Effect of increased shear stress along a plate boundary fault on the formation of an out-of-sequence thrust and a break in surface slope within an accretionary wedge, based on numerical simulations

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ABSTRACT

We investigated the effect on accretionary wedge structure of increased shear stress, which describes the frictional sliding resistance along a decollement arising from an increase in material friction or reduction in pore pressure. To clarify the nature of the effect, we performed numerical simulations using two models: a Stable Friction model and an Increased Friction model. The Stable Friction model produced a low-angle, smooth, surface slope and an in-sequence thrust, whereas the Increased Friction model produced a break in surface slope (scarp) and an out-of-sequence thrust (OST) that cuts through the thrust sheet. The OST formed via the connection of segments of two adjacent thrusts, and its formation resulted in a change in the thickening mode of the wedge from thrust-sheet rotation and back-thrust activity to underplating. This contrast in thickening mode between the landward high-friction zone and seaward low-friction zone resulted in the formation of a clear break in slope, as the landward zone is steeper than the seaward zone, consistent with critical taper theory. The subduction of a basement slice or seamount can produce similar structures arising from an increase in resistance to basal shear sliding. However the distinctive structures arising in an accretionary wedge as a result of increased shear sliding resistance include a flat basal plane and absence of slope-failure sediments beneath the OST. These structural features are observed in accretionary wedges of the Nankai Trough off Muroto (Japan), the Sunda Strait, and the Barbados Ridge.

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1. Introduction

The overall mechanics of accretionary wedges located along compressive plate boundaries is considered to be that of a Coulomb wedge. The theory of a critically tapered Coulomb wedge (Davis et al., 1983; Dahlen, 1984) states that the taper angle is controlled by the internal friction coefficient of the wedge body and the friction coefficient of the basal plane; however, the natural wedge shape is not that of a simple wedge. Recent studies have investigated changes in the frictional behavior of the basal fault beneath an accretionary wedge, including 1) temperature-controlled transitions in clay minerals (Hyndman and Wang, 1993; Hyndman et al., 1995, 1997; Oleskevich et al., 1999), 2) a reduction in fluid pressure and diagenesis (Moore and Saffer, 2001), 3) a change in the location of the plate boundary fault within basement basalt (Matsumura et al., 2003), and 4) reactivation of a roof thrust (Kitamura et al., 2005). These changes in frictional behavior can affect aspects of the overall wedge structure (Kimura et al., 2007) (Fig. 1), including 1) the development of a trench slope break, 2) changes in the wedge taper and the thickening mode of the accretionary wedge from in-sequence thrusting to out-of-sequence thrusting, 3) a step-down of the aseismic decollement, and 4) ramping up of a low-angle, out-of-sequence thrust (OST) above the underplated complex. However, the detailed dynamics of the formation of the OST and the break in surface slope remain poorly understood.

Geological modeling is a useful technique for detailed examinations of the geometry and deformation processes of geological structure. Previous studies have used analog models to investigate variations in physical properties within accretionary wedges and in fold-and-thrust belts (e.g., Lohrmann et al., 2003). In the present paper, we investigate the effect on accretionary wedge structure of increasing shear stress, which describes the frictional sliding resistance along the decollement, which arises from an increase in material friction or reduction in pore pressure.

Numerical simulations are a suitable method for conducting experiments in which the physical properties are changed over time; this is difficult to realize using analog materials. We employed the distinct element method to examine the effect on wedge structure of varying physical properties along the decollement. By controlling the internal friction along the basal fault, we sought to determine whether an increase in shear sliding resistance would generate an OST and slope break, and how these features might form. We also compared the modeled OST and slope break structures with other types of OSTs and slope breaks, and with naturally occurring accretionary wedges.
Enforcement of displacement. Geophysical logging and core analysis suggests that a preferred layer for the decollement exists prior to the surface in undeformed sediments, seaward of the deformation front (Bangs et al., 2004). The proto-decollement is the extension of the decollement top of the volcanic basement (Bangs et al., 2004). The reverse polarity this area reveal a decollement within the accreted sediments, not at the surface (Fig. 2). Extensive seismic surveys in this area suggest that the layer may have extremely high rate of 4 cm/yr (Seno et al., 1993)( Fig. 2). Extensive seismic surveys in this area reveal a decollement within the accreted sediments, not at the surface (Fig. 2). Extensive seismic surveys in this area reveal a decollement within the accreted sediments, not at the surface (Fig. 2). Extensive seismic surveys in this area reveal a decollement within the accreted sediments, not at the surface (Fig. 2). Extensive seismic surveys in this area reveal a decollement within the accreted sediments, not at the surface (Fig. 2).

2. Background

2.1. Decollement beneath an accretionary wedge

Recent investigations have revealed that accretion at a subduction margin generally results in the development of a sub-horizontal detachment (i.e., a decollement) within the sedimentary sequences accumulated in the trench area (e.g., Moore, 1989). Such decollement zones are considered to be weak, due to either high pore-fluid pressure (e.g., Moore, 1989) or high concentrations of clay minerals with a low coefficient of friction (Vrolijk, 1990; Deng and Underwood, 2001). The sediments above the decollement are typically deformed by a series of imbricate thrusts that converge with the decollement surface, whereas sediments beneath the decollement are subducted without internal deformation.

