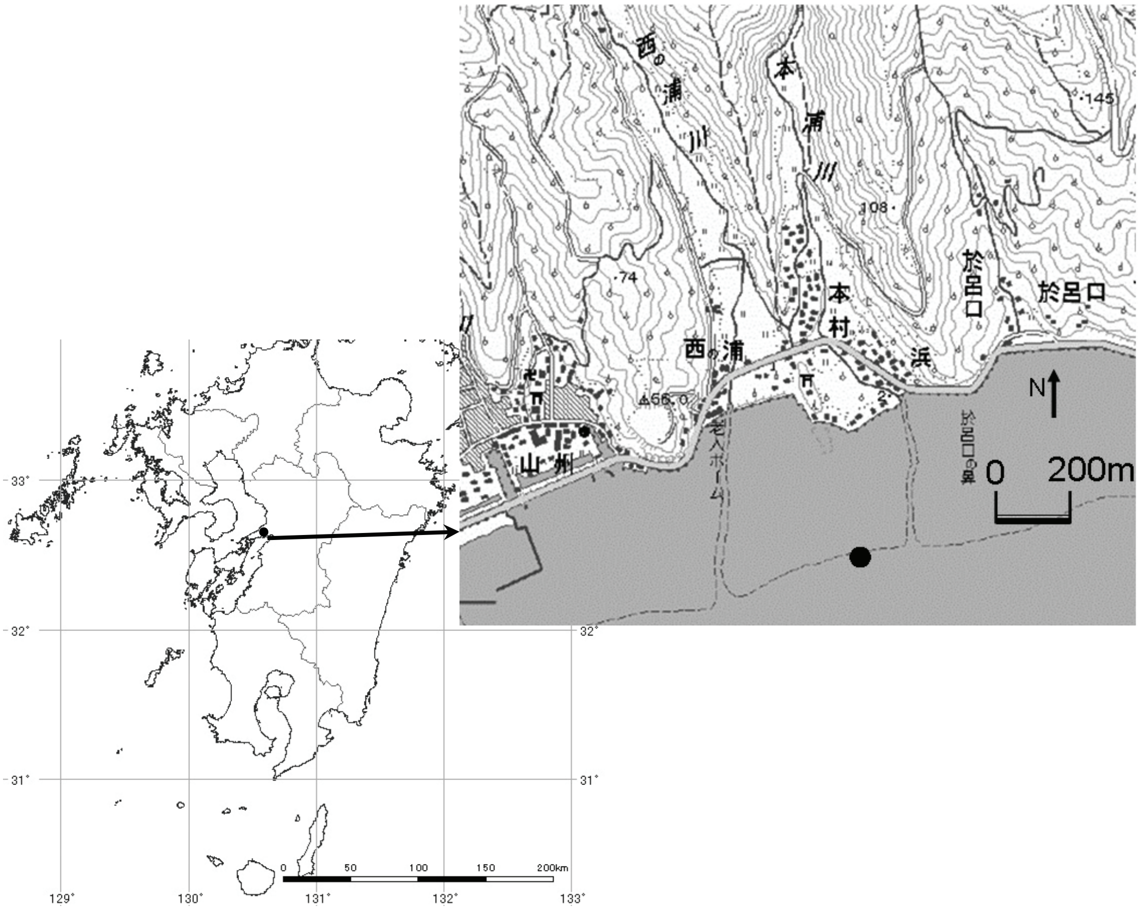

Fig. 2 Location map of the borehole studied. Topographic map (right) is a part of 1:25 000 scale "Matsuai" by the Geographical Survey Institute, Japan. The dot indicates the location.

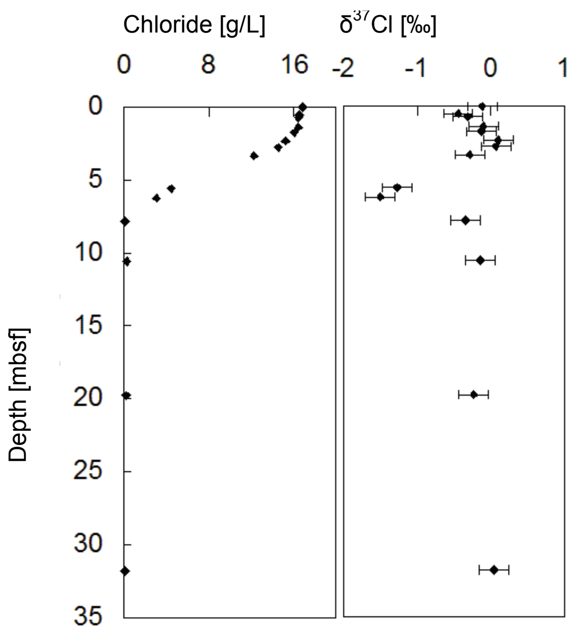

Fig. 3 Chloride concentration and stable chlorine isotopic ratios.

permeability clay formation. Further studies on modelling the process, and age determination of the fresh groundwater in the sub-sea formation are in progress, and we believe that quantitative understanding of the intrusion process is achievable.

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