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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

Ayumu Miyakawa *, Yasuhiro Yamada, Toshifumi Matsuoka

Department of Civil and Earth Resource Engineering, Kyoto University, Katsura, Kyoto 615-8246, Japan

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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.

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.

* Corresponding author. Tel.: +81 75 383 3206; fax: +81 75 383 3203.
E-mail address: miyakawa@earth.kumst.kyoto-u.ac.jp (A. Miyakawa).

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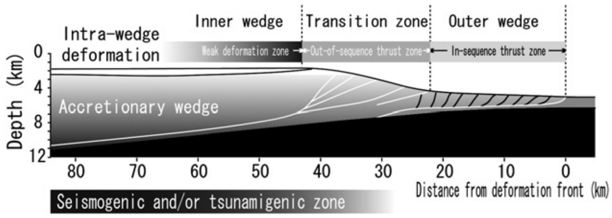

Fig. 1. Generalized structure around the up-dip limit of the seismogenic zone within the Nankai Trough (from Kimura et al., 2007). The wedge is divided into three segments based on differences in frictional behavior along the basal fault.

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 (Tsuji 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 hemi-pelagic mudstone sequence (Mikada and Becker, 2002).

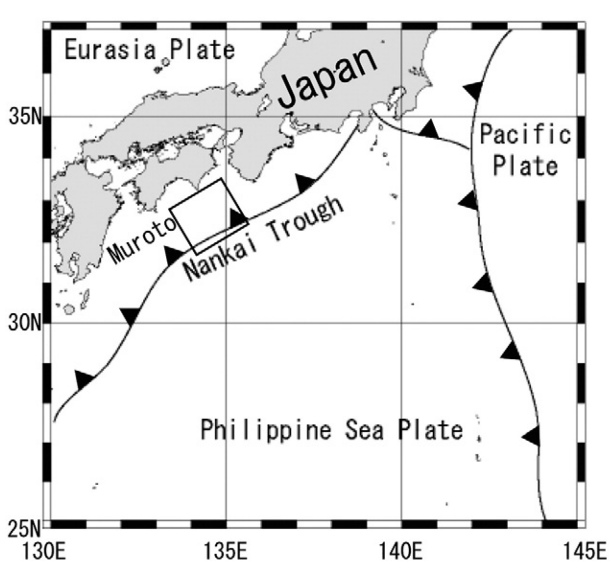

Fig. 2. Map of the plate boundary south of Japan. The Nankai trough is located at the boundary between the Eurasia and Philippine Sea Plates. The rectangle indicates the Muroto region.

The above features of decollement development are also observed in Barbados (DiLeonardo 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 turbidities and underlying hemi-pelagic 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

$$\tau_b = C_0 + \mu(\sigma_n - p_f) \tag{1}$$

where C_0 is cohesive strength, μ is the coefficient of friction, σ_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 ϕ:

$$\mu = \tan\phi. \tag{2}$$

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 (Tsuji et al., 2008), which ensures low frictional sliding resistance τ_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 τ_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., 1995, 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.