

# Large Mass Transport Deposits in Kumano Basin, Nankai Trough, Japan

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**Abstract** Large-scale landsliding is a common process in the Kumano Forearc Basin of the Nankai Trough accretionary prism. We use a 3D seismic data volume to map the seafloor reflection, which shows that there are two surficial landslides, one rotational slump  $\sim 3.4$  km wide, 1.8 km long and 150 m thick and one disintegrative slide that has left a seafloor scar  $\sim > 3.65$  km wide, 2.6 km long and  $\sim 200$  m deep. We see no evidence for any deposits related to the latter in our data, so the entire mass must have been transported as debris flows/turbidites outside the area covered by 3D data. The slump failures occurred along a bedding plane that dips  $\sim 5-7^\circ$  landward, but the disintegrative landslide has a gently-dipping base and is associated with steep normal fault scarps. Several large subsurface mass-transport deposits (MTD)s are mapped in the 3D seismic data – all have slid along single landward-dipping bedding planes. Their bases range in depth from 140-700 metres below sea floor (mbsf). The thickest MTD is  $\sim 6.5$  km<sup>2</sup> x 155 m thick, encompassing a volume of  $\sim 1.0$  km<sup>3</sup>. The three other large MTDs range from 0.3-0.6 km<sup>3</sup> in volume. The toes of the MTDs are imbricated, and the imbricate structure, as imaged in continuity displays, is aligned parallel to the slope. Many less extensive, thinner ( $< 20$ m thick) MTDs are also present in the Kumano Basin. Regional seismic-stratigraphy and age-constraints on MTD-correlative seismic reflections drilled at IODP drill Sites C0009 and C0002 reveal that four of the investigated MTDs are younger than 0.3-0.44 Ma, three are 0.44-0.9 Ma, and three others are between  $\sim 0.9$  and 1.24 Ma.

**Keywords:** Nankai Trough, Kumano Basin, submarine landslides, MTD

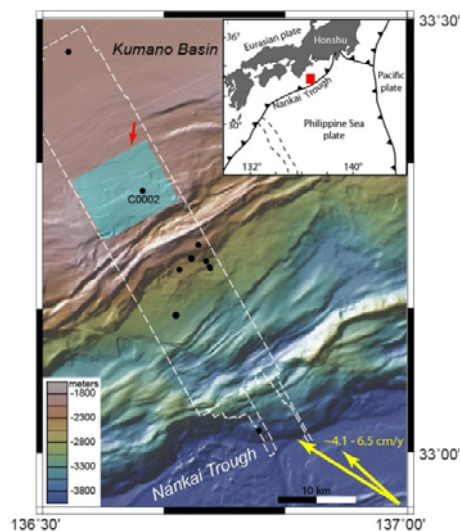
## 1 Introduction

Submarine landslides are common on active margins because of the interaction between tectonic uplift that creates steep slopes and frequent earthquakes that serve as landslide triggers. The landslides are capable of generating destructive tsunamis that can devastate nearby coastal communities (e.g., Bardet et al 2003; Satake 2012). Quaternary landslides on the Nankai Trough outer accretionary wedge have occurred at toe (Kawamura et al., 2012) and in trench slope basins (Strasser et al. 2011, 2012).

In this study, we describe several Quaternary submarine landslides and their deposits in the Kumano Basin of the Nankai Trough inner accretionary prism. We restrict our analysis to the seaward part of the basin (blue area in Fig. 1) because the recent slide scars and most of the large buried mass-transport deposits (MTDs) are restricted to this region.

### 1.1 Geologic Setting

The Nankai Trough is the locus of subduction of the Philippine Sea plate beneath southern Japan (Fig. 1). Plate convergence occurs at a rate of  $\sim 4.0$ - $6.5$  cm/yr at an azimuth of  $\sim 300$ - $315$  (Seno et al. 1993; Miyazaki and Heki 2001). Accretion of a thick section ( $> 1$  km) of terrigenous sediment has built a wide accretionary prism (Aoki et al. 1982). Landward of the actively deforming outer prism is the less active inner prism (Wang and Hu 2006) that is capped by the Kumano forearc basin (Okino and Kato 1995). Kumano Basin has formed since  $\sim 1.95$ - $2.0$  Ma behind a ridge that is believed to have been uplifted by movement along the mega-splay fault (Gulick et al. 2010; Moore et al. in press). The basin strata are cut by a series of normal faults that cut the seafloor, indicating that they were very recently active (Moore et al. 2013).