A typical example of an accretionary wedge with a basal decollement is found in Nankai Trough, where the Philippine Sea Plate is subducting beneath the Eurasian Plate (toward 310–315°) at a rate of 4 cm/yr (Seno et al., 1993)( Fig. 2). Extensive seismic surveys in this area reveal a decollement within the accreted sediments, not at the top of the volcanic basement (Bangs et al., 2004). The reverse polarity of the decollement suggests that the layer may have extremely high fluid pressure, even in the proto-decollement region (Tsujii et al., 2005). The proto-decollement is the extension of the decollement surface in undeformed sediments, seaward of the deformation front. The clear depiction of the proto-decollement in seismic profiles suggests that a preferred layer for the decollement exists prior to the initiation of displacement. Geophysical logging and core analysis at Site 1174 of Ocean Drilling Project Leg 196 revealed that the decollement at Nankai is located within a hemipelagic mudstone sequence (Mikada and Becker, 2002).

The above features of decollement development are also observed in Barbados (Dileoardo et al., 2002) and Cascadia (Tobin et al., 1994). The decollement in the Barbados accretionary wedge, where the Atlantic Plate is subducting beneath the Caribbean Plate, is located in a radiolarian mudstone with high porosity and low strength (Moore et al., 1998). This horizon also forms the proto-decollement. In Cascadia, a large-scale accretionary wedge has developed in association with subduction of the Juan de Fuca Plate beneath the North American Plate. The decollement (and proto-decollement) occur at the boundary between overlying turbidites and underlying hemipelagic mudstones (Westbrook et al., 1994). A decollement is also clearly observed at the Sunda margin, where the Indo-Australian Plate is colliding with Eurasia. Here, excess pore-fluid pressures are inhibited by intense faulting and fracturing that is initiated in the trench and that intensifies along the frontal accretionary wedge (Kopp and Kukowski, 2003). However, low levels of stress are found along the Sunda decollement because of the intrinsically weak material along this zone (Kopp and Kukowski, 2003); consequently, the decollement is the mechanically weak layer in this area.

2.2. Temporal and spatial changes in pore pressure and shear strength along a decollement

The shear stress at the base of a wedge, which describes the frictional sliding resistance in a general Coulomb wedge, is given by

$$\tau_b = C_0 + \mu (\sigma_n - p_f)$$

(1)

where $C_0$ is cohesive strength, $\mu$ is the coefficient of friction, $\sigma_n$ is traction normal to the base, and $p_f$ is pore-fluid pressure (Davis et al., 1983). The coefficient of friction is described by the internal friction angle $\phi$:

$$\mu = \tan \phi$$

(2)

The cohesion $C_0$ is relatively unimportant in terms of the mechanics of an accretionary wedge composed mainly of silicate sediments (Davis et al., 1983). Therefore, the shear sliding resistance is controlled by the coefficient of friction, the normal traction, and pore-fluid pressure. However, in analog modeling and numerical simulations, normal traction is basically taken into account as overburden upon the basal fault, based on the wedge geometry. In this paper, we focus on the effect on wedge structure of the coefficient of friction and pore-fluid pressure.

The proto-decollement and decollement beneath the toe of a wedge sustain high pore-fluid pressure (Tsujii et al., 2008), which ensures low frictional sliding resistance $\tau_b$. However, Bangs et al. (2004) suggested a landward reduction in pore-fluid pressure $p_f$ along the decollement. This view is supported by estimates of consolidation based on steady-state hydrogeologic models that account for subduction geometry, subduction rate, bulk permeability, and fluid derived from dehydration reactions (Saffer and Bekins, 1998). Likewise, Matmon and Bekins (2006) reported a landward reduction in pore pressure along the decollement beneath Peru, based on a numerical simulation. This reduction in pore pressure leads to an increase in frictional sliding resistance $\tau_b$ to the forearc.

Landward changes are also seen in material friction along decollements. The temperature-dependent transition from smectite to illite/chlorite results in a change in material properties along the basal fault (Hyndman and Wang, 1993; Hyndman et al., 1993, 1997; Oleskevich et al., 1999). However, the nature of the overall change in material friction along decollements remains unknown. In our modeling, we considered the case that friction increases landward, although it is also possible that friction remains constant or decreases landward.
The aim of the present simulations is to investigate the effects on accretionary wedge structure of increasing shear sliding resistance along the decollement caused by an increase in material friction or reduction in pore pressure. The increase in material friction is reproduced by increasing the friction coefficient in the distinct element method (DEM). However, it is difficult to directly accommodate pore-fluid pressure in the DEM, as it was originally constructed for solid granular mechanics; a fluid–solid coupling technique remains to be developed. Consequently, the increase in shear sliding resistance arising from a reduction in pore pressure is replaced by an increase in the friction coefficient in Eq. (1). In this analysis, the effects on wedge structure of an increase in material friction and reduction in pore pressure are reproduced by increasing the friction coefficient along the decollement in the DEM. This approach enables us to simplify the natural phenomena such that it can be represented in numerical modeling; however, a potential limitation of this approach is difficulties encountered in distinguishing the effects on wedge structure related to the reduction in pore pressure from those related to the increase in material friction.

