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Fluid-sediment interactions in the Nankai subduction zone (NanTroSEIZE): pore fluid and mineralogical records

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Abstract

The Nankai Trough Seismogenic Zone Experiment (IODP), SW Japan, aimed at unraveling hydrologic processes at subduction megathrusts and *in situ* rock and fluid properties to understand the fault zone behavior during earthquake nucleation and rupture propagation. At different sites, characterization of the sediments at high resolution allows tracing fluid–rock reactions that are either associated to early transformations (hydration or dehydration of clay minerals) during the accretion phase or to mineral recrystallization processes linked to deformation phases in gouge zones. In the sedimentary strata at the front of the accretionary prism changes in clay composition are inferred from chemical trends observed in pore fluids, which further indicate the influence of volcanic ash alteration (zeolite formation). Along the megasplay fault, recrystallization processes (e.g. pyrite) are observed in foliated gouge zones at the contact with non-foliated silty clay. The data highlight the importance of small-scale observations for process and reactive phases such as clays in such variable fluid-sediment reactions.

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Keywords: sediments; subduction front; pore fluids; deformation; gouge; clays ; NanTroSEIZE; IODP 316; IODP 322; IODP 333.

1. Introduction and background

A main goal of the IODP NanTroSEIZE Experiment is to determine the seismo-mechanical behavior of the major thrust faults of the Nankai accretionary prism offshore SW Japan. The Nankai prism is characterized by a basal décollement that is regarded as the plate boundary SW of the Kii peninsula. The

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prism is crossed by a major megasplay fault and is considered to have experienced co-seismic slip during the 1944 M 8.2 Tonankai earthquake. At the prism front, drill hole investigation documents the incoming sedimentary pile and basement (Fig.1). Two aspects of the effects of fluid flow and fluid-sediment reactions were investigated at different sites of the prism (i) the processes evidenced by the chemical evolution of interstitial fluids in relation to the lithology and mineralogy of the sedimentary strata (IODP 322 and 333, [1, 2]) and (ii) the record of deformation induced fluid-rock interaction in gouge zones linked to the splay fault (IDOP 313, [3, 4]).

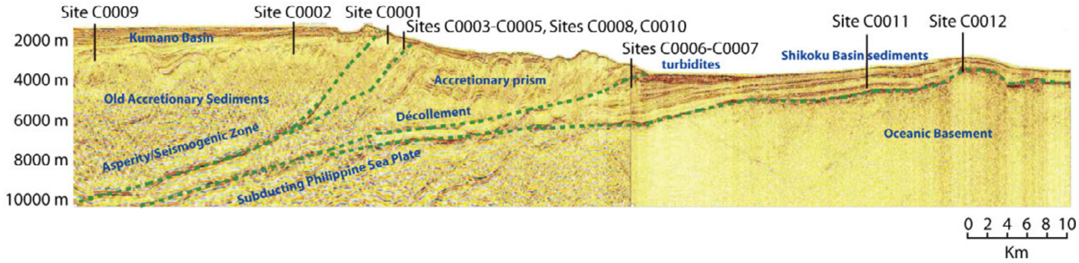

Fig.1. Seismic profile along the Nankai Trough axis, with the major geologic features along the transect and all NanTroSEIZE drill sites (©IODP-document sci. prosp. 332). Studied Sites are C0007 at accretionary prism wedge and C0011-C0012 inward the basin.

2. Interstitial fluids chemistry as tracer of early diagenetic processes in incoming sedimentary pile

The compositions of hemipelagic muds, turbidites and volcaniclastic beds vary slightly with depth as a function of their contents in pelagic, detrital, volcanogenic and authigenic mineral phases. These compositional changes are also reflected in the composition of extracted pore fluids.

Pore fluids were obtained from two sites drilled in the Shikoku Basin (IODP 322-333) on the northwestern flank (C0011) and near the crest of the Kashinosaki Knoll (C0012) where the basement was reached at 537.81 m CSF (Cored below Sea Floor) [1, 2]. Immediately after whole-rock samples squeezing, extracted pore fluids were analyzed for pH and alkalinity. Routine shipboard chemical analyses comprised chlorinity via titration with silver nitrate, sulfate and cations by ion chromatography and minor chemical elements by ICP-AES [5]. In order to test the equilibrium state of pore fluids of the sedimentary pile regarding to observed mineral phases and to explore the chemical evolution due to secondary mineral precipitation, the saturation states of pore waters were calculated using the PhreeqcI code [6] and the EQ3/6 database (llnl.dat, [7]) Heat fluxes measurements [2] evidenced a positive anomaly on Kashinosaki Knoll and provided temperature gradients of T(°C) = 1.7 + 0.091 x depth (m CSF) for Site C0011 and of T(°C) = 2.8 + 0.135 x depth (m CSF) for Site C0012. The changing fluid temperature was taken into account in the thermodynamic simulations.

pH values in both sites increase with depth from 7.5 to 8.5. In the upper part of the sedimentary piles microbiological sulfate reduction produces carbonate alkalinity which becomes controlled by calcite precipitation at greater depth as Ca is produced by alteration of ash levels (Fig. 2). Ba concentration is controlled by barite precipitation. The evolution of pore fluid chemistry is consistent with alteration processes of volcanic ashes, which modify the primary clay association (illite, chlorite, smectite, I/S interlayers) by an increase of authigenic smectite contents and significant occurrence of very small-sized zeolites (≈10µm, e.g. clinoptilolite). In the pore fluid chemistry this is indicated by the total consumption of Mg and K and the increase of Ca concentration with increasing depth. Zeolite precipitation in highly altered lower half of the C0012 profile results in the consumption of Na.

