Chapter 37
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 ~3.4 km wide, 1.8 km long and 150 m thick and one disintegrative slide that has left a seafloor scar ~ >3.65 km wide, 2.6 km long and ~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 ~5–7° 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 to 700 m below sea floor (mbsf). The thickest MTD is ~6.5 km^2 × 155 m thick, encompassing a volume of ~1.0 km^3. The three other large MTDs range from 0.3 to 0.6 km^3 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 ~0.9 and 1.24 Ma.

37.1 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

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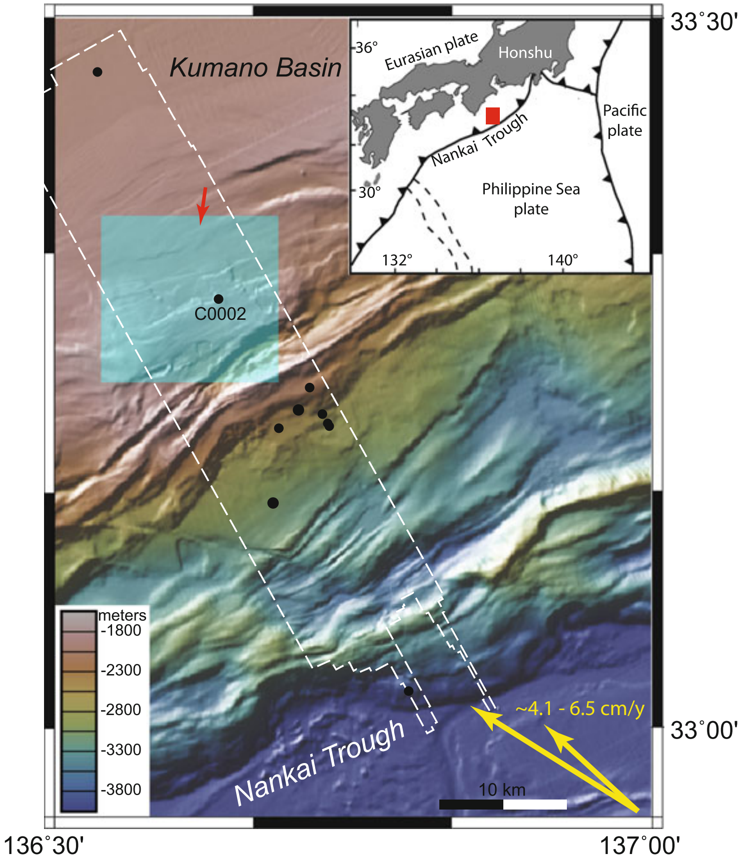

Fig. 37.1 Location map with regional bathymetry showing location of 3D seismic survey (*dashed white box*), location of Fig. 37.2 (*green box*) and IODP drill sites (*black dots*). *Red arrow* indicates look direction for Fig. 37.2. *Yellow arrows* indicate convergence vectors for Philippine Sea plate 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

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. 37.1) because the recent slide scars and most of the large buried mass-transport deposits (MTDs) are restricted to this region.

37.1.1 Geologic Setting

The Nankai Trough is the locus of subduction of the Philippine Sea plate beneath southern Japan (Fig. 37.1). Plate convergence occurs at a rate of ~4.0–6.5 cm/year at an azimuth of ~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 ~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. 2015). 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).

37.1.2 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 3,090 in.^{3} (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 m near the seafloor and ~10–20 m at depths near 1,400 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. 2015). 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).

37.2 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.

37.2.1 Surficial Landslides

A large rotational slump (slide #1) occurs at the seafloor along the NE margin of our survey area (Figs. 37.2, 37.3 and 37.4). The basal sliding surface is developed along a bedding plane that dips landward ~7°. The slump has a well-developed headwall,