3. Method

3.1. Distinct element method (DEM)

The distinct element method (DEM) (Cundall and Strack, 1979) has been applied in a broad range of studies, including investigations of shear zones (Morgan, 1999; Morgan and Boettcher, 1999), gravity-driven volcanic deformation (Morgan and McGovern, 2005a,b), and the evolution of thrust systems (Benesh et al., 2007). The most important advantage of DEM (Burbidge and Braun, 2002) is its ability to express spontaneous strain localization and large-scale strain accumulation along discontinuous surfaces, which is generally difficult to achieve using alternative approaches such as the finite element method. Changes in force and displacement are calculated individually for each particle in the model, from which deformation is obtained throughout the entire model.

The DEM is calculated in incremental steps as follows: the contact point and amount of overlap are calculated from the particle and wall positions; then, the force oriented normal to the contact plane \((F_{n})\) is calculated from the overlap. Also exerted on each element is a shear force proportional to the amount of displacement parallel to the contact plane \((F_{s})\). The shear force is limited to a value less than \(\mu F_{n}\), where \(\mu\) is the shear drag factor between the elements at the contact point. The particle positions are then calculated from Newton’s laws of motion, with the contact force obtained from the previous time step. By calculating this process every time step, the bulk deformation of the model is simulated. Because the DEM describes only those parameters related to element contacts, parameter testing is necessary to measure the bulk physical properties of the element assembly (Yamada et al., 2006). In this paper, the bulk internal friction angle of the particles is increased to reproduce the increase in frictional sliding resistance along the decollement. This increase in bulk internal friction is achieved by increasing the shear drag factor between particles. We use a 2D DEM in which particles are assumed to be 2D discs. The simulation is run using the software PFC2D (ITASCA Corp., Minneapolis, USA).

3.2. Particle parameters

The DEM simulation can reproduce accretionary wedge structures and a decollement developed in sediments by considering particle parameters that represent sand and microbeads, respectively (Yamada et al., 2006). It is difficult to accurately simulate natural physical properties because of the heterogeneous nature of natural materials and because of technical limitations. However, sand–microbead analog modeling has been successful in reproducing an accretionary wedge with a decollement, and in simplifying the natural geometry of wedge structures and investigating relevant deformation processes (Kukowski et al., 2002; Yamada et al., 2005, 2006). Dry sand is an appropriate material for modeling brittle deformation (McClay, 1990), and microbeads are a suitable analog material for simulating a weak layer such as a decollement, as they are a Coulomb material and their density and size are similar to those of dry sand, yet their near-perfect sphericity results in a smaller coefficient of internal friction than that of dry sand, with almost negligible cohesion (Kukowski et al., 2002).

Following Yamada et al. (2006), we determined the parameters related to element contacts. Table 1 lists the physical characteristics of three particle types, as obtained from a series of simulated biaxial compression tests. The properties of Particle A represent those of sand, and the properties of Particle B represent those of microbeads. The properties of Particle C represent those of microbeads, although the bulk internal friction angle can be increased from that of microbeads (25°) to that of sand (35°) by increasing the shear drag factor from 0.5 to 30. This variation in the shear drag factor reproduces the documented variation in physical properties along the decollement from incoming to the deeper, Initial cohesion and bonding between elements are not introduced because of the cohesionless nature of the analog materials. Although the sizes of the elements in this study are larger than those of the natural materials or those used in analog experiments, previous studies have accurately reproduced geological structures using DEM particles with larger diameters (e.g., Saltzer, 1992; Burbidge and Braun, 2002; Strayer and Suppe, 2002; Finch et al., 2003; Yamada et al., 2004; Benesh et al., 2007). The elements are of variable size to avoid the formation of a preferential weak plane in the initial arrangement of the elements.

3.3. Model settings

Given the aim of this study (i.e., to estimate the effect on an accretionary wedge of increasing sliding resistance along a basal fault), we performed simulations using two types of model settings: a Stable Friction model and an Increased Friction model. The model settings are based on those used in previous studies that succeeded in reproducing accretionary wedge structures (e.g., Yamada et al., 2006).

3.4. Stable Friction model

In the Stable Friction model, we set a constantly low internal friction angle in the bottom layer to simulate a decollement that is a mechanically weak layer due to high pore pressure or the presence of weak materials. Sediment in the models occupies an initial area of 40,000 m in width and 900–1000 m in thickness (Fig. 3). The bottom layer, up to ~100 m thick, is composed of Particle B, which has a low friction angle as a bulk material. The upper layer consists of Particle A. The set-up for the model is shown in Fig. 3. Rigid walls are used for the model boundaries. The shear drag factor between particles and the basal wall is the same as that within the bottom layer (Particle B), whereas the shear drag factor between particles and the side walls is the same as that within the upper layer (Particle A). The basal plate in the simulation is set horizontally. A moving wall with a basal slip (~60 m in height; see Fig. 3) shortens the sediments to represent the accretion

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Physical and numerical parameters used in the simulations.</th>
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<tbody>
<tr>
<td>Particle A</td>
<td>Particle B</td>
</tr>
<tr>
<td>Radius (m)</td>
<td>12–30</td>
</tr>
<tr>
<td>Density(kg/m³)</td>
<td>2650</td>
</tr>
<tr>
<td>Grain shape</td>
<td>Circular</td>
</tr>
<tr>
<td>Shear drag coefficient</td>
<td>30</td>
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<tr>
<td>Internal friction angle (deg)</td>
<td>35</td>
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</table>
process. The slit generates a detachment horizon within the first layer. The displacement rate should be small enough to approximate the deformation as quasi-static, and is therefore set to 0.009 m for each calculation cycle. In this study, we refer to the moving wall side as “landward” and the other side as “seaward,” reflecting the terminology used for natural accretionary wedges.

