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Structural constraints on the subduction of mass-transport deposits in convergent margins

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Abstract: The subduction of large and heterogeneous mass-transport deposits (MTDs) is discussed to modify the structure and physical state of the plate boundary and therewith exert an influence on seismicity in convergent margins. Understanding which subduction-zone architectures and structural boundary conditions favour the subduction of MTDs, primarily deposited in oceanic trenches, is therefore highly significant. We use bathymetric and seismic reflection data from modern convergent margins to show that a large landslide volume and long runout, in concert with thin trench sediments, increase the chances for an MTD to become subducted. In regions where the plate boundary develops within the upper plate or at its base (non-accretionary margins), and in little-sedimented trenches (sediment thickness $\lesssim 2$ km), an MTD has the highest potential to become subducted, particularly when characterized by a long runout. On the contrary, in the case of a heavily sedimented trench (sediment thickness $\gtrsim 4$ km) and short runout, an MTD will only be subducted if the thickness of subducting sediments is higher than the thickness of sediments under the MTD. The results allow identification of convergent margins where MTDs are preferentially subducted and thus potentially alter plate-boundary seismicity.

Submarine landslides occur on all types of continental margins and geological provinces in the oceans where inclined seafloors are present (Fig. 1). They include the largest sedimentary movements on Earth, forming different types of mass-transport deposits (MTDs). Such MTDs cover areas of hundreds to thousands of square kilometres in the oceans and range from tens to hundreds, and up to thousands of metres in thickness (Moscardelli and Wood 2016 and references therein). The Ruatoria Debris Avalanches off the coast of New Zealand (Fig. 2a), for

example, moved around 2000 km^3 of sediment and basement rocks (thickness of the MTD up to c. 2000 m; Collot et al. 2001). The Storrega Slide off Norway affected around 3000 km^3 of slope material (Hafliðason et al. 2004). MTDs related to large landslides ($\sim 1000 \text{ km}^2$) can have runout distances of some hundreds of kilometres (Urgeles and Camerlenghi 2013; Moscardelli and Wood 2016).

Along convergent margins, submarine landslides can mobilize both the sediments that drape the forearc slope and the underlying basement rock of the upper plate. As a consequence, their MTDs often consist of debris-blocky flows (Fig. 2a) with kilometre-sized megablocks embedded in a

mud-rich to debrite matrix (Collot et al. 2001). Field studies on exhumed ancient analogues of convergent margins also documented mud-rich MTDs with block-in-matrix deposits, such as sedimentary mélanges or olistostromes (Pini 1999; Remitti et al.

2011; Pini et al. 2012; Festa et al. 2016; Ogata et al. 2019, 2020). They are commonly characterized by centimetre- to metre-sized lithic blocks that are randomly distributed in a clay- or shale-rich matrix, which may sustain bedding packages that locally reach tens of metres or up to kilometres in size (floaters or oversized blocks; e.g. Festa et al. 2016, 2019).

Based on the observation that earthquake rupture during the moment magnitude (M_W) 9.5 Great Chile (1960) and M_W 8.8 Maule (2010) earthquakes decreased across the region where the MTDs of large submarine slope failures are currently subducted (Fig. 3b), Geersen et al. (2013) suggested that submarine landslides may affect seismicity at the plate boundary. In their model, the subduction of a section of chaotic MTDs, up to 700 m in thickness and including kilometre-scale blocks of upper-plate basement rocks, contributes to the development of a rough, structurally and lithologically complex plate boundary (Fig. 2c–e). Such a complex plate

Fig. 1. Bathymetric map of the Pacific Ocean. White stars indicate submarine landslides shown in Figures 2–5. All slides occurred along convergent margins (red lines) except for Nuuanu and Wailau, which affected the Hawaiian Islands of Oahu and Molokai.