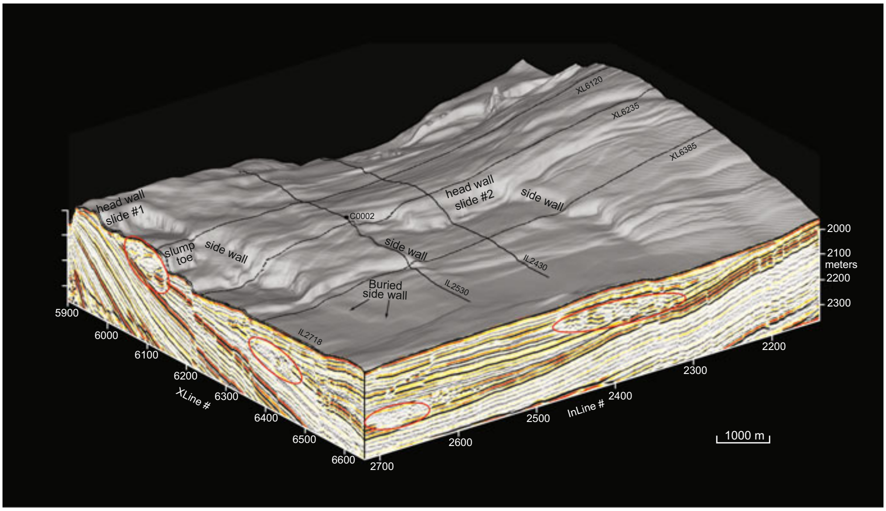

Fig. 37.2 Perspective view of 3D seismic volume with surface bathymetry showing prominent slide scars #1 and #2. *Black lines* on surface = locations of in-lines (IL) and cross-lines (XL) displayed in Figs. 37.3 and 37.4. Major MTDs circled in *red*. Location shown as *green* box in Fig. 37.1. View is looking to the SSW (*red arrow* in Fig. 37.1)

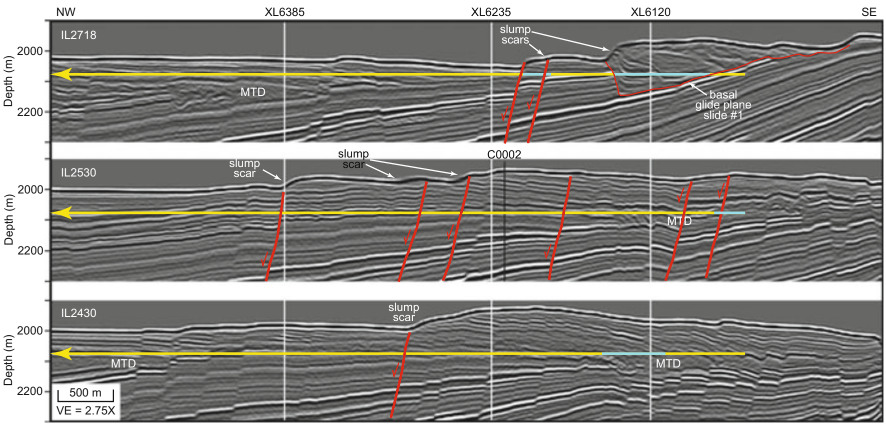

Fig. 37.3 Seismic in-lines (IL) extracted from 3D volume. The upper panel crosses slide #1 and the lower two panels cross slide #2. A few normal faults (*red lines*) that are associated with surficial slumps are annotated. *Yellow line* shows depth and extent of map in Fig. 37.5; *blue lines* show extent of slumps on Fig. 37.5

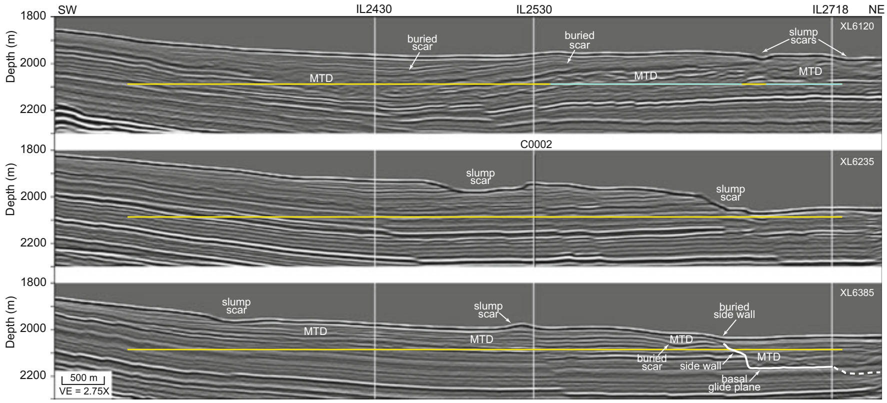

Fig. 37.4 Seismic cross-lines (XL) extracted from 3D volume. Several recent as well as buried MTDs and a buried slide scar are imaged. A buried side wall scarp has been covered by younger strata in the lower panel. *Yellow line* shows depth and extent of map in Fig. 37.5; *blue lines* show extent of slumps on Fig. 37.5

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 × 1.8 km long and 0.15 km thick, and thus covers at least 6 km^2 area and has a volume of at least 0.9 km^3. The seismic cross-line that crosses the lower reaches of the slide (Fig. 37.4, XL6385) shows that the area is covered by younger strata that have buried the side wall of the slide.