**Fig. 1.** Location map with regional bathymetry showing location of 3D seismic survey (dashed white box), location of figure 2 (green box) and IODP drill sites (black dots). Red arrow indicates look direction for figure 2. Yellow arrows indicate convergence vectors for Philippine Sea plate with respect to Japan (Seno et al. 1993; Miyazaki and Heki, 2001; Heki 2007). Inset in upper right is a regional tectonics map showing the setting of the Nankai Trough study area. Red box shows location of main map.

## ***1.2 3D Seismic Data***

We use a three-dimensional (3D) seismic reflection data set collected across the outer part of Kumano Basin and the Nankai prism in 2006 by Petroleum Geo-Services (Moore et al., 2009). The 12-km-wide, 56-km-long survey was acquired with four 4.5 km-long hydrophone streamers and dual 3090 in<sup>3</sup> (50.6 l) airgun source arrays. Basic processing through pre-stack time migration was carried out by Compagnie Générale de Géophysique (CGG) and full 3D pre-stack depth migration (3D PSDM) was completed by the Japan Agency for Marine Earth Science and Technology (JAMSTEC). See details of processing procedures in Moore et al. (2009). The interval between inlines (oriented NW-SE) and cross lines (oriented SW-NE) of the resulting dataset is 18.75 m and 12.5 m, respectively. The vertical resolution for the interval of interest in this study is ~5-7 metres near the seafloor and ~10-20 metres at depths near 1400 mbsf (Moore et al., 2009). We extracted a coherency volume from the final 3D PSDM (Bahorich and Farmer 1995; Marfurt et al 1998), which facilitated recognition of the boundaries and internal structure of the MTDs.

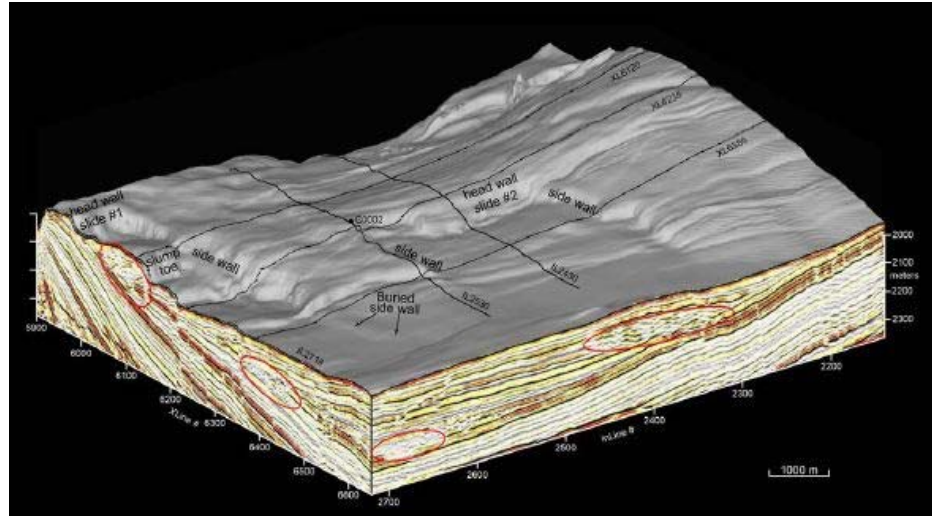
The evolution of Kumano Basin is documented by seismic stratigraphic analysis and ocean drilling (Gulick et al 2010; Underwood and Moore 2012; Moore et al. in press). The Quaternary section is divided into 12 landward-dipping seismic stratigraphic units (K1-K12 after Gulick et al., 2010). We concentrate on the section younger than ~0.9 Ma (sequences K4-K1).