boundary may hamper the development of a spatially continuous and homogeneous shear zone as it might be required for large earthquake rupture propagation (Wang and Bilek 2011, 2014; Bilek and Lay 2018; Geersen 2019). This interpretation agrees with observations from exhumed subduction zones, where mud-rich MTDs with a chaotic internal fabric have been documented and thought to be responsible for modifying the structure and physical state of the ancient plate boundary (Festa et al. 2018). The scattered distribution of several MTDs may favour the development of an anastomosing fault network within the subduction plate boundary, and their heterogeneous (often less permeable) internal composition and block-in-matrix fabric with respect to the surrounding normal sediments is expected to influence the redistribution of overpressured fluids and shear strain (Fig. 2c–e). The mixture of clay-rich (incompetent) matrix and competent blocks exhibits both discrete and distributed deformation with minimum interaction between adjacent blocks (Festa

et al. 2018). This scenario creates unstable sliding material enclosed by frictionally stable sliding or conditionally stable matrix, similar to that proposed for tectonic mélanges (Fagereng and Sibson 2010; Fagereng 2011; Beall et al. 2019). Therefore, large ruptures may not nucleate, but the development of several micro slip surfaces can trigger repetitive slip with micro-displacements, favouring the slow end-member of the spectrum of fault slip behaviour (e.g. tsunami earthquakes, slow slip events, very low frequency earthquakes, non-volcanic tremors, aseismic creep).

Considering the potential influence of subducting MTDs on the seismic behaviour of the plate boundary, it is important to better understand which subduction-zone architectures and structural boundary conditions favour the subduction of MTDs. In this work we use multibeam bathymetric and seismic reflection data to show field examples of MTDs in different convergent margins, representing a wide spectrum of landslide sizes and subduction-zone

Fig. 2. (a) Bathymetric map of the Ruatoria Slide and debris avalanche off the North Island of New Zealand. (b) Bathymetric map of the Nuuanu Slide and Wailau Slide which affected the Hawaiian Islands of Oahu and Molokai. (c) Conceptual model on how subducting MTDs may affect the structural development of the plate boundary (modified from Festa et al. 2018). The subduction of several scattered distributed MTDs favours the formation of a heterogeneous fault network. This may support different seismic behaviours ranging from interseismic locking to aseismic creep. (d) Detail of the internal mesoscale block-in-matrix fabric of an MTD subducted to the up-dip limit of a shallow seismogenic zone. Note the inferred strain partitioning along some anastomosing shear surfaces around blocks and clasts, causing limited interaction between them. (e) Schematic view of a subduction plate boundary affected by the subduction of MTDs (modified from Festa et al. 2018).

Fig. 4. (a) Overview bathymetric map of the convergent margin of Costa Rica with submarine landslides circled by black lines (Harders et al. 2011). (b) Bathymetric map of Jaco Scar and Parrita Scar. Red line indicates the seismic profile shown in (c). (c) Seismic line SO81-13 across the trench and marine forearc of Central America at the location of Jaco Scar.

settings across both erosional and accretionary margins (Figs 2–5). We use the different cases to discuss the structural parameters that govern a possible subduction of MTDs. Finally we evaluate which of the global subduction zones are more likely to be affected by subducting MTDs. We consider only the chaotic part of an MTD that does not disintegrate into a turbidity current. Turbidites do not represent a

chaotic deposit and often form the bulk of a sedimentary trench-fill.

MTDs in convergent margins

We first evaluate the structural boundary conditions, which control whether an MTD derived from the

Fig. 3. (a) Bathymetric map of the Reloca Slide and the Valdes Slide at the convergent margin of Central Chile. Red lines indicate seismic profiles shown in c and d. (b) Overview bathymetric map of the Central Chilean margin with the rupture areas of the 1960 Great Chile Earthquake (Mw. 9.5) and the 2010 Maule Earthquake (Mw. 8.8) indicated by orange (1960) and grey (2010) shaded areas (Moreno et al. 2009, 2012). Slip contour lines are given at intervals of 5 m (1960) and 2 m (2010). The purple polygons mark the source regions of submarine landslides (Völker et al. 2012) and the three red arrows point at the giant slope failures (Geersen et al. 2011a, 2013) which coincide with the region where earthquake rupture decreased. Red lines on the right side of the map mark the latitudinal extent of past megathrust earthquakes (Contreras-Reyes and Carrizo 2011). (c) Seismic line JC23-120 across the Valdes Slide which occurred on the landward inclined side of a thrust ridge. (d) Seismic line JC23-009 showing the MTD associated with the Reloca slide at the lowermost continental slope and trench of Central Chile. (e) Bathymetric map of the Northern Giant Slope Failure. Red line indicates the seismic profile shown in Figures 3f. (f) Seismic line SPOC-47 highlighting the up to 500 m thick MTD associated with the Northern Giant Slope Failure.