A second surficial landslide (slide #2) in the central part of the area is 3.65 km wide × 2.6 km long and 0.2 km thick, thus covering ~9.5 km^2 area with a volume of ~1.9 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 1–2° either landward or seaward. The slump scars are closely associated with normal faults that have offsets of 20–30 m (Fig. 37.3).

37.2.2 Buried MTDs

The seismic data image two large buried MTDs (Figs. 37.5 and 37.6). 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. 37.6). Its area is 6.5 km^2 and its volume is ~1.0 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. 37.5) that shows the orientation of the blocks. The blocks form arc-like structures on coherence plot. The base of MTD-U is less than 60 m

Fig. 37.5 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 Figs. 37.3 and 37.4; *blue lines* show extent of slumps on Figs. 37.3 and 37.4; *blue lines* show extent of slumps on Figs. 37.3 and 37.4. "Arb Line" = shows location of arbitrary line extracted from the seismic volume and shown in Fig. 37.6. Most *dark* lineations are normal faults

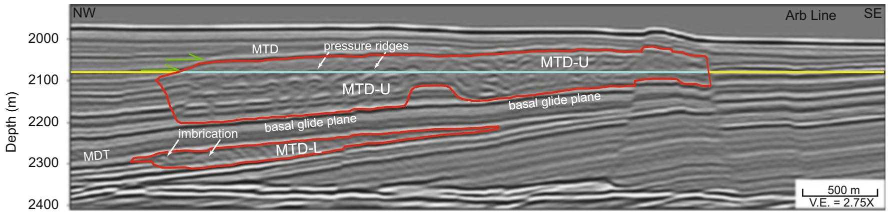

Fig. 37.6 Arbitrary seismic line extracted from 3D seismic volume orientated approximately perpendicular to the direction of structural trends within MTD-U. *Green arrows* show onlap onto MTD. Note imbricate structure within MTD-L. Thinner MTDs overlie both MTD-U and MTD-L. *Yellow line* shows location of depth slice shown in Fig. 37.5

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 ~100 m thick (area ~28 km^2; volume ~2.8 km^3) and is less than 50 m 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 (Figs. 37.2, 37.3, 37.4, and 37.6). Most are recognised by their chaotic internal reflection character. Both MTD-L and MTD-U are overlain by thinner MTDs.

37.3 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 year, 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).

37.4 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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References

Ando M (1975) Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. Tectonophysics 27:119–140

Aoki Y, Tamano T, Kato S (1982) Detailed structure of the Nankai Trough from migrated seismic sections. In: Watkins, JS, Drake, CL, (eds) Studies in continental margin geology, Am Assoc Petrol Geol Mem 34:309–322

Bahorich M, Farmer S (1995) The coherence cube. Lead Edge 14:1053–1058

Bangs NL, Hornbach MJ, Moore GF, Park JO (2010) Massive methane release triggered by seafloor erosion offshore southwestern Japan. Geology 38(11):1019–1022. doi:10.1130/g31491.1

Bardet JP, Okal EA, Synolakis CE, Davies HL, Imamura F (2003) Landslide tsunamis: recent findings and research directions. Pure Appl Geophys 160(10–11):1793–1809

Expedition 315 Scientists (2009) Expedition 315 Site C0002. In: Kinoshita M, Tobin H, Ashi J et al. (eds) Proc. IODP 314/315/316. Integrated Ocean Drilling Program Management Int., Washington, DC. doi:10.2204/iodp.proc.314315316.124.2009

Gulick SPS, Bangs NLB, Moore GF, Ashi J, Martin KM, Sawyer DS, Tobin HJ, Kuramoto S, Taira A (2010) Rapid forearc basin uplift and megasplay fault development from 3D seismic images of Nankai Margin off Kii Peninsula, Japan. Earth Planet Sci Lett 300(1–2):55–62. doi:10.1016/j.epsl.2010.09.034

Heki K (2007) Secular, transient and seasonal crustal movements in Japan from a dense GPS array: implications for plate dynamics in convergent boundaries. In: Dixon T, Moore JC (eds) The seismogenic zone of subduction thrust faults. Columbia University Press, New York, pp 512–539