## **2. Characteristics of Mass Wasting in Kumano Basin**

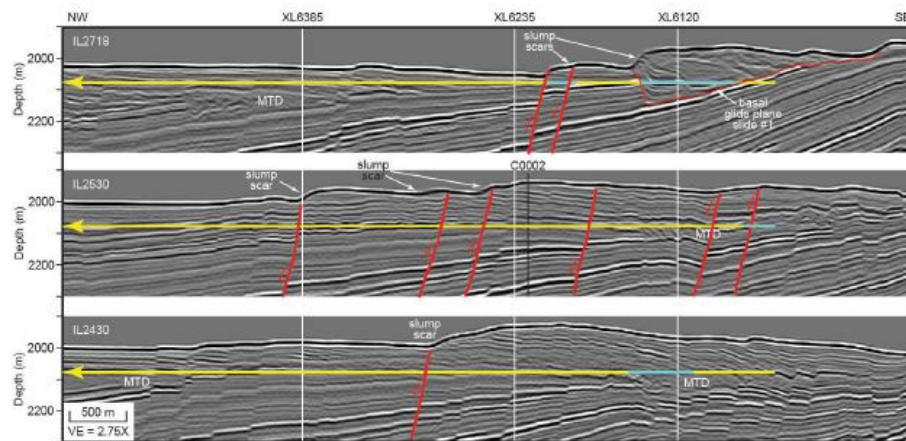
Two basic types of submarine landslides and their deposits occur in the Kumano forearc basin: Surficial slumps and older, buried MTDs.

### ***2.1 Surficial Landslides***

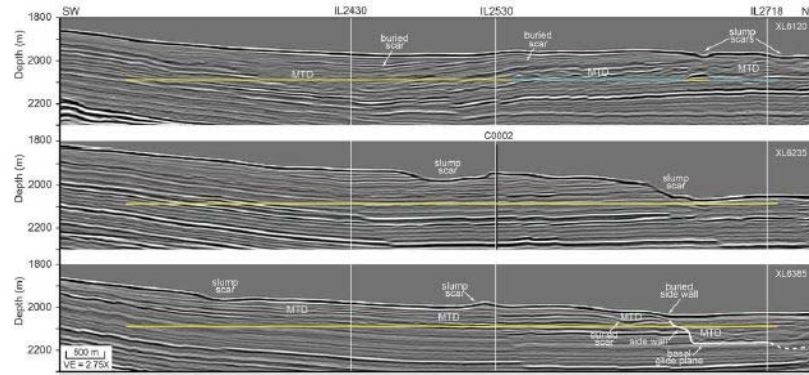
A large rotational slump (slide #1) occurs at the seafloor along the NE margin of our survey area (Figs. 2, 3 and 4). The basal sliding surface is developed along a bedding plane that dips landward ~7°. The slump has a well-developed headwall, SW sidewall and slump toe. The NE sidewall is beyond the edge of our survey; the slump is imaged on a 2D seismic line (KR0413-D5) 2 km to the east, so the slump is at least 3.4 km wide x 1.8 km long and 0.15 km thick, and thus covers at least 6 km<sup>2</sup> area and has a volume of at least 0.9 km<sup>3</sup>. The seismic cross-line that crosses the lower reaches of the slide (Fig. 4, XL6385) shows that the area is covered by younger strata that have buried the side wall of the slide.



**Fig. 2.** . Perspective view of 3D seismic volume with surface bathymetry showing prominent slide scars #1 and #2. Black lines on surface = locations of in-lines (IL) and cross-lines (XL) displayed in figures 3 and 4. Major MTDs circled in red. Location shown as green box in Fig. 1. View is looking to the SSW (red arrow in figure 1).



**Fig. 3.** . Seismic in-lines (IL) extracted from 3D volume. The upper panel crosses slide #1 and the lower two panels cross slide #2. A few normal faults (red lines) that are associated with surficial slumps are annotated. Yellow line shows depth and extent of map in Figure 5; blue lines show extent of slumps on Figure 5.



**Fig. 4.** Seismic cross-lines (XL) extracted from 3D volume. Several recent as well as buried MTDs and a buried slide scar are imaged. A buried side wall scarp has been covered by younger strata in the lower panel. Yellow line shows depth and extent of map in Figure 5; blue lines show extent of slumps on Figure 5.