3.5. Increased Friction model

In the Increased Friction model, a layer of progressively increasing friction was placed at the bottom of the model to simulate a landward increase in shear stress, which describes the frictional sliding resistance along the decollement. Although the pore pressure distribution and material properties are affected by changes in temperature, overburden thickness, porosity, and the development of faults and fractures that act as fluid conduits, it is difficult to take these factors into account in the model. However, the distribution of pore-fluid pressure can be accommodated in the model: it is described by the distance from the deformation front of the wedge when the wedge grows in a self-similar manner (Saffer and Bekins, 1998). Once the distribution of pore-fluid pressure has been determined, the increasing rate of the shear drag factor is determined from several preliminary experiments with the aim of setting the front of the friction-increasing area at a near-constant distance (~5000 m) from the deformation front of the wedge, and setting the region of the friction-increasing at a near-constant value (c 3000 m). This enables the use of a simplified model compared with the case of considering several of the factors that control pore pressure. The basic settings (i.e., size of the experimental apparatus and kinematics) are the same as those in the Stable Friction model, except for the particles in the bottom layer. The bottom layer (~100 m thick) consists of Particle C, which has a low shear drag factor (0.5). The bottom layer is divided into 890 groups (numbered as n) by setting vertical partitions at 45 m intervals from the moving wall at the initial position. After 4500 m of initial shortening (500,000 time steps), the shear drag factor was incrementally increased after every 90 m (10,000 time steps) of shortening (Fig. 4). Here, \( t \) is the time step used in the calculations and \( f_{th}^T \) is the shear drag factor of group \( n \) at the renewal interval \( T \):

\[
f_{th}^T = 0.25 \times (3T - n + 6)
\]

\[
T = \left[ \frac{t - \text{500,000}}{10,000} \right]
\]

For each group, we imposed a maximum value of 30 for the shear drag factor. The bottom layer (Particle C) becomes highly sheared and deformed due to the force of the moving wall, and some particles are taken into the wedge during the simulation. Therefore, the assembly of particles set as groups at the initial condition are also sheared and deformed. Consequently, the friction-increasing zone shows a sheared rather than rectangular shape (Fig. 5).

4. Results

4.1. Deformation features

The Stable Friction model is able to reproduce typical structures of a fold-and-thrust belt, including the wedge geometry and foreland-vergent thrusts that propagate upward from the basal decollement in a foreland-propagating (piggyback) sequence (Fig. 6). The frontal thrust is always the most active fault in this model. During deformation, the earlier-formed thrusts were back-rotated with reactivation. Some minor back-thrusts were formed after approximately 9000 m of shortening. Displacement along these structures cut through and slightly steepened the upper part of the previously formed foreland-vergent thrusts.

The overall structure style of the Increased Friction model is a wedge shape that increases in size with ongoing displacement of the wall (Fig. 7). Foreland-vergent thrusts formed at the toe of the wedge as part of a piggy-back sequence. Back-thrusts formed after 9000 m of shortening. Some of the thrust sheets were highly deformed by the back-thrusts, especially the fourth and fifth thrust sheets from the left (Fig. 7, those panels showing 13,500–18,000 m of shortening). The intense deformation is observed in the high-friction zone. The foreland-vergent thrusts are rotated anticlockwise as the wedge grows; in particular, the upper parts of thrusts are strongly rotated by back-thrusting. The upper part of the fifth thrust (see Fig. 7) is strongly rotated from 13,500 to 15,750 m of shortening. A small break in the surface slope—the surface inflection point that separates the steep landward slope from the gentle seaward slope—is observed at the tip of the fourth thrust after 15,750 m of shortening. The break jumps to the tip of the sixth thrust after 18,000 m of shortening. The difference in slope between the landward and
seaward surfaces continues to increase with ongoing shortening. The lower part of the fifth thrust and the upper part of the sixth thrust become connected by a new low-angle reverse fault, after approximately 18,900 m of shortening (Fig. 7, 20,250 and 22,500 m). The connected faults act as a single large fault until the end of shortening (22,500 m).

The shape of the connected faults is initially slightly sigmoidal, but becomes increasingly planar with ongoing displacement. The seaward thrust sheet was underplated beneath the rear of the wedge as a result of displacement along the connected fault (Fig. 8).
4.2. Generation interval of new frontal thrusts

The generation of a new frontal thrust can be detected from minor uplift in the undeformed foreland sediments. The average generation interval of frontal thrusts (shortening (in meters)/number of frontal thrusts) can be calculated using a least squares approximation. This average interval represents how much shortening is required to generate a new frontal thrust. In the Stable Friction model, the generation interval during the early stages of deformation (i.e., during the first 9000 m of shortening) is 1802.6 m; subsequent to approximately 9000 m of shortening, the generation interval is 2638.3 m (Fig. 9 (a)). In the Increased Friction model, the generation interval during the first 9900 m of shortening is 1874.6 m; thereafter, the interval is 3141.0 m (Fig. 9 (b)). The generation intervals are similar between the two models during the early stages of shortening; however, during the later stages of shortening the Increased Friction model shows a longer generation interval than does the Stable Friction model.

