Surface Observations of Subduction Related Mud Volcanoes and Large Thrust Sheets in the Nankai Subduction Margin; Report on YK00-10 and YK01-04 Cruises

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This paper mainly presents preliminary dive results of the YK00-10 Leg-1 cruise which was conducted at the Nankai subduction margin from October 19th to November 11th, 2000 by the "Shinkai 6500" manned submersible of JAMSTEC. Four dives were carried out in the Kumano forearc basin, and another four dives were off Muroto. Dive results of the YK01-04 cruise also involved and reported in this paper. Dives in the Kumano basin revealed that the several mud volcanoes are existing associated with cold seeps and biological colonies on the top of them. However, each mud volcano has different activity. We identified the activity and classified them based on the dive results and the pre-dive geophysical survey data. Dives at the large thrust sheets off Muroto revealed that the thrusts are active and discovered some evidences of cold seeps from the cliff. Those observations links surface manifestations of crustal deformation that caused by the Philippine Sea Plate subduction beneath the SW Honshu arc.

Keywords: Nankai Trough, Mud Volcano, Seismogenic Zone, Large Thrust Sheet, Out-of-Sequence Thrust, Cold Seep, Calyptogena, Methane Gas Hydrate

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1. Introduction

The Nankai Trough is the subduction margin between the Shikoku Basin (Philippine Sea Plate) and the SW Honshu arc (Eurasia Plate) at 4cm/yr (Fig. 1). The current accretionary prism is building from the trench axis and increasing in thickness landward. Several seismic profiles provide excellent images of this prism building. The Cretaceous to Tertiary Shimanto Belt is exposed from the Ryukyu arc to the middle of Honshu arc. The subducting oceanic plate beneath the Shikoku Basin was spreaded by 15 Ma. Many geological, geophysical and geochemical data have been accumulated and are available for use now.

The YK00-10 Leg-1 cruise has two target areas to survey with the "Shinkai 6500" manned submersible in the Nankai subduction margin. One target area is the Kumano forearc basin area and the other is the offshore Muroto Peninsula area.

The Kumano forearc basin is located east of the Kii peninsula. The water depth is approximately 2,100m, and the basin is filled with thick terrigeneous and hemipelagic sediments. Kuramoto et al. (1998) revealed the existence of several mud volcanoes in the basin by using a side-scan sonar image (Fig. 2). Several seismic profiles, which cross near the mud volcanoes, suggest the origin of these mud volcanoes is caused by thrust activity beneath the forearc basin. The thrust faults may originate in the seismogenic zone of the plate boundary between the subducting Philippine Sea Plate and the overriding Eurasia Plate. Kanamori (1972) showed a fault plane model of the Tonankai earthquake that occurred in 1944. That earthquake should be a substantial candidate for the suggested fault that continues from the seismogenic zone to the mud volcanoes. If this assumption is correct, the mud volcanoes are windows into the deep crustal section where large inter plate earthquakes will be generated in the future. Seismic profiles also show obvious gas hydrate BSRs (Bottom Simulating Reflectors) beneath the mud volcanoes. Methane gas hydrates, escaped gas bubbles, cold water seeps and related biological colonies are expected on the summit of the mud volcanoes. The formation mechanism of the
mud volcanoes in the Kumano forearc basin relates to various kinds of scientific problems; seismogenic zone, methane gas hydrate, fluid circulation, etc. These problems are closely related to each other and to the subduction dynamics of the Nankai subduction margin.