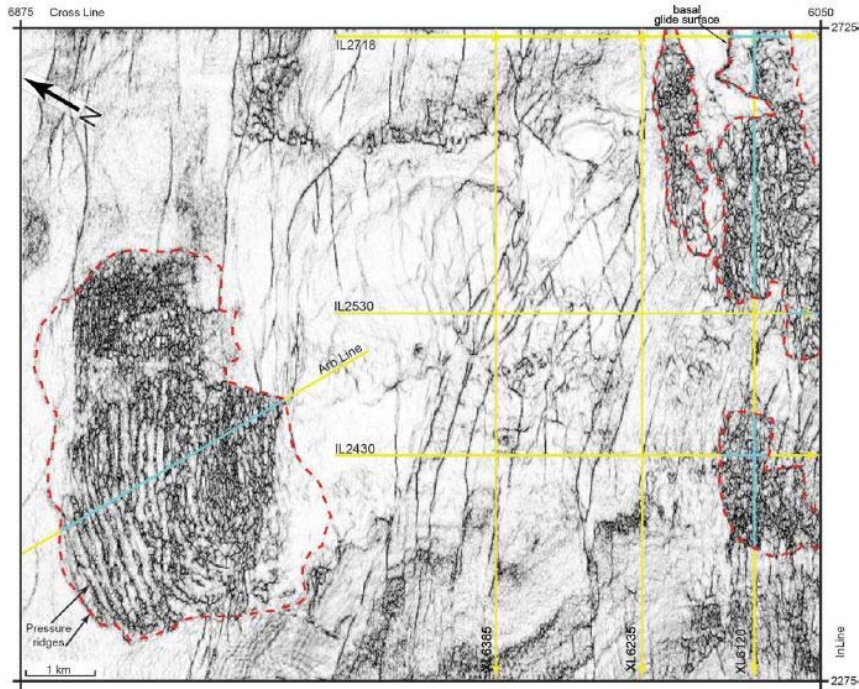
A second surficial landslide (slide #2) in the central part of the area is 3.65 km wide x 2.6 km long and 0.2 km thick, thus covering  $\sim 9.5 \text{ km}^2$  area with a volume of  $\sim 1.9 \text{ km}^3$ . Most of that material has been completely removed from the region and was probably deposited as debris flows/turbidites in the deeper part of the basin. The slump scars all dip to the NW, and the underlying strata dip  $1\text{-}2^\circ$  either landward or seaward. The slump scars are closely associated with normal faults that have offsets of 20-30 m (Fig. 3).

## 2.2 Buried MTDs

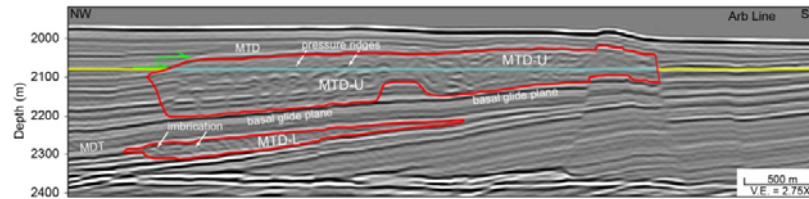
The seismic data image two large buried MTDs (Figs. 5 and 6). The younger deposit (MTD-U) was a slump that formed a positive topographic feature on the seafloor, as indicated by the onlap relations of the overlying strata (Fig. 6). Its area is  $6.5 \text{ km}^2$  and its volume is  $\sim 1.0 \text{ km}^3$ . It has a well-defined basal glide plane and its internal structure is characterized by coherent blocks with small-offset thrust faults between them. These internal pressure ridges are displayed well in the coherency plot (Fig. 5) that shows the orientation of the blocks. The blocks form arc-like structures on coherency plot. The base of MTD-U is less than 60 m above the top of seismic stratigraphic unit K4 of Gulick et al. (2010), which has an age of 0.3-0.44 Ma at IODP Site C0002 (Exp 315 Scientists, 2009; Moore et al., 2014).