4.3. Slope angle

We measured the surface slope angle of the wedge (along the lines linking the tips of the thrusts) after every 900 m of shortening in both models (Fig. 10). The surface slope in the Stable Friction model varies from 13.1 to 18.2°, and the slope in the Increased Friction model varies from 13.7 to 20.0°. In the Stable Friction model, fluctuations in the surface slope gradually converge to a low angle of 14–15°. In the Increased Friction model, the fluctuations also converge, although to a wider range (14–17°). In the latter stages of shortening in the Increased Friction model, the surface slope is divided by a slope break (Fig. 7); subsequently, the landward surface slope increased from 17.5 to 19.8° whereas the seaward surface slope remained low (11.7–14.4°) (Fig. 8).

4.4. Length of the wedge (position of the tip of the frontal thrust)

The length of the wedge is measured as the distance from the moving wall to the tip of the frontal thrust (Fig. 11). The length of the wedge is similar between the two models until approximately 9000 m of shortening, from where the two models behave differently. The wedge length shows a saw-teeth pattern that consists of abrupt increases associated with the initiation of frontal thrusts, followed by gradual decreases.

5. Discussion

5.1. Internal deformation

In our simulations, the accretionary wedge grows and deforms to release the compressional stress imparted by the moving wall. We identified two types of deformation processes that act to release the compressional stress: generation of a frontal thrust, whereby deformation results in the formation of a new thrust fault in the foreland, and internal deformation, representing any deformation within the wedge, except for the generation of a frontal thrust. In both models, the surface slope and wedge length vary according to the type of deformation. The surface slope shows an abrupt decrease following the generation of a new frontal thrust, and shows a gradual increase during periods of internal deformation (Fig. 10). The length of the wedge shows an abrupt increase following the generation of a new frontal thrust, and a gradual decrease during periods of internal deformation (Fig. 11). This episodic pattern of wedge accretion has been reported previously in analog modeling studies (Mulugeta and Koyi, 1992; Koyi, 1995; Koyi and Vendeville, 2003). The generation of a new frontal thrust accommodates compressional stress by an increase in wedge length, thereby reducing the wedge taper. In contrast, internal deformation accommodates compressional stress by increasing wedge thickness, thereby increasing the surface slope (Mulugeta and Koyi, 1992). The wedge releases compressional stress via these two deformation processes.

In the Stable Friction model, the average generation interval of new frontal thrusts is longer after approximately 9000 m of shortening.
compared with the period before 9000 m of shortening (Fig. 9). This finding means that wedge lengthening was suppressed during the later stages of shortening, even though the shortening rate of the moving wall was kept constant. The development of various internal deformation structures (e.g., back-thrusts) became obvious during the later stages of shortening (Fig. 6). These observations suggest that with ongoing shortening, less compressional stress was released by the generation of new frontal thrusts; instead, it was increasingly consumed by internal deformation. This trend was also observed in the Increased Friction model.

For the period after approximately 9000 m of shortening, the average generation interval of new frontal thrusts is larger in the Increased Friction model than in the Stable Friction model, whereas prior to 9000 m of shortening the interval is similar between the two models. This difference between the two models indicates that a greater amount of compressional stress is released by internal deformation in the Increased Friction model than in the Stable Friction model, even though the compression rate is the same in both cases. The only physical difference between the two models during the later stages of shortening is the degree of friction along the basal fault. In the case of high friction along the basal fault, a greater amount of compressional stress is released by internal deformation, with less compressional stress being conveyed to the frontal part of the wedge to generate a new frontal thrust.

During the later stages of the experiment using the Increased Friction model, internal deformation (e.g., back-thrusts) is localized in the landward high-friction zone and the deformation is more intense than that in the Stable Friction model. The enhanced internal deformation acts to steepen the upper parts of pre-existing thrusts (Fig. 7). This rotation means that the thrusts are mechanically less favorable in terms of reactivation (Sibson, 1995). To release compressional stress via faulting, new favorably oriented faults are formed in the zone of increased friction. The favorably oriented parts of the thrusts represent reusable planes of weakness. At around 15,750 m of shortening (Fig. 7), the lower part of the fifth thrust remains at a low angle, whereas the upper part is strongly rotated. The upper part of the sixth thrust is less strongly steepened than is the fifth thrust, as the sixth thrust was located outside the high-friction zone prior to 15,750 m of shortening. Therefore, the lower part of the fifth thrust and the upper part of the sixth thrust become connected by a new reverse fault and act as a single sigmoidal fault. This new fault corresponds to a natural OST observed in the accretionary wedge within the Nankai Trough, off Muroto, Japan (Park et al., 2000).

The formation of the slope break in the Increased Friction model is interpreted to result from internal deformation. Basically, the wedge was thickened via internal deformation such as thrust-sheet rotation and back-thrusting. With increasing friction along the basal fault, internal deformation is enhanced in the landward high-friction zone relative to the seaward low-friction zone. The enhanced internal deformation acts to thicken the wedge, and this contrast in thickening within different parts of the wedge results in a corresponding contrast in surface slope and formation of a slope break. Consequently, the slope break jumps trenchward, following the movement of the increased-friction zone. However, the contrast in thickening is minor, as is the slope break, because prior to OST formation thickening occurs via internal deformation in both the high- and low-friction zones. OST formation results in a change in thickening mode within the wedge from internal deformation to underplating. The OST enables the seaward thrust sheet to subduct underneath the OST. The thickening via underplating is efficient in lifting the landward segment of the wedge, and continues for a long term via OST thrusting. The difference in thickening mode between internal

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Fig. 10. Angle of surface slope versus shortening. Arrows indicate the timing of the generation of a new frontal thrust. For the Increased Friction model, the landward and seaward surface slopes are plotted separately for the period after 18,000 m of shortening.