In 1999, a Japan-U.S. collaborative 3-D reflection seismic survey of the seismogenic zone of the western Nankai subduction margin was successfully carried out (Bangs et al., 1999; Kuramoto et al., 2000). The research group imaged an 8×80 km area with 81, 80-km-long, high-quality, seismic reflection lines. All of the seismic lines have nearly continuous coverage. The clear image of the Nankai margin gives us a significantly obvious picture of the inner structure of the accretionary wedge at the offshore Muroto Peninsula area survey site (Fig. 3 & 4). One remarkable image from the seismic profiles is the identification of large thrust sheets (LTS) zone in the middle of the 3-D survey box. The thrusts are identified as out-of-sequence thrusts (OSTs). The OSTs may be derived from the up-dip limit of the seismogenic zone of the Nankai subduction margin based on a preliminary 3-D interpretation (Kuramoto et al., 2000). Therefore, surface manifestations such as cold water seeps on the seafloor, may be suggestive of the activity of OSTs and may yield direct information about the seismogenic zone. Submersible dives will focus on finding surface manifestations caused by the OST activities such as; cold seeps, chemosynthetic biological colonies, authigenic carbonate veneers, bacterial mats, thrust outcrops, etc. It is surface observation, but it may be equivalent to deep crustal observation.

2. Kumano Mud Volcanoes
2.1. Recent Scientific Activities
IZANAGI side-scan sonar imagery shows significant black dots in the Kumano forearc basin (Kuramoto et al., 1998). The data were collected by cooperative experiments between the Geological Survey of Japan (GSJ) and the Ocean Research Institute, University of Tokyo (ORI). "IZANAGI" is a nickname of ORI's wide-range side-scan sonar system. The black dots are located...
in the middle of the basin and arranged in a line. High-precision topographic data in the Kumano basin shows that the black dots are mounds or small seamounts. In 1999, we proposed to dive with “Shinkai 6500” on the high backscatter mounds. Three dives were conducted to confirm that the high backscattered mounds were mud volcanoes, which consisted of mud-supported angular rocks (Nakamura et al., in preparation). Some seafloor manifestations of cold water seeps were also observed on the summits of the mud volcanoes. The origin of the mud volcanoes may be closely related to a thrust fault which is expected just beneath the mounds.

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Fig. 3 A 3-D seismic survey area in the western Nankai accretionary prism (white dashed line box). A shaded topography derived from the 3-D seismic survey is overlaid with a multibeam swath bathymetric data. Solid rectangle shows the area of figure 8.

Fig. 4 An example of 2-D seismic profile from the 3-D seismic survey box is presented with a structural interpretation (modified from Kuramoto (2000)). Dive area is indicated by an arrow.
2.2. Dive Observations on the Kumano Mud Volcanoes

Four dive observations are conducted at the Kumano Mud Volcanoes, Dive #585-588 (Table 1). The dive #585 surveyed the summit of mud volcano #6 (Fig. 2). This mud volcano has an ellipsoidal shape with 2,000m in N-S and 1,300m in E-W at the base. It is 80m high above the basin floor and has a 600m wide summit. The mud volcano covered by hemipelagic sediments and has no evidence of recent fluid expulsion on the summit. A Calyptogena shell was observed during the entire dive track.

Dive #586 and 587 were carried out on the mud volcano #5 that has two peaks. Dives were conducted on the southern summit, because previous dive surveys have been carried out at the northern peak by Nakamura in 1998 (Dive #527 & #528). The height of the mud volcano is approximately 160m from the seafloor which is 2,060m. The diameter of the mud volcano is about 1,500m. The topography of summit shows a little bit bumpy, and small depressions are observed. The depressions are filled with Calyptogena colonies that covered by some bacterial mats (Fig. 5). On the summit, many gravels and boulder-sized rocks are exposed (Fig. 6). The number of exposed rocks increases from the flank to the summit. Some debris flows sediments are also observed on the flank that suggest an active expulsion process of the mud volcano #5.

Dive #588 surveyed at the mud volcano #3 which was characterized by prominent back-scatter signal but by a weak morphological expression. Its height above the surrounding seafloor is approximately 20m at the most and the aerial extent probably less than 500m in diameter. The mud volcano has a broad summit of slightly undulating mound that contains scattered small and medium size Calyptogena colonies (Fig. 7). Absence of any ejecta, small diameter, and smooth morphology strongly suggest the feature is an incipient mud volcano, perhaps in "building" stage with fluid and/or gas front preceding eruption.