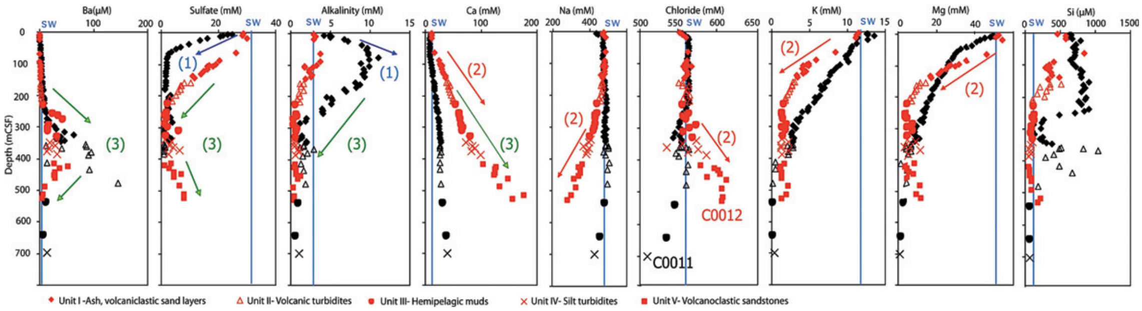

Fig. 2. Interstitial fluid chemistry at sites C0011 (black) and C0012 (red). The blue line (SW) indicates the seawater. Trend lines are given for sulfate reduction near surface (1), alteration of volcanic phases (2), mineral precipitation reactions as deduced from mineral saturation states (3).

Chloride concentrations show two different trends between the two sites. On site C0012, Cl concentrations increase below about 300 m CSF due to the formation of hydrated minerals (e.g. smectite and zeolite in volcanic layers). In contrast, Cl decreases below 500 m CSF on site C0011 concordant with an increase in the I/S content. Smectite dehydration and early illitization under compressive conditions may explain this trend in Cl as also encountered in other boreholes from Nankai Trough.

3. Fluid reactions in the foliated gouges

Drillcores were recovered from both the basal décollement and the megasplay fault of the Nankai accretionary wedge (IODP 316, [3, 4]). In the frontal part of the prism, three fault zones were identified at Site C0007. From each of the two lower fault zones, two 30 cm-long core intervals containing intact (not drilling-disturbed) millimeter-thick dark fault gouge zones were the subject of non-destructive mineralogical and chemical (XRF core imaging scanner) investigations [8, 9, 10], and subsequently cut for microstructural analyses in thin sections.

The lowermost fault in borehole C0007D separates Pliocene hemipelagic muds with minor ashes (unit III) from subducted Pleistocene trench turbidites (unit IV) at about 435.8 m CSF. It is interpreted to define the basal décollement of the wedge [3, 4]. A gently dipping dark brown gouge zone (316-C0007D-29R-2, 37-73 cm) divides the basal décollement in the core interval into a hanging-wall consisting of intensely fractured green hemipelagic mudstones and a footwall made of weakly fractured green siltstones with grey ash intercalations. The gouge zone is only 2-8 mm thick with a dip of 8°. It displays sharp boundaries with the surrounding host rock. Two other gouge zones are found 10 cm and 14 cm above the main one. Near the fractures, the otherwise greenish color of the mudstone color gets darker, suggesting fluid-rock interaction.

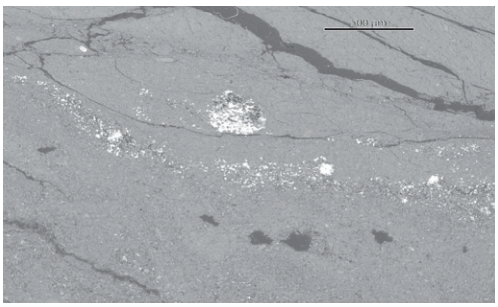

Fig. 3. Recrystallized pyrites (white) outlining the boundary between the shear zone foliated gouge and undeformed footwall siltstones. The large spherical primary pyrite was not affected by deformation (SEM-EBSD, C0007 438.35 mCSF; scale bar 500µm).

Microscopic and SEM observations show that gouge zones consist of foliated clayey material with very small < 0.1 mm clasts of hemipelagic mudstone. In the main gouge, shear bands deflect the foliation, suggesting a non-coaxial deformation compatible with a reversed shear direction.

The lower boundary of the main shear zone is sharp and is outlined by tiny (about 20 µm long) euhedral to subhedral pyrite crystals possibly formed at the expense of primary pyrite framboids observed in the intact rock above and below the gouge zone (Fig. 3). Pyrite recrystallization suggests that at the lower boundary of the gouge significant small-scale fluid-rock reaction occurred. The conditions of such localized reactions are further defined by potential illitization processes as e.g., observed in other gouges (Site C0004, [10]).

4. Conclusions

At the reference Sites C0011-C0012 for the incoming sedimentary input in the Nankai subduction zone, the complexity of sediment-fluid interactions is a function of the compositional variability of deposited sediment layers such as local influence of volcaniclastic layers in the early diagenetic processes and the transfer of solutes in the pore fluids. Such variation in rock and fluid compositions implies investigations at small scale prior to define a global mass transfer and fluid flow. In the accretionary wedge at Site C0007 near the décollement zone, the deformation forms gouges zones. The imprint of fluid reactions in foliated clayey gouges is localized, and marked by recrystallization of pyrite and possibly illitization. In both domains of the subduction megathrust, main reactions appear to be the evolution of the clay mineral assemblage with hydration-dehydration reactions. Integration of data from others sites will further specify the importance of such small-scale processes during the evolution, deformation and rupture events of the subduction zone.

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