Fig. 11. Length of the wedge versus shortening. The length was measured at the timing of generation of a new frontal thrust and prior to generation.
deformation and underplating means that the slope break becomes evident after OST formation.

5.2. Correspondence of the simulation results to the theory of a non-cohesive Coulomb wedge

The basic theory of a non-cohesive critical Coulomb wedges states that a critical wedge taper is dependent on the internal and basal friction coefficients, internal and basal fluid pressure ratios, and the dip of the basal detachment (Davis et al., 1983; Dahlen, 1984; Dahlen et al., 1984). Because these factors (except for basal friction) are constant in the present analysis, the theory predicts that increased basal friction results in a steeper critical taper, and vice versa.

In the Increased Friction model, after approximately 15,750 m of shortening, there exist two wedge segments separated by the slope break. The landward surface slope is steeper than the seaward slope. The slope break is located above the friction-increasing zone, and it jumps trenchward with migration of the increased-friction zone (Fig. 7). The difference between the landward and seaward segments is the friction along the basal fault; therefore, the difference in surface slope within an individual wedge results from a difference in basal friction. These observations are consistent with critical taper theory.

To maintain a critical taper, internal deformation is required within the pre-deformed wedge (Davis et al., 1983). Hence, OSTs and forethrusting, which act to maintain the critical wedge taper, are an integral part of thrust belt formation (Platt, 1986). Morley (1988) reported two end-member types of OST: (1) pre-existing in-sequence thrusts that are reactivated along their entire length, and (2) completely new thrusts that propagate through a pre-deformed thrust sheet. Intermediate between the two end-members are thrusts that consist in part of a reactivated in-sequence thrust and in part of a new thrust (Morley 1988). According this classification, the OST observed in the present simulation is an intermediate type.

5.3. Comparison of the simulation results with other types of slope breaks and out-of-sequence thrusts

Here we consider other mechanisms that generate OSTs and slope breaks, and examine the structural features of accretionary wedges to clarify how to distinguish between the different mechanisms.

5.3.1. Surface erosion and sedimentation

A reduction in surface slope by syntectonic erosion favors cycling between accretion and underthrusting modes (Fig. 13 (a)). In contrast, a sudden syntectonic sediment load in the pro-wedge region promotes a prolonged phase of underthrusting, retarding the accretion of new imbricates thrusts at the pro-wedge toe (Del Castello et al., 2004) (Fig. 13 (b)). This observation suggests that surface erosion and sedimentation can generate OSTs and accompanying underthrusting. In fact, a thrust-cutting OST is observed in the case of syntectonic erosion (Fig. 13 (a)); however, a break in surface slope was not observed. Deformation features such as OSTs in the pro-wedge force the wedge to regain its characteristic minimum critical taper, as predicted by the theory of a critically tapered Coulomb wedge (Del Castello et al., 2004).

5.3.2. Increase in bulk wedge strength

The bulk strength of a wedge increases toward its rear as a consequence of pervasive deformation and bulk compaction; in such a case, the taper shows a steady decrease toward the rear of the wedge, resulting in a convex geometry (Lohrmann et al., 2003) (Fig. 13 (c)). These observations are consistent with the theory of a critical tapered Coulomb wedge (Davis et al., 1983). The experiments performed by Lohrmann et al. (2003) produced back-thrusts and OSTs that represent the reactivation of pre-existing in-sequence thrusts, but did not produce thrust-cutting OSTs. In the case that a slope break is generated, it accompanies the gentler slope as it migrates landward. These structural features are observed in the Nankai Trough, off Muroto (Moore et al., 1990; Lohrmann et al., 2003).

5.3.3. Differences in basal friction between coseismic and inter-seismic periods

The dynamic Coulomb wedge theory, as proposed by Wang and Hu (2006), consists of two key components: (1) it postulates that the actively deforming, most seaward part of an accretionary wedge (the outer wedge) overlies the up-dip velocity-strengthening part of the subduction fault, and that the less-deformed inner wedge overlies the velocity-weakening part (the seismogenic zone); and (2) it states an exact stress solution for a elastic–perfectly Coulomb plastic wedge. The theory provides a first-order explanation for the sharp contrast in structural style between the inner and outer wedges, which is commonly accompanied by a break in surface slope, and for the coexistence of a relatively steep surface slope in the outer wedge (Fig. 13 (d)). These types of structures are seen, for example, at Nankai off the Kii Peninsula (Park et al., 2002) and in Alaska between the Kenai Peninsula and Kodiak Island (von Huene and Klaeschen, 1999; Wang and Hu, 2006).