<table>
<thead>
<tr>
<th>Dive #</th>
<th>Date</th>
<th>Observer</th>
<th>Site</th>
<th>Objectives</th>
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<tr>
<td>585</td>
<td>2000.10.21</td>
<td>K. Nakamura</td>
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<td>reconnaissance survey of the #6 mud volcano and instruments test</td>
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<td>find any surface manifestation of OST activities</td>
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<tr>
<td>590</td>
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<tr>
<td>591</td>
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<tr>
<td>517</td>
<td>2001.6.5</td>
<td>S. Morita</td>
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<td>find any surface manifestation of OST activities</td>
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Fig. 5  A Calyptogena colony covered with bacterial mats on the summit of #5 mud volcano. Water depth is 1.910m.

Fig. 6  Many garvels and boulder sized rocks are exposed on the summit of #5 mud volcano. Water depth is 1.917m.
3. Offshore Muroto Peninsula
3.1. Recent Scientific Activities

A 3-D reflection survey was conducted in 1999 during a Japan-U.S. cooperative study of the seismogenic zone of the Nankai subduction margin. One of the prominent features is an identification of a large thrust sheets (LTS) zone that is located about 35km from the trench axis of the Nankai subduction margin. The LTS zone is characterized by the development of at least four major OSTs that separate tectonic slices of coherent thick sedimentary sequences. This LTS zone, which makes a relatively steep scarp, and the landward-tilted slope sediments suggest recent uplift activity. The large OSTs may be derived from the up-dip limit of the Nankai seismogenic zone (Kuramoto et al., 2000).

ODP drilling (Leg 190) was carried out on the LTS zone in 2000 (sites 1175 and 1176). According to the preliminary results of the drilling, the LTS zone is composed of very young and differing kinds of lithology from the trench sediments (Taira, per. comm.). These results probably suggest that the LTS zone has grown by an extraordinarily quick accretion process. The loose and highly permeable sediments may exist on the scarp are expected to be observed during submersible dives. The focus of the submersible dives is to find some surface manifestations caused by the OST activities, such as cold seeps, chemosynthetic biological colonies, authigenic carbonate veneers, bacterial mats, thrust outcrops, etc. These dives may be the first such experiments planned based on 3-D seismic data.

The upper slope of the LTS zone was investigated by the "Shinkai 6500" in 1999 (Fig. 8). Dive #519 (observer: Saito, S., ORI) discovered a Calyptogena colony with bacterial mats at a water depth of ~3,250 meters. Dive #578 was also done near this seep site for the purpose of pilot training of the "Shinkai 6500". The uppermost peak of the large OST zone is located 5km landward of Dive #519. Dives #582 and 584 found Calyptogena colonies at the seaward slope of this peak (observer: Tanahashi, M., GSJ). There is no indication of cold seeps during Dive #525 conducted on the north-eastern slope (observer: Matsubayashi, O., GSJ).

3.2. Dive Observations on the Large Thrust Sheets off Muroto

Five dives were carried out at the large thrust sheet zone which was identified by Kuramoto et al. (2000) based on the results of 3-D seismic survey. Dive #589 was just touch the seafloor and canceled because of a bad weather. Dives #590 and #591 were continuously surveyed in the middle of thrust sheets from approximately 4,000m to 3,500m in the 3-D survey box (Fig. 8). The LTS zone has a steep scarp and covered by thin sliding sediments in general. Some boulder-sized mud crusts (not consolidated well) were observed at the base of the scarp. Several "flat and cliff" or step like topography is common feature at the scarp. It is suggesting that the scarp is young and associated with active thrusts. A Calyptogena...
A colony was discovered at one of the slope breaks. The colony is associated with bacterial mats (Fig. 9).