Fig. 5. (a) Overview bathymetric map of the Cascadia margin. Slip contour lines of the 1700 earthquake (M_w c. 9) are given at 4 m intervals (Wang et al. 2013). Red semi-circles in the trench mark the latitudinal extent of the MTDs associated with the Blanco, Coos Basin and Heceta slides which are buried in the trench (Goldfinger et al. 2000). Black lines on the right side of the map mark the latitudinal extent of past megathrust earthquakes reconstructed from turbidites (Goldfinger et al. 2012; Wang and Trehu 2016). (b) Bathymetric map of the 44-North Slide. Red line indicates the seismic profile shown in c. (c) Seismic line RR1718-15 across the 44-North Slide (compare Tominaga et al. 2017; Lenz et al. 2019).

marine forearc is deposited on the continental slope or in the trench. For the latter we subsequently distinguish between little-sedimented trenches (sediment thickness ~ 2 km), where the likelihood that MTDs can reach the plate boundary is high, and moderately (sediment thickness 2–4 km) to heavily (sediment thickness ~ 4 km) sedimented trenches, where the probability is low. Subsequently we evaluate additional structural domains in the ocean basins (other than continental margins) where submarine landslides can cause the deposition of MTDs on oceanic plates before reaching a subduction zone.

Examples from MTDs on continental slopes

MTDs that become mobilized by a submarine land-slide in a convergent margin do not automatically evacuate into the adjacent trench. Instead they can also be deposited on the forearc slope or within fore-arc basins. Figures 3a and c show the Valdes Slide off the coast of Central Chile as an example of a submarine landslide deposited in the marine forearc (Völker et al. 2012; Weiss et al. 2013). The Valdes Slide occurred at a water depth of around 1000 m on the landward inclined side of a thrust ridge and the mobilized sediments were deposited in the

adjacent piggy-back basin (Geersen et al. 2011b; Völker et al. 2012). Another submarine landslide that occurred at the upper-continental slope (c. 500 m water depth) and did not evacuate into the trench is the Tuaheni Slide at the Hikurangi margin, New Zealand (Mountjoy et al. 2009; Fig. 2a). Factors that support the deposition of an MTD within a marine forearc (instead of being evacuated into the trench) include:

- (1) a complex margin structure and surface morphology that blocks downslope-directed sediment transport (e.g. thrust ridges) and/or provides effective sediment traps (e.g. forearc basins);
- (2) a low inclination angle of the continental slope that reduces the released energy and runout distance of the mobilized material;
- (3) a shallow water depth of the submarine landslide, which increases the distance to the trench and the possibility that the mobilized material is blocked or trapped on the way to the trench;
- (4) a small volume of mobilized material, which again increases the possibility that the mobilized material is blocked or trapped on the way to the trench.

The first two parameters are frequently met at accretionary margins which develop adjacent to heavily sedimented trenches. Here the transfer of sediments from the subducting to the overriding plate leads to compressional tectonics and the development of thrust ridges and adjacent piggy-back basins (Moore and Karig 1976; von Huene and Scholl 1991). Folding and thrusting associated with the compressional tectonic regime further reduce the inclination angle of the continental slope.

In contrast, non-accretionary margins, which develop adjacent to trenches with limited sediment accumulation, usually host steep continental slopes with upper-plate faulting dominated by extensional tectonics often expressed by margin-parallel normal fault scarps at the seafloor (von Huene and Scholl 1991; Clift and Vannucchi 2004). The large-scale structure and surface morphology of non-accretionary margins therefore support the unimpeded down-slope transport of slide material and possible deposition into the adjacent trench. Moreover, frontal tectonic erosion and subsequent under-thrusting of the eroded material increase the possibility of MTD subduction.

