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ABSTRACT

Mechanical models are used to investigate the formation of accretionary prisms and related basins fed by sediments supplied from adjacent continents and subjected to sediment subduction. Results show that prisms forming under the influence of a hinterland sediment flux exhibit markedly different characteristics compared to classic critical wedges with identical mechanical properties forming by frontal accretion of a preexisting layer. The main differences are reduced surface slopes, increased spacing between thrusts, widespread wedge-top basins, and the presence of buried structures. These differences are explained by the ability of continuous sedimentation to reduce differential stresses in the wedge, leading to stable (supercritical) geometries. Thus, in regions of active sedimentation, wedge geometries cannot be explained solely in terms of relative strengths of the wedge and its décollement, as is the case for critical wedges. Results also show that variations in the relative rates of sediment supply (e.g., linked to climate changes) and sediment subduction may lead to pulsed growth and decline of wedges though time, as has been evidenced for some natural wedges. Thus, rather than viewing compressive plate margins as accretionary versus erosive, the dominant mode may repeatedly switch back and forth through time in response to variations in relative rates of sediment supply and sediment subduction.

INTRODUCTION

Although it is recognized that trenches, accretionary prisms, and forearc basins form in response to accretion, sediment subduction, and sediment input from nearby continents (Scholl et al., 1977; von Huene and Scholl, 1991; Clift and Vannucchi, 2004), it remains uncertain as to how these various processes are reflected in the geometry and dynamics of compressive plate margins. Traditionally, accretionary prisms have been modeled as being analogous to the wedges of snow or soil that form in front of moving bulldozers (Davis et al., 1983; Dahlen et al., 1984). The material deforms until it attains a constant critical taper and then slides stably, continuing to grow self-similarly as additional material is encountered at the toe (Fig. 1A). The critical wedge bulldozer model agrees well with analogue sandbox experiments and has been powerful in accounting for the large-scale geometry of modern accretionary prisms (Davis et al., 1983). However, several recent developments have begun to affect views of how convergent margins function. One is the acquisition of high-resolution data, which have advanced our understanding of the internal architecture and timing of events at compressive margins (e.g., Park et al., 2002; Bangs et al., 2004). Another is the result of analogue modeling and field-based studies that have highlighted the importance of factors such as sediment subduction (Gutscher et al., 1998) and active sedimentation (Storti and McClay, 1995; Mugnier et al., 1997; Bonnet et al., 2007; Morley, 2007) in influencing the geometry and evolution of accretionary prisms. Theoretical models incorporating dynamic mechanical effects (Wang and Hu, 2006) or hinterland sediment supply and the large-scale geometry of subduction zones (Fuller et al., 2006) have led to renewed interest in the formation of wedges and forearc basins and their potential link with subduction zone earthquakes. These developments raise the question of whether accretionary margins can continue to be explained adequately with classic critical wedge models, or whether is it necessary to call upon more sophisticated models incorporating processes such as hinterland sediment input and sediment subduction that are known to be important in such settings. Herein I examine the formation of accretionary wedges fed by sediment supply from the hinterland and influenced by sediment subduction (Fig. 1B) using a two-dimensional, coupled mechanical-surface process, finite element model (Simpson, 2006). The intention of this work is to show how these prisms differ from those forming by the classic critical wedge bulldozer model and to sharpen focus on the mechanisms controlling wedge geometry and evolution.