Dive #592 conducted at the western edge of the 3-D box (Fig. 8). The dive observed a series of outcrops that consist of mudstone dominated or alternation of sands and siltstones turbidites from approximately 3,670m to 3,620m. This lithology seems to be very similar as reported by ODP Leg 190 drilling results at Site 1175 and 1176 (Taira, per. comm.). Dive #617 surveyed rather western area of the dive #592 where is out of the 3-D survey box. Both dives were not observed any biological manifestation of cold seep during the dives.

4. Summary on Dive Observations

4.1. Kumano Mud Volcanoes

Kuramoto et al. (1998) recognized seven shaded circular features in the towed side-scan sonar (IZANAGI) image in Kumano Basin. The image comes arise an idea that these features are the expression of high acoustic reflectivity at the surface of mud volcanoes. Most of them correspond to the features appeared on the previously taken seismic lines. We tentatively named these features from east to west through #1 to #7 Kumano mud volcanoes (Fig. 2).

Among seven shaded circular features, five of them appeared as cone-shaped mounds on the R/V Yokosuka's swath bathymetric survey prior to the "Shinkai 6500" dive program in November, 1999. The detailed bathymetric map also revealed that #5 mud volcano has two peaks aligned from NW to SE. Nakamura dove once on the #4 mud volcano and three times on both summits of the #5 mud volcano in the succeeding dive program in 1999. He collected various types of rocks in the mud on the summits (Nakamura et al., in preparation), which were about a hundred-meters higher than the surrounding basin floor. The rock occurrence could not be explained by surface transport from the continental shelf. Some of the rock samples were highly fractured and indicated their origin from deep beneath the seafloor.

Four dives were conducted on the Kumano mud volcanoes during the YK00-10 cruise, we summarize the mud volcanoes activity an developmental stage that includes previous dive results as follows:

Incipient stage (#3 mud volcano)

Its relief from the basin floor is only 10 to 15m with 500m in diameter. However, the shaded relief on the side-scan image and the back scatter attenuation by the swath bathymetry is almost the same as those of the other mud volcanoes. Active Calyptogena colonies developed on the broad summit. The number of the Calyptogenas in each colony was less than twenty. Dark-colored mud patches with 20 to 50cm in diameter, which were probably stained by sulfidic iron were sporadically distributed near the colonies. One push-core sample in a colony showed slight (% negative chloride anomaly in the sediment pore water. Several rock fragments were also observed near the colonies. The mud diapir must have penetrated the basin floor very recently or is about to do so.

Highly active stage (southern summit of #5 mud volcano)

The summit of #5 mud volcano is the narrowest from among the five dived mud volcanoes investigated. It is 300m in diameter at the top and about 150m high above the surrounding basin floor. The basal diameter of this cone feature is about 1,200m. The small-scale summit topography is characterized by 10 to 20m wide and 10m high undulation. It appeared be a mix of ridges, troughs, and depressions. Dense Calyptogena colonies with more than hundreds of specimens were scattered mostly in the troughs or depressions. Black iron sulfide-colored mud patches were mostly associated with the active colonies. One push-core sample near the sulfidic mud showed ca. 10% chloride depletion in the sediment pore water.

Fig. 9 A Calyptogena colony in the LTS zone. Bacterial mats are seen in the upper-left corner of this picture. Water depth is 3,706m.
which indicates continuous fluid supply from depth. Rock fragments of fine to coarse sandstone, fractured mudstone with carbonate veins and carbonate precipitates (less than 30 cm size) are abundant throughout the summit. This mud volcano exhibited the most prominent activity from among the five mud volcanoes surveyed.

Low active stage (northern summit of #5 mud volcano)
This mud volcano has biggest basal diameter, which is about 1,600m. Although it is slightly over 100m high above the basin floor, it has a clear summit depression nearly 1,000m wide as seen in the swath bathymetry map. Only one colony with ca. 30 Calyptogena individuals was observed. Sparse distribution of dead Calyptogena were scattered throughout the summit as well as abundant rock fragments.