Examples from MTDs in little-sedimented trenches

Figure 4b shows the bathymetric signature of the Jaco and Parrita scars, which both resulted from repeated submarine landsliding at an uplifted and oversteepened continental slope in the wake of subducting seamounts (von Huene et al. 2000; Harders

et al. 2011). Seismic line SO81-13 (Fig. 4c), which runs perpendicular to the margin across Jaco scar and the adjacent trench, shows c. 300 m of layered and reflective pelagic sediment within the trench axis overlain by a c. 400 m thick unit of less reflective and partly chaotic sediment. The seismic image does not allow one to conclude whether the less reflective character of the shallow sediments results from small-scale faulting or if they correspond to the most recent and distal MTD related to submarine landsliding within Jaco scar. The pelagic sediment section seems to be completely subducted (also compare von Huene et al. 2000). Due to the chaotic nature of the shallower sediments it remains unclear how much of them are incorporated into a frontal prism and how much are subducted.

Ongoing and long-lasting subduction of Jaco slide deposits is, however, suggested by mass-balance calculations for the margin segment affected by the subducting seamount. Based on reconstruction of the undisturbed geometry of the continental slope (i.e. if not affected by a subducting seamount), Hühnerbach et al. (2005) suggested that around 20–23 km³ of the slide MTD were deposited in the trench and subsequently subducted. In contrast, about 80 km³ (75–80% of the total material involved in landsliding within the scar) were deposited on the continental slope and did not reach the trench (Hühnerbach et al. 2005). The latter is supported by chaotic seismic sequences in the shallow subsurface of the marine forearc which have been interpreted as MTDs (von Huene et al. 2000). Similar volumes of MTDs have likely been subducted at other locations along the margin (e.g. Parrita scar, Tarcoles scar, Nicoya slump) where seamount subduction resulted in large-scale instability of the continental slope (von Huene et al. 2000, 2004; Hühnerbach et al. 2005; Harders et al. 2011).

In summary, along little-sedimented trenches the chances for an MTD to become subducted are particularly high. They are usually located in front of non-accretionary margins where the plate boundary develops in the upper plate or at the top of the subducting plate. Due to the lack of significant amounts of trench sediment an MTD sourced from the marine forearc is deposited on top of (or close to) the pelagic sediments. In such a setting, the only possibility to not subduct the MTD (or at least a fraction of it) is when the plate boundary develops on top of (or close to) the oceanic basement. However, oceanic basement usually exhibits a rough morphology, including first-order structural features such as spreading-related abyssal hills, bending-related horst-and-graben, basement ridges, seamounts and oceanic fracture zones (e.g. Geersen 2019). A plate boundary that strictly follows a rough basement topography and that avoids any subducted sediment might be difficult to develop kinetically.

Examples from MTDs in moderately to heavily sedimented trenches

Figure 3f shows the seismic signature of the MTD related to the Northern Giant Slope Failure (for bathymetric expression see Fig. 3e), which occurred off the coast of Central Chile around 0.4 Ma (Geersen et al. 2011a; Völker et al. 2012). The MTD can be traced as a chaotic seismic unit up to

500 m thick about 30 km seaward of the deformation front. As the oceanic Nazca Plate has moved about 25 km since the slide occurred, the original extent of the MTD at the time of the slope failure was possibly an additional 55 km seaward of the deformation front and the thickness of the already subducted MTD likely largely exceeded 500 m. At c. 15 km from the deformation front, the MTD is located directly above the top of the oceanic basement while the maximum sediment thickness at the trench depression, including the MTD, ranges about 1.5–2.0 km. A high-amplitude seismic reflection in the marine forearc, which likely represents the shallow plate boundary, indicates that the MTD is currently subducted.

Another giant active margin landslide, which occurred in a comparable geological setting (accretionary margin, partly sediment-filled trench), is the Ruatoria Debris Avalanche at the Hikurangi margin (New Zealand) (Fig. 2a; Collot et al. 2001; Barnes et al. 2018). The maximum thickness of the MTD related to the slope failure ranges around 2000 m (Collot et al. 2001) on an average trench sediment thickness of c. 3 km (see Scholl et al. 2015). The Ruatoria Debris Avalanche moved c. 2000 km³ of slope sediments and basement rocks (Collot et al. 2001), which have been recycled back into the subduction zone (Barnes et al. 2018).