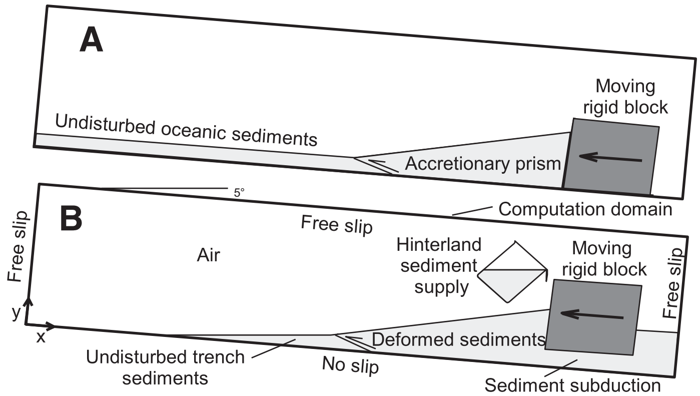

Figure 1. Illustration of accretionary prisms. A: Formed by offscraping of oceanic sediments from underthrust plate. B: Formed by deformation of sediment derived from neighboring continent. Sediments supplied from hinterland may either be ponded in wedge-top basins and deformed in situ, or may bypass wedge (e.g., in canyons) and be deposited directly in trench where they are frontally accreted or subducted beneath indentor. Growth of prism in A is controlled by convergence rate and thickness of undisturbed sediments on underthrust plate, whereas in B it is controlled by relative rates of hinterland sediment supply and sediment subduction. B also depicts basic setup and boundary conditions investigated in numerical model. Model domain was discretized into 250 × 50 9-node finite elements. Details of model are provided in GSA Data Repository (see footnote 1).

GEODYNAMIC MODELING

A series of numerical simulations have been carried out to identify how the presence of an active sediment supply influences accretionary wedges subjected to sediment subduction (Fig. 1B). More than 80 simulations have been performed, 4 of which are presented. Because all experiments have exactly the same mechanical properties, differences in results are entirely due to different sediment supply and/or thickness of the initial layer. More details on the numerical model are provided in the GSA Data Repository.[1]

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[1]GSA Data Repository item 2010026, supplementary explanation of numerical model, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 2A shows results of a simulation typical of a classic critical accretionary wedge formed by pushing an indentor into a preexisting layer of sediment. Because this model does not include any hinterland sediment input, it serves as a reference with which succeeding experiments can be compared. Results show the development of a wedge comprising a series of forward-verging thrusts separated by deep but narrow wedge-top basins displaying growth strata. The wedge surface slope varies between ~15° near the front of the wedge to ~5° toward the back of the wedge. The decrease in wedge slope toward the rear is due to a combination of the lack of vertical slip between the wedge and the indentor (creating drag) and the zero sediment flux boundary condition. Thrusts are nucleated in a nearly periodic fashion close to the toe of the wedge and remain active, along with their neighboring basins, until new frontal thrusts are initiated. Thereafter, the thrusts that have been incorporated into the wedge remain relatively inactive, but they steepen as the wedge continues to readjust in response to continued accretion, sediment subduction, and erosion. Because surface mass transport is controlled by linear diffusion, all sediment that fills wedge-top basins is derived locally from adjacent active thrusts. Together, these features are consistent with the main morphological and structural features of wedges forming by frontal accretion of a preexisting layer studied in analogue sandbox experiments (e.g., Storti and McClay, 1995).

Figure 2B shows results of a simulation that differs from the previous experiment only in that sediment input is at the top of the accretionary prism (i.e., adjacent to the indentor) before cascading down over the prism toward the trench, filling local basins to their spill level on the way. This may correspond to a situation whereby there is a high sediment supply from the adjacent continent but the margin lacks throughgoing transverse canyons. Results show that introducing a constant hinterland sediment supply has a profound influence on the development of the accretionary wedge. The wedge consists of a series of widely spaced foreland-verging thrusts separated by, and in some cases completely overlain by, thick and extensive wedge-top basins. Because most sediment is ponded on top of the wedge behind active structures, the trench remains virtually empty. The surface morphology is generally very flat (<1°) except toward the front of the wedge, where active structures may escape the influence of wedge-top sedimentation, resulting in local relief. The reason the overall width of the wedge is greater than in model 1 is due to the higher input flux, which includes contributions from both hinterland sediment input and frontal accretion of the preexisting layer.

Figure 2C shows results of a simulation wherein, rather than sediment input being at the top of the accretionary prism as in the proceeding experiment, it is introduced directly to the currently lowest topography (i.e., the trench) before back-filling into progressively higher depressions. This case may correspond to a situation whereby sediment input from the hinterland bypasses the accretionary prism in a series of well-developed canyons, or enters the trench from along-axis flow. In this case, deformation tends to be focused toward the rear of the wedge, leading to substantial local relief behind the zone of active sedimentation, characterized by very low mean surface slopes (~0.5°). Deformation is also sporadically active within the zone of active sedimentation on widely spaced thrusts, though these structures accumulate relatively small displacements compared to those in the back of the wedge. As in the previous simulations, some structures become completely buried due to active sedimentation within the region of active deformation.