The older deposit (MTD-L) is lens-shaped and pinches out in the seaward (SE) direction. It is thicker in the north and thins gradually to the south. It also has a well-defined basal glide plane, and the toe of the slide is imbricated. The base of MTD-

L is ~8 km wide, 3.5 km long and ~100m thick (area ~28km<sup>2</sup>; volume ~2.8 km<sup>3</sup>) and is less than 50m above seismic unit K5 (< 0.9 Ma). There are many more buried MTDs that range from a few metres to a few 10's of metres in thickness (Fig. 2, 3, 4, 6). Most are recognised by their chaotic internal reflection character. Both MTD-L and MTD-U are overlain by thinner MTDs.



**Fig. 5.** Depth slice at 2078 m through 3D coherency volume. Darker masses outlined by red dashed lines are MTDs. Yellow lines show extent of seismic in-lines (IL) and cross-lines (XL) shown in figures 3 and 4; blue lines show extent of slumps on figure 3 and 4; blue lines show extent of slumps on figures 3 and 4. "Arb Line" = shows location of arbitrary line extracted from the seismic volume and shown in figure 6. Most dark lineations are normal faults.



**Fig. 6.** Arbitrary seismic line extracted from 3D seismic volume orientated approximately perpendicular to the direction of structural trends within MTD-U. Green arrows show onlap onto MTD. Note imbricate structure within MTD-L. Thinner MTDs overlie both MTD-U and MTD-L. Yellow line shows location of depth slice shown in figure 5.

### 3. Discussion

As expected in this tectonically active setting, submarine landsliding has been an active process in the Kumano Basin during the Quaternary. Four of the slumps/slides are younger than seismic sequence K4 (~0.3-0.44 Ma), three MTDs are within sequence K4 (~0.44-0.9 Ma) and there is one MTD each in sequences K5 (~0.9-1.04 Ma), K6 (~1.04 -1.07 Ma) and K7 (~1.07-1.24 Ma). Thus, the approximate recurrence interval is ~ 0.05-0.10 Ma. This is much less frequent than the recurrence rate for Nankai Trough great earthquakes (~100-200 yr, Ando 1975). Thus, although the slides may ultimately be triggered by earthquake shaking, the region must be pre-conditioned in order to be susceptible to failure during the quakes, as suggested for slides in the slope basins seaward of Kumano Basin (Strasser et al. 2012). One recent slide occurred along a landward-dipping slope of ~5-7°, but other slides are closely associated with regional normal faults that have 20-30 m of vertical slip. It is thus likely that the slides occurred along the exposed fault scarps, so this is one type of potential pre-conditioning in Kumano Basin. It is also possible that gas hydrate dissociation may play a role in slope destabilization (e.g., Bangs et al. 2010), or potentially even bottom current activity. The timing of slide activity in Kumano Basin is roughly similar to activity seaward of the basin (Strasser et al 2012), so it will be important for future studies to more precisely date the Kumano MTDs.

Although there are many MTDs in the basin, all were derived locally. That is, all of the sediment transported in the MTDs came from the flanks of the basin, a process that simply redistributes the existing sediment.

Compared to submarine slides generated on the Nankai frontal prism, the larger volume of the Kumano Basin MTDs, their coherent mass, the shallower water depth, closer distance to the shoreline and, most importantly, the landward-facing transport direction are all important ingredients to increasing their hazard potential with respect to tsunami generated from such slides (e.g., Satake 2012).

## 4 Concluding Remarks

Submarine landslides are ubiquitous in the Quaternary strata of Kumano Basin. One surficial slide and at least one buried MTD are coherent slumps that accumulated as positive features on the seafloor, but most other slides evolved downslope into debris flows and spread out into the deeper parts of the basin.

The Kumano Basin MTDs were all generated by local submarine landslides. Thus, although there are many MTDs in the basin, this sliding process only displaces local sediment into deeper parts of the basin and is not responsible for supplying shelf sediment to the basin as in most passive continental margins.

The number of Quaternary submarine slides in Kumano Basin is much less than the number of major earthquakes that occurred during this time, so earthquake shaking might have been the final trigger for these slides, but the regions were preconditioned to fail prior to the quakes. For instance, many of the surficial slides were generated as failures along normal fault scarps.

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