5.3.4. Subduction of a basement thrust slice

Lallemand et al. (1992) modeled the effects on wedge structure of an active basement thrust slice (e.g., Tsuji et al., 2009) as it enters a subduction zone. The subduction of the slice resulted in a change in topographic slope, and thickening of the wedge above the basement slice generated a break in topographic slope. These changes resulted in the development of a deeply propagating accretionary wedge characterized by a small taper (Lallemand et al., 1992) (Fig. 13 (e)). A flattened thrust develops from the top of the edge of the slice to the
5.3.5. Subduction of a seamount

The subduction of a seamount can lead to the formation of an OST and break in surface slope within a Coulomb wedge (Lallemand et al., 1992; Dominguez et al., 2000). Seamount subduction results in large-scale tectonic erosion of the frontal margin of the wedge and thickening of the rear part of the margin (Dominguez et al., 2000) (Fig. 13(f)). The bulk of the margin and trench-fill sediments, dragged into the subduction zone behind the seamount, are underplated beneath the accretionary wedge (Dominguez et al., 2000); consequently, the rear part of the wedge becomes thicker than the frontal part, and a typical slope break (suture) separates those parts of the accretionary wedge developed before and after subduction of the seamount. OSTs develop from above the top of the seamount and propagate seaward, connecting with pre-existing thrusts within the accretionary wedge (Dominguez et al., 2000). A large part of the frontal margin is therefore underthrust beneath the rear part of the accretionary wedge. In the wake of the subducted seamount, a strongly deformed seaward-dipping thrust unit is observed.

Based on the above descriptions, the subduction of a basement thrust slice or seamount has the potential to generate OSTs with a coexisting slope break; however, these structures are less likely to be developed in response to an increase in the bulk strength of the wedge, surface erosion and sedimentation, or differences in basal friction between coseismic and inter-seismic periods in a perfectly elastic Coulomb wedge.

Coulomb wedge theory states that the slope angle maintains a critical taper as long as the bulk strength of the wedge and basal friction remain constant. Therefore, internal deformation, including OSTs, occurs after disturbance of the taper by syntectonic erosion or sedimentation, and the flat surface slope adjusts to its critical state following such deformation. Even in the case of a change in the bulk strength of the wedge, the surface slope becomes small toward the rear of the wedge, as the bulk strength of the wedge generally increases toward its rear. The style of deformation according to dynamic Coulomb theory also results in a smaller slope angle in the rear part of the wedge.

With the subduction of a basement thrust slice or seamount, trenchward sediments or sediments upon the seamount are underplated beneath the rear part of the wedge. The underplated sediments act to thicken the rear of the wedge and disturb the critical state of the Coulomb wedge. The local thickening in the rear part of the wedge results in the formation of a slope break (scarp), and the roof thrust of the underplated sediments acts as an OST. The following features can be used to distinguish between the structures originating from subduction of a basement slice, subduction of a seamount, and an increase in basal friction: (1) subduction of a basement slice results in a flattened OST and the occurrence of a basement slice at the root of the OST (Fig. 13(e)), (2) subduction of a seamount results in a seamount located behind the slope break and the deposition of margin- and trench-fill sediments beneath the slope break (Fig. 13(f)), and (3) an increase in basal friction is not accompanied by the existence of a basement slice or seamount, but may produce a flat decollement beneath the slope break and OSTs that cut through pre-existing thrust sheets (Fig. 8).

5.4. Comparison of the simulation results with natural wedges

The above discussion concluded that in the case of OSTs with a coexisting scarp, the absence of a subducted seamount or a basement slice indicates an increase in basal shear stress, which describes the frictional sliding resistance. We found three sites that match these conditions: the Nankai Trough off Muroto, Sunda Strait, and the Barbados Ridge. Each of these is now considered in detail.

The Muroto accretionary wedge is subdivided into seven tectonic/structural domains: the Shikoku Basin, axial zone of the Nankai Trough, protothrust zone, imbricate thrust zone (ITZ), out-of-sequence thrust zone (OTZ), large thrust-slice zone, and landward-dipping reflector zone (Moore et al., 2001). Structural features of the Stable Friction model (e.g., the low-angle slope and in-sequence folds and thrusts) correspond well to the structural features in the ITZ of the Muroto accretionary wedge, at the deformation front. The structural features of the Increased Friction model (e.g., the break in surface slope and OST) correspond well to the structural features in the Muroto
accretionary wedge within the transition area between the ITZ and the OTZ. This region corresponds to the area in which the pore pressure along the basal fault shows a reduction toward the forearc (Saffer and Bekins, 1998; Bangs et al., 2004). A reduction in pore pressure can result in an increase in material strength (Hubbert and Rubey, 1959). Park et al. (2000) reported the details of OSTs in the transition area between the ITZ and the OTZ (Fig. 12 (a)). In a seismic profile across the Muroto wedge, the landward surface slope, from the tip of OST2, shows a steeper slope (8°) than that of the seaward surface (21°). In the Increased Friction model of the present study, the landward surface slope from the tip of the OST also shows a steeper slope (19.8°) than that of the seaward slope (12.1°). The sigmoidal OST2 shows a gentler fault slope (10°) than the other thrusts, and is connected to two thrusts: one in the hanging wall and another in the footwall. In the Increased Friction model, the OST also shows a gentler fault slope than the other thrusts, and again, it appears to be connected to two thrusts (Fig. 14).