Kawamura K, Sakaguchi A, Strasser M, Anma R, Ikeda H (2012) Detailed observation of topography and geologic architecture of a submarine landslide scar in a toe of an accretionary prism. In: Yamada Y. et al (eds) Submarine mass movements and their consequences. Springer, Dordrecht/Heidelberg/London/New York pp 301–309, 10.1007/978-94-007-2162-3_27

Marfurt KJ, Kirlin RL, Farmer SL, Bahorich MS (1998) 3-D seismic attributes using a semblance-based coherency algorithm. Geophysics 63:1150–1165

Miyazaki SI, Heki K (2001) Crustal velocity field of southwest Japan: subduction and arc-arc collision. J Geophys Res 106(3):4305–4326

Moore GF, Park J-O, Bangs NL, Gulick SP, Tobin HJ, Nakamura Y, Sato S, Tsuji T, Yoro T, Tanaka H, Uraki S, Kido Y, Sanada Y, Kuramoto S, Taira A (2009). Structural and seismic stratigraphic framework of the NanTroSEIZE Stage 1 transect. In: Kinoshita M, Tobin H, Ashi J, Kimura G, Lallement S, Screaton EJ, Curewitz D, Masago H, Moe KT, The Expedition 314/315/316 Scientists (ed) Proceedings of the IODP, 314/315/316. Integrated Ocean Drilling Program Management International, Inc., Washington, DC. doi:10.2204/iodp.proc.314315316.102.2009

Moore GF, Boston BB, Sacks AF, Saffer DM (2013) Analysis of normal fault populations in the Kumano Forearc Basin, Nankai Trough, Japan: 1. Multiple orientations and generations of faults from 3-D coherency mapping. Geochem Geophys Geosyst 14(6):1989–2002. doi:10.1002/ggge.20119

Moore GF, Kanagawa K, Strasser M, Dugan B, Maeda L, Toczko S, Sci. Party IODP Exp. 338 (2014) IODP Expedition 338: NanTroSEIZE Stage 3: NanTroSEIZE plate boundary deep riser 2. Sci Drill 17:1–12. doi:10.5194/sd-17-1-2014

Moore, GF, Boston, BB, Strasser, M, Underwood, MB, Ratliff, RA (2015) Evolution of tectono-sedimentary systems in the Kumano Basin, Nankai Trough forearc. Mar Petrol Geol 67:604–616. doi:10.1016/j.marpetgeo.2015.05.032

Okino K, Kato Y (1995) Geomorphological study on a clastic accretionary prism: the Nankai Trough. Island Arc 4:182–198

Satake K (2012) Tsunamis generated by submarine landslides. In: Yamada Y (ed) Submarine mass movements and their consequences. Advances in natural and technological hazards research, vol 31. Springer, Dordrecht/Heidelberg/London/New York pp 475–484. doi:10.1007/978-94-007-2162-3_42

Seno T, Stein S, Gripp AE (1993) A model for the motion of the Philippine Sea plate consistent with NUVEL-1 and geological data. J Geophys Res 98:17, 941–917, 948

Strasser M, Moore GF, Kimura G, Kopf AJ, Underwood MB, Guo J, Screaton EJ (2011) Slumping and mass transport deposition in the Nankai fore arc: evidence from IODP drilling and 3-D reflection seismic data. Geochem Geophys Geosyst 12. doi:10.1029/2010gc003431

Strasser M, Henry P, Kanamatsu T, Thu MK, Moore GF, IODP Expedition 333 scientists (2012) Scientific drilling of mass-transport deposits in the Nankai accretionary wedge: first results from IODP Exp 333. In: Yamada Y et al (eds) Submarine mass movements and their consequences. Advances in natural and technological hazards research, vol 31. Springer, Dordrecht/Heidelberg/London/New York pp 671–681. doi:10.1007/978-94-007-2162-3_60

Underwood MB, Moore GF (2012) Evolution of sedimentary environments in the subduction zone of southwest Japan: recent results from the NanTroSEIZE Kumano transect. In: Busby CJ, Azor AP (eds) Tectonics of sedimentary basins: recent advances. Wiley-Blackwell, New York, pp 310–326

Wang K, Hu Y (2006) Accretionary prisms in subduction earthquake cycles: the theory of dynamic Coulomb wedge. J Geophys Res 111(B6):B06410. doi:10.1029/2005jb004094