The previously discussed giant active margin landslides deposited material over tens of kilometres seaward of the deformation front. However, the MTDs of many small- and medium-sized landslides that occur in comparable geological settings are often spatially confined to the region close to the deformation front. The Reloca Slide off Central Chile (Fig. 3a) affected around 24 km³ of the lowermost continental slope (Völker et al. 2009) and the maximum runout distance of the MTD is 18 km seaward of the deformation front. As a consequence, the MTD of the Reloca Slide is confined to shallow (max. 200 m) depths within the trench sediment section (Fig. 3d; also compare Völker et al. 2009). Due to the presence of underlying trench and pelagic sediment c. 2300 m thick (Völker et al. 2013), the only structural framework that would lead to a subduction of the Reloca Slide MTD is a very thick (>2100 m) section of subducting sediment. Another example of a lower-slope failure with limited runout (c. 20–30 km) is the 44-North Slide, offshore Oregon

(Tominaga et al. 2017; Fig. 5). The associated MTD covers an area of c. 100 km², reaching a thickness of up to 275 m (Lenz et al. 2019). More than 2000 m of underlying trench and pelagic sediments and a décollement position close to the oceanic basement (Mackay 1995) make it unlikely that the 44-North Slide alters the characteristics of the plate boundary. However, another chaotic seismic unit is visible in the trench closely above the oceanic basement. This unit, which may correspond to the MTD of the huge Heceta Slide (Goldfinger et al. 2000), is likely subducted together with the oceanic plate.

Generally, the chances for an MTD to become subducted in heavily sedimented trenches decrease with increasing thickness of the underlying trench sediments. Usually these are accretionary margins where the plate boundary develops within, or at the base of the trench sedimentary cover. For MTDs located at the seafloor or at shallow depth within the trench sediment section (e.g. Reloca Slide, Fig. 3d) there is a high chance that the plate boundary will form somewhere below and that the MTD will be incorporated into the accretionary prism.

However, large MTDs with a long runout (e.g. the Giant Slope Failure off Chile or the Ruatoria Debris Avalanche off New Zealand) can be deposited seaward of the point where the trench sediments overlap the pelagic sediments on the outer trench slope (e.g. Fig. 3f). In this case they are deposited on top of the pelagic sediment section. On their journey back towards the subduction zone their relative depth within the trench stratigraphy increases continuously. In general, the further the runout distance of the MTD, the deeper it will be located within the trench sediment section when arriving at the deformation front and the larger its chances to become subducted. Yet it has to be noted that in some heavily sedimented trenches, the thick sediments extend far on to the oceanic plate. In the case of Makran about 5 km of sediment rest on top of the oceanic basement at a distance of c. 100 km from the deformation front (Fruehn et al. 1997). Off northernmost Sumatra the thickness of the Bengal and Nicobar Fan sediments is c. 3 km at the same distance (Geersen et al. 2015). In these cases even a very long runout of an MTD would not significantly increase its chances to become subducted.

Other sources for MTDs in the ocean basins

In the previous sections we discussed the recycling of MTDs sourced from the marine forearc. MTDs that enter a subduction zone can, however, also be sourced from other geological domains within the oceanic basins. Figure 2b shows the deposits of the giant Nuuanu and Wailau Landslides off the Hawaiian Islands. The MTDs, which are up to 900 m thick, resulted from the collapse of Koolau

Volcano on Oahu (Nuuanu) and East Molokai Volcano (Wailau) (Moore et al. 1989, 1994; Garcia et al. 2006). The Nuuanu landslide occurred in multiple phases, with the initial slope failure between 1.7 and 2.6 Ma (Moore et al. 1994; Garcia et al. 2006). The runout of the slide debris is more than 200 km, and the slide mass includes huge individual blocks such as the Tuscaloosa Seamount, which is c. 30 km long, 17 km wide and more than 2 km tall. The sliding material likely eroded the pelagic sediment of the Pacific Plate and the MTD now sits above the Cretaceous oceanic basement. Although the MTDs are currently located about 6000 km (c. 67 Ma) away from the Izu-Bonin trench they will likely enter a subduction zone and become subducted at some point in their geological future. Other examples of MTDs within the ocean basins include submarine slope failures at the Owen Fracture Zone in the Indian Ocean (30–220 m thick MTDs; Rodriguez et al. 2012) or the Lomonosov Ridge in the Arctic Ocean (c. 200 m thick MTDs; Kristoffersen et al. 2007).