In nature, the sediment supply (or sedimentation) rate is known to vary strongly with changes in climate (Molnar, 2004) or due to modifications in the sediment routing system in response to channel avulsion or creation of new channels. The final experiment investigates how these variations might affect the development of an accretionary wedge (Fig. 3; Video DR1). The sediment supply rate, introduced at the top of the wedge,

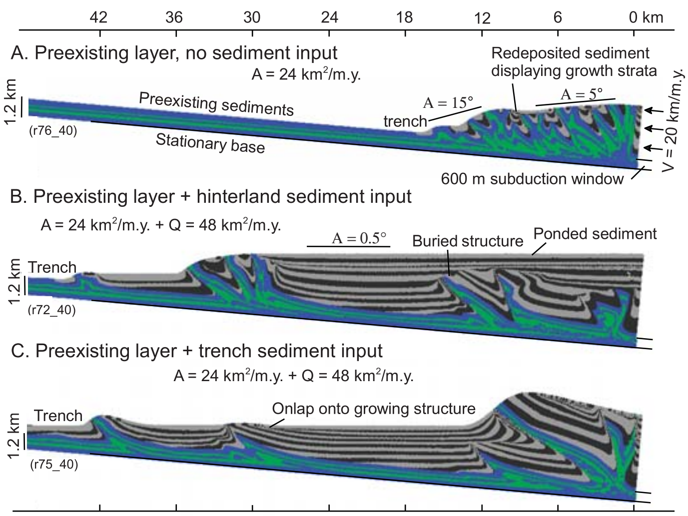

Figure 2. Numerical results showing comparison between three different numerical experiments after 2.2 m.y. of convergence. Deformed cross sections show synthetic stratigraphy where colors are repeated at regular time intervals (60 k.y.). Sediments present prior to onset of convergence are shown in blue and green, whereas sediments in light and dark gray were introduced during deformation and/or were redeposited by surface processes. Both sediment types nevertheless have identical mechanical properties. A: Classical critical wedge formed by frontal accretion of 1.2-km-thick preexisting sedimentary layer. B: Wedge forming in presence of a constant hinterland sediment supply, introduced at top of wedge beside indentor. At each time step, a fixed volume (or area in two dimensions) of sediment is introduced into model domain. C: Wedge forming in presence of constant hinterland sediment supply, introduced directly to trench. Each panel shows background accretionary flux A (computed as product of convergence velocity and thickness of preexisting sediments) and sediment supply rate Q. Total sediment delivery in B and C is 72 km²/m.y., similar to that estimated for Nankai prism (Clift and Vannucchi, 2004). Note that flux due to sediment subduction beneath indentor is 12 km²/m.y. [taken as product of gap under indentor (0.6 km) and convergence velocity V = 20 km/m.y.] in each model.

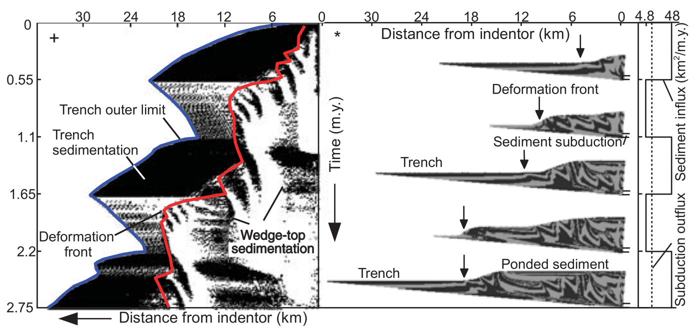

Figure 3. Results of numerical model showing formation of accretionary wedge fed by time-varying sediment supply rate (Video DR1; see footnote 1). Sediment supply rate introduced at top of wedge oscillates in stepwise manner between 48 km²/m.y. and 4.8 km²/m.y. with a period of 0.55 m.y., while flux of sediment exiting wedge by subduction is maintained at 12 km²/m.y. A: Chronostratigraphic diagram where stipple pattern shows locations undergoing sedimentation in time and space coordinates. B: Deformed cross sections show synthetic stratigraphy where colors are repeated at regular time intervals (60 k.y.). When sediment input exceeds output due to subduction, wedge has low surface slope and thick, wide trench due to high sedimentation rates. A 10-fold reduction in sediment supply rate starves trench and wedge of sediment, causing it to narrow and steepen (i.e., toward becoming critical). Note, however, that deformation front remains relatively stable during periods of high sediment flux, whereas it rapidly advances as soon as sedimentation rates drop.