Suspended or intermittent stage (#4 mud volcano)
This feature is characterized by gentle and wide slope near the base. The diameter at the base is nearly 2,000m, whereas that of the steep slope base is about 1,000m. It is 120m high from the basin floor and has a 400m wide summit. Although the dead Calyptogena were distributed throughout the summit, there was no active colony observed. Rock fragments were present throughout the summit as well as the flank. The fluid emission must have recently ceased.

Sediment-draped stage (#6 mud volcano)
This volcano has an ellipsoidal shape with 2,000m in N-S and 1,300m in E-W at the base. It is 80m high above the basin floor and has a 600m wide summit. Only one dead Calyptogena specimen was observed along the entire 2,000m dive track. Crustacean burrows were frequently observed as well as garbage on the surface mud. Only one small cluster of rock fragments was found at the SE-corner of the summit. There was no evidence of fluid expulsion on the summit; however, ejected rock fragments were clearly evident.

The five mud volcanoes investigated by "Shinkai 6500" dives showed a range of maturity in fluid venting activity as well as different stages of build-up of the main mud volcano’s body. They appear to range from the very incipient stage to the nearly extinct or buried stage.

4.2. Offshore Muroto LTS
Five dives were conducted on a large fault scarp, which lies 30km landward of the deformation front of the Nankai subduction zone. A 3-D seismic reflection survey reveals that several OSTs are developed beneath this scarp (Kuramoto et al., 2000). The faults are well imaged among the landward-dipping reflectors that correspond to stratified sedimentary sequences (Fig. 4). Dips of the faults are about 10 degrees. The main slope of the scarp dips southeastward at an average angle of ~8 degrees. The bathymetric map shows slope breaks trending both NNE-SSW and NE-SW, respectively (Fig. 8). The IZANAGI sidescan image also exhibits three lineaments with NNE-SSW and NE-SW trends. The northeastern and southwestern margins of this large OST zone consist of eastward and southward steeply dipping slopes.

The continuous surveys by Dives #590 and #591 crossed three major fault scarps at water depths of 3,900, 3,700 and 3,500 meters, respectively (Fig. 8). The previous Dive, #519, also crossed a fault scarp at a water depth of 3,200 meters. We named these four fault scarps as Scarps "A" to "F" (Fig. 10). No cold seeps were found along Scarp A, although loose consolidated siltstone strata crop out. The siltstone is occasionally fractured and dispersed among an unconsolidated mud veneer. Calyptogena colonies and bacterial mats were found at the western end of the dive track along Scarp B (Fig. 8). Zigzag surveys along Scarp B showed continuity of the NE-NW-trending steep slope. There was no other indication of seeps except for an observation of dead clams at the eastern end of the dive track. Partly consolidated siltstone strata were exposed along a steep portion of Scarp B. Dive #592 was conducted to confirm the southwestward continuity of seeps along Scarp B. Consolidated siltstone were well exposed along the scarp. Surfaces of a siltstone sample exhibit slickensides although the fault outcrop itself was not observed. Shell fragments were observed at a water depth of 3670m. Alternating sand and siltstone were exposed at a water depth of 3,623m. Scarp C was observed as a steep slope with small outcrops composed of consolidated mudstone. This scarp is characterized by a few shell fragments and possible Calyptogena search traces. Dives #589 and #617 were conducted at the base of the northeastern slope. There was no indication of tectonic defor-
Scarp C may also indicate recent venting. These scarps correspond to OSTs that were imaged on MCS profiles (Fig. 4 & 10). The thrust faults may be regarded as conduits of up-dip fluid flow. Shorebased geochemical studies may provide us with information about the fluid sources. The MCS profile crossing Scarp A shows that probable surface sliding of the sediment veneer completely covered the OST. These surface sediments could prevent fluid expulsion from the thrust fault.

This paper presented a brief dive result of the YK00-10 and a part of the YK01-04 cruises. More detail analysis and shorebased studies (i.e. geochemical analysis of sampled water, microbiological analysis, etc.) are in preparation by authors, and will be reported as soon as possible.

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