MTDs that are deposited on the oceanic plate before arriving at a convergent margin are at the same stratigraphic level as the pelagic sediments. Located deep within the trench stratigraphy, the chances are high that they will be part of the subducting sediment section. This even accounts for subduction zones adjacent to heavily sedimented trenches (case c in Fig. 6e). Although they may not be as frequent as submarine landslides at continental margins, the examples discussed above indicate the possibility that MTDs sourced from within the ocean basins are subducted.

Discussion

The combined analysis of bathymetric images and several seismic lines allows development of a conceptual model (Fig. 6) on how the (1) location of the plate boundary décollement, (2) runout distance of the MTD, (3) thickness of the sedimentary trench-fill and (4) subducting sediment thickness control whether an MTD is accreted to the upper plate or subducted with the down-going plate (see section ‘Conceptual model on MTD subduction in convergent margins’). The knowledge gained can then be used to identify convergent margins at which MTDs are more or less likely to be subducted (see section ‘Global evaluation of convergent margins affected by MTD subduction’).

Conceptual model on MTD subduction in convergent margins

The cases discussed indicate that MTDs are likely subducted in several subduction zones. However,

the subduction of an MTD does not automatically imply that it exerts an influence on plate boundary seismicity. This will happen only if the subducted MTD interacts with the plate boundary shear zone and represents a significant portion of it (Festa et al. 2018). Direct measurements of plate boundary thicknesses between 0 and 15 km depths in modern and ancient convergent margins show that the total thickness of the shear zone increases to 100–350 m at 1–2 km below seafloor, and this thickness is maintained to a depth of c. 15 km (Rowe et al. 2013). Therefore, MTD thicknesses of up to some hundreds to thousands of metres, as observed off Central Chile (Geersen et al. 2011a; Fig. 3f), Cascadia (Goldfinger et al. 2000) and New Zealand (Collot et al. 2001; Barnes et al. 2018), as well as in ancient convergent margins (Festa et al. 2016, 2018), are prone to potentially modify the structure and physical state of the shallow plate boundary.

The chances for an MTD to become subducted are always high in subduction zones where the plate boundary develops within the upper plate or at its base (non-accretionary margins) (Fig. 6c). In little-sedimented trenches an MTD is often located directly on top or closely above the oceanic basement. This implies that even for thin subducting sediment sections, the chances are high that the MTD is subducted and possibly interacts with the plate boundary shear zone (Fig. 6c).

A long runout distance of the MTD increases its chances to get subducted if the trench is filled with sediment (case c in Fig. 6d & e). The further away from the deformation front the mobilized material is deposited the thinner is usually the underlying sediment section. On its way back towards the deformation front (i.e. while riding passively on the oceanic plate), the relative depth of the MTD within the trench stratigraphy increases successively. If deposited beyond (seaward of) the onlap point of the trench sediments on the pelagic sediments (case c in Fig. 6d), the MTD will be located directly above the pelagic sediments.

In heavily sedimented trenches, or in cases where the MTD covers only a short runout distance, the section of sediment under the MTD is usually thick. In these cases, an MTD will only be subducted if the thickness of the subducting sediments exceeds the thickness of the sediments under the MTD. The likelihood of the interaction with the plate-boundary shear-zone depends on the ratio between MTD thickness and trench sediment thickness (Fig. 6d & e).

An MTD which is sourced from somewhere within an ocean basin (e.g. seamount, oceanic island, oceanic fracture-zone, basement ridge) is usually deposited on the oceanic plate before the trench sediments start to accumulate (Fig. 6a). This implies that its chances to become subducted are high due to its location directly on top of or closely above the

Fig. 6. Conceptual model of the structural controls on MTD subduction in convergent margins. (a) MTDs sourced from geological domains within the deep ocean basins are usually deposited on top of the pelagic sediments or the oceanic basement. When arriving at a subduction zone the MTDs are located deep within the trench stratigraphy and thus likely subducted. (b) Locations where MTDs sourced from the continental slope might be deposited. (c) Recycling and subduction of MTDs in an erosive margin adjacent to a sediment-starved trench. (d) Recycling and subduction of MTDs in an accretionary margin adjacent to a partly sediment-filled trench. (e) Recycling and subduction of MTDs in an accretionary margin adjacent to a sediment-flooded trench.

oceanic basement. However, increasing the thickness of the trench sediments decreases the likelihood that the MTD will interact with the plate boundary shear zone (case c in Fig. 6d & e).