is assumed to oscillate in a stepwise manner between 48 km^2/m.y. and 4.8 km^2/m.y. with a period of 0.55 m.y., while the flux of sediment exiting the wedge by subduction is maintained at 12 km^2/m.y. Results show that during periods of high sediment supply, accommodation space on the wedge top is filled, resulting in sediment bypass directly to the trench, which expands rapidly outward over the overthrust plate. During this time, the deformation front continues to advance slowly outward, accreting trench sediments. When the sediment supply rate drops such that the wedge has a net outflux, the deformation front initially steps rapidly outward, accreting the thick trench deposits accumulated during the previous episode of elevated flux. Thereafter, the deformation front remains pinned to the inner side of the trench, resulting in narrowing and steepening of the wedge with time. Renewed outward propagation of the deformation front only begins until more than 150 k.y. after the sediment flux has returned to its high value. At the end of the experiment, the wedge is composed almost entirely of sediments deposited during periods of high sediment flux.

DISCUSSION AND CONCLUSIONS

The results presented herein highlight the potential importance of the hinterland sediment supply and active sedimentation in controlling the morphology, structures, and dynamics of accretionary wedges. Generally, wedges that form in the face of active sedimentation have lower surface slopes, more widely spaced thrusts, and more extensive wedge-top basins relative to normal critical wedges that form in response to frontal accretion of a preexisting layer. Similar features have been observed in analogue modeling studies (e.g., Storti and McClay, 1995; Mugnier et al., 1997). Exactly how the sediment supply modifies the wedge depends on the nature of the sediment routing system. If sediment supply to the trench is inefficient (e.g., due to the absence of transverse canyons), sediments become ponded behind, and may completely bury, growing structures. Similar features have been observed in natural fold-thrust belts in regions of active sedimentation (e.g., Ori and Friend, 1984; Pieri, 1989). If, however, sediments bypass the wedge top and are deposited directly in the trench, deformation tends to be concentrated behind the zone of active sedimentation. However, it is remarkable that even this case leads to wedges that are distinctly different from those forming by the frontal accretion of a preexisting layer. Because modern accretionary prisms are invariably associated with regions of high sediment supply from nearby continents (Clift and Vannucchi, 2004), these results imply that wedge tapers cannot be interpreted solely in terms of relative strengths between the wedge and its décollement, as is the case for critical wedges. The reason why such wedges exhibit low tapers is related to wedge-top sedimentation causing supercritical (stable) forms. This is because sedimentation increases the vertical stress in the wedge (more than the horizontal stress), thereby decreasing the differential stress and unloading the stress state from the failure surface (Fig. DR1). Thus, even though sedimentation tends to reduce the surface slope compared to a critical wedge, these wedges are unable to reestablish a critical state by internal brittle failure. This can only be achieved if wedge-top sedimentation rates decrease sufficiently, as would occur during climatic periods of reduced erodability on nearby continents. Periods of low sediment supply may cause steepening of the wedge surface (i.e., to achieve criticality) and a decrease in the overall wedge size, which could eventually lead to complete disappearance of the wedge by sediment subduction. Paradoxically, a decrease in sediment supply actually enables the deformation front to initially advance more rapidly outward, accreting thick trench deposits dating from previous episodes of high sediment flux. This is due to the stabilizing effect of continuous sedimentation. Similar pulsed behavior has been inferred for some natural wedges (Byrne and Fisher, 1987; von Huene and Lallemand, 1990; Kimura, 1994; Underwood et al., 2003), though periods of rapid outward growth are normally thought to be associated with rapid sediment input (Mountney and Westbrook, 1996). These results imply that compressive plate margins cannot be classified statically as accretionary versus erosive, but that the dominant character may change repeatedly through time.