Based on the present simulation results, we reconstructed the deformation history of the Muroto wedge in the transition area between the ITZ and the OTZ (Fig. 14). In the landward ITZ, shear stress along the decollement, which describes the frictional sliding resistance, increases due to a decrease in pore-fluid pressure as the Philippine Sea Plate is subducted. In the zone of increased frictional resistance, internal deformation (e.g., back-thrusts), intensifies, and uplift associated with the increase in surface slope is enhanced by internal deformation. During this stage, a small break in the surface slope may develop in response to the contrast in internal deformation between the zones of high and low frictional resistance. As the upper parts of the thrusts became cut and steepened by internal deformation, they became inactive. To release the horizontal compressional stress, a new thrust formed via the connection of favorably oriented segments of adjacent faults: the lower part of the landward thrust and the upper part of the seaward thrust. The development of an OST results in a change in the thickening mode, which becomes dominated by underplating; in addition, a surface break becomes clear. During this stage, we observe OST2 in the Muroto region and a surface break at the tip of OST2. As the plate subducts, the shear stress along the basal fault increases in a seaward direction. The position of the break in surface slope jumps seaward, following the high-friction zone. The geometry of OST2 changes from sigmoidal to planar with ongoing deformation, as observed in the Increased Friction model. A landward, planar OST1 in the Muroto region may represent an earlier OST that once had a sigmoidal geometry (Fig. 12 (a)).

In the Sunda Strait accretionary wedge, OSTs are found at the base of the scarp (Kopp et al., 2001, 2002; Kopp and Kukowski, 2003) (Fig. 12 (b)), consistent with the Increased Friction model. The decollement in the Sunda Strait accretionary wedge is characterized by weak material rather than excess pore-fluid pressure; therefore, it is possible that a reduction in pore-fluid pressure has not occurred. Instead, material friction may have increased over time, resulting in an increase in basal shear stress in this region.

A break in the surface slope is also observed across the Barbados Ridge complex at latitude 16°12'N (Westbrook et al., 1988) (Fig. 12 (c)). Large thrusts are observed beneath the slope break, possibly representing OSTs that cut the thrust sheet. These structures are also assumed to be the products of an increase in basal shear stress.

Relatively planar and gentle slopes are observed toward the rear part of the wedges in the Nankai Trough off Muroto and in the Sunda Strait. These gentle slopes were not observed in the Increased Friction model. If the basal friction had decreased in response to the decollement stepping down to a lower plane with high fluid pressure or low-friction material, the decreased basal friction may have resulted in a decrease in the taper angle, as described in critical taper theory. Such a convex slope break may have resulted from an increase in the bulk strength of the wedge (Kopp and Kukowski, 2003; Lohrmann et al., 2003) or a difference in basal friction between coseismic and inter-seismic periods (Wang and Hu, 2006), as described above.

The Increased Friction model reproduces the structural features generated by an increase in shear sliding resistance. However, the effects of a reduction in pore pressure and increase in material friction along the decollement are restricted to the friction coefficient. Therefore, we are unable to estimate the magnitudes of these effects. Because the internal friction angle in the simulation is set to reproduce various properties of sand and microbead analog materials, it is difficult to quantitatively assess the effect on structure of variations in friction in natural accretionary wedge. In the present analysis, the increasing rate of the friction coefficient was set to reproduce a fixed distribution from the deformation front. The pore-fluid pressure and properties of the material are controlled by several factors, including overburden pressure, existence of permeable faults and fractures, and thermal effects. To make advances in this regard and to perform more realistic simulations, it would be necessary to develop a more advanced simulation technique that is able to simulate fluid–solid interactions.

6. Conclusion

We performed numerical simulations using two models, the Stable Friction model and the Increased Friction model, to clarify the effect on wedge structure of increasing shear stress, which describes the frictional sliding resistance beneath the accretionary wedge. The Stable Friction model produces a smooth, low-angle surface slope and an in-sequence thrust, whereas the Increased Friction model produces a break in surface slope (scarp) and an OST that cuts through the thrust sheet. An increase in the shear stress along the basal fault induces strong internal deformation (e.g., back-thrusts). The back-thrusts cut through and steepen the upper parts of pre-existing thrusts, making them inactive. To release the lateral compressional stress, OSTs are formed when low-angle and favorably oriented segments of two adjacent thrusts become connected (i.e., the lower part of the landward thrust and the upper part of the seaward thrust). The development of an OST results in a change in the thickening mode of the wedge from thrust-sheet rotation and back-thrust activity to underplating (Fig. 14). This contrast in thickening mode between the landward high-friction zone and the seaward low-friction zone results in a break in surface slope, with the landward part being steeper than the seaward part. This observation is consistent with critical taper theory.

In the two models, an increase in basal shear sliding resistance generates OSTs and a coexisting scarp. These structural features are observed in the cases of subduction of a basement slice or a seamount,
but the origin of the OSTs and scarp can be determined based on a detailed analysis of the structures in the wedge. The subduction of a basement slice results in a flattened OST and the occurrence of a basement slice at the root of the OST. The subduction of a seamount results in a seamount located behind the slope break and the deposition of margin- and trench-fill sediments beneath the slope break. An increase in shear sliding resistance produces a flat basal plane, without slope-failure sediments beneath the OST.

The structural features observed in the above numerical simulations are also observed in natural accretionary wedges. Scars and sigmoidal OSTs cutting thrust sheets are observed in the Nankai trough, off Muroto, as well as in the Sunda Strait and Barbados Ridge complexes. Although there exists little information regarding basal shear sliding resistance in these complexes, these structures might reflect an increase in basal shear stress.

The simulations reproduced the structural features expected to be generated by an increase in shear sliding resistance. However, the pore-fluid pressure and the properties of the material are likely to be controlled by several factors. To advance our understanding in this regard and to perform more realistic simulations, it would be necessary to develop a more advanced simulation technique that is able to simulate fluid–solid interactions.

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