Global evaluation of convergent margins affected by MTDsubduction

Figure 7 summarizes trench sediment thickness adjacent to the global subduction zones (modified from Festa et al. 2018). The values need to be considered as an average over a large margin segment and do not capture short wavelength variations as, for example, induced by topographic features (seamounts, basement ridges, fracture zones) on the oceanic plates. Figure 3f shows how a seamount on the oceanic plate locally reduces sediment thickness in the Central Chilean trench.

The length of all subduction zone segments shown in Figure 7 is 49 270 km. From these about 8% are located adjacent to the heavily sedimented trenches (sediment thickness ≥ 4 km) in the Mediterranean, off northern Sumatra to Myanmar, and off Iran and Pakistan (Makran). Based on the conditions discussed above we conclude that subduction of MTDs originating from the continental slope is unlikely in these subduction zones.

Another 23% of global subduction zones are linked to oceanic trenches hosting 2–4 km thick sediments. The Northern Giant Slope Failure (Central Chile, Fig. 3e–f) generated a c. 500 m thick MTD

within a 1.5–2 km thick trench sediment section. From seismic reflection data there is evidence that the décollement of Central Chile develops at shallow depth within the trench sediments and that c. 2 km of trench sediments are subducted with the down-going plate (Olsen et al. 2017; also compare Fig. 3f). The deposits of the Northern Giant Slope Failure, as well as other large Central Chilean landslides (Fig. 3b, also compare Geersen et al. 2011a; Völker et al. 2012), are thus likely included in the subducting sediment section. Other examples for large MTDs (some hundreds of metres thick) within 2.0–

4.0 km thick trench sediments include the deposits of the Blanco, Coos Basin and Heceta slides from the Cascadia subduction zone (Fig. 5a, also compare Goldfinger et al. 2000). As is the case in Central Chile, a subducting sediment section (up to 1.7 km thick) of Cascadia (Han et al. 2017) possibly allows the subduction of at least a significant fraction of these MTDs.

From the remaining subduction zones, 17% are located adjacent to oceanic trenches with 1–2 km of sediment and 52% develop in places where less than 1 km of sediment is found in the trench depression. For these subduction zones, the incorporation of MTDs in the subducting sediment section might be a common phenomenon, at least in places where MTDs are located in the trench. Frontal tectonic erosion of an upper plate made at least partly of MTDs (Fig. 6c) may add to the overall volume of subducting MTDs in these settings.

Fig. 7. Trench sediment thickness for global subduction-zones. The length of all subduction-zone segments shown in Figure 5 is 49 270 km. From these about 8% are located adjacent to trenches with ≥ 4 km of sediment fill, 23% are located adjacent to trenches with 2–4 km sediment fill, 17% are located adjacent to trenches with 1–2 km sediment fill, and 52% are located adjacent to trenches with < 1 km sediment fill. Green stars indicate the locations of submarine landslides shown in Figures 2–5.

Conclusions

It has been suggested that subducting MTDs in convergent margins can alter plate boundary seismicity (Sage et al. 2006; Geersen et al. 2013; Festa et al. 2018). By reviewing marine geophysical images of MTDs of different sizes in modern subduction zones we evaluate the structural boundary conditions that control whether an MTD in a trench is subducted, and therefore may potentially exert an influence on the structure and physical state of the plate boundary. The likelihood that an MTD in a trench is subducted increases with (a) increasing size of the MTD, (b) decreasing thickness of the trench sediments, (c) increasing runout distance of the MTDs and (d) increasing thickness of the subducting sediment section. At the present state of knowledge, however, the formulation of a concrete cause-and-effect relationship between a subducting MTD and a distinct earthquake pattern proves difficult. A better understanding of the mechanical influence of a subducting MTD on the physical state of the plate boundary is usually hampered by the inaccessibility of subduction plate boundaries and challenges associated with detailed seismic imaging of plate boundary structure and composition under the marine forearc. Advances in marine geophysical imaging and detailed field studies on exhumed plate boundaries, possibly in concert with numerical modelling of plate boundary deformation, are required to overcome this shortcoming.

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