The mechanism proposed to explain how active sedimentation and the resulting reduction in surface slope can lead to supercritical (not subcritical) accretionary wedges is not within the realm of classic critical wedge theory, which assumes that the state of stress within the wedge and on its base is everywhere on the verge of Coulomb failure. This condition is probably normally achieved in wedges forming by accretion of a preexisting layer due to continued deformation, but may not be so in the presence of rapid active sedimentation. This mechanism may contribute to the very low surface slopes associated with some accretionary wedges forming in the presence of a large sediment supply (e.g., Northern Apennines, Makran), something normally ascribed to other effects such as anomalously weak detachments or slab processes. In cases where there is no major hinterland terrigenous supply (e.g., Mariana), one expects that any prism that does form would be a standard critical one. The proposed mechanism is also distinctly different from that suggested to be responsible for the formation of forearc basins (Fuller et al., 2006). In that case, landward-dipping ($\alpha < 0$) portions of the critical wedge (related to a landward increase in the slab dip) trap sediment originating from the nearby continent, causing the wedge to become shallower ($\alpha = 0$) than critical (i.e., supercritical).

Results of the modeling presented here may provide new insight and aid in interpreting the geometry and evolution of modern accretionary margins. As an example, Figure 4 presents two published cross sections based on seismic profiles across the Nankai trough. The Kumano transect reveals a large out-of-sequence (or mega-splay) fault (OOST, Fig. 4) that separates a large, nearly flat forearc basin from the outer wedge, comprising sandy turbidites and hemipelagic trench deposits deformed by normal in-sequence deformation (Park et al., 2002; Bangs et al., 2004). The Muroto transect lacks a well-developed forearc basin, but contains two major thrust zones (large thrust slice zone, out-of-sequence thrust) behind the frontal outer wedge, which comprises deep-sea fans and axial channel deposits (Moore et al., 2001). Quaternary sedimentation rates in the trench region of the Moroto transect (600–760 m/m.y.) are similar to the rates estimated for the Kumano forearc basin over the past 2 m.y. (600 m/m.y.), but are significantly larger than the rates measured on the upper slope of the prism in the Kumano transect (160 m/m.y.) (Moore et al., 2001). Together, these results could indicate a link between the sedimentation history and the accretionary prism growth and evolution of the splay fault system. In the Kumano transect, sediment trapping in the forearc basin may starve the frontal part of the prism, which may tend to maintain activity on the splay fault (as in Fig. 2B). When the sediment influx is elevated, as it appears to have been during the past 2 m.y., sediment may bypass the forearc basin and be deposited directly in the trench. This presumably

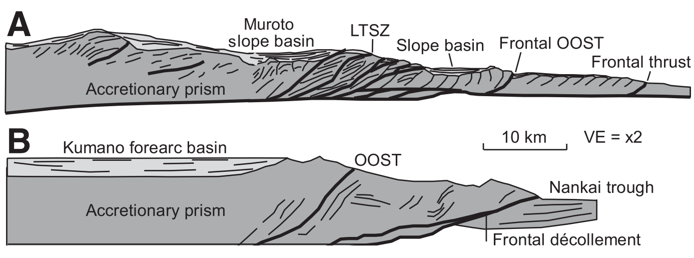

Figure 4. Cross sections interpreted from seismic profile transects of Nankai subduction margin off southwest Japan. A: Muroto (after Moore et al., 2001). B: Kumano (after Park et al., 2002). As discussed in text, growth of these accretionary prisms and major fault systems may be linked to sedimentation history in adjacent trench and forearc basins. OOST—out-of-sequence thrust; LTSZ—large thrust slice zone. VE—vertical exaggeration.

enables renewed frontal accretion, though its timing may not coincide precisely with the period during which sediment rates are high (see Fig. 3). In the Muroto transect, the hinterland sediment supply appears to have been less important, probably due to its location off the Muroto headland. Rather, the accretionary prism appears to have been fed mainly by axial channels and deep-sea fans in the trench. In this case, rapid trench sedimentation rates over the past 2 m.y. may have hindered deformation on the frontal structures at the expense of sporadic deformation on the large thrust slice zone or out-of-sequence thrust (as in Fig. 2C).

ACKNOWLEDGMENTS

I am grateful for help, comments, encouragement, and support from Sean Willett, Katja Petrini, Patience Cowie, reviewers, and the Swiss National Science Foundation.

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Manuscript received 16 June 2009
Revised manuscript received 6 August 2009
Manuscript accepted 27 August 2009

Printed in USA