Sediment accretion against a buttress beneath the Peruvian continental margin at 12° S as simulated with sandbox modeling

Abstract Reflection seismic data from the Peruvian continental margin at 12° S clearly reveal an accretionary wedge and buttress. Sandbox experiments applying the physical concept of the Coulomb theory allow the systematic investigation of the growth and deformation of such an accretionary structure. The style of deformation of the buttress and the internal structure of the wedge is observed in the sandbox models. The possibility of underplating material beneath the buttress and the amount of tectonic erosion depend on the physical properties of the materials, mainly internal friction, cohesion and basal friction. Boundary conditions such as the height of the subduction gate and the thickness of incoming sand also constrain the style of growth of the model accretionary structure.

Introduction

The concept of a buttress or backstop has been firmly implanted in published work on convergent margins (Byrne et al., 1988; 1993). It is considered to be the seaward edge of the island arc or continental margin older rock framework against which an accretionary prism forms (von Huene and Scholl, 1993). Conceptually, this body is the anvil against which offscraped trench sediment is accreted and tectonically deformed.

A good example of an actual buttress is imaged in seismic records across the Peruvian margin. Beneath the slope, a wedge-shaped body of crystalline rock with probable continental affinity has been imaged through careful processing of seismic records (Moore and Taylor 1988; von Huene and Miller 1988; von Huene, in press). Against this wedge-shaped buttress a prism of trench sediment about 10 km wide has been accreted. Deformation visible in the overlying sediments may give a hint that deformation also occurs in the narrow tapered end of the buttress.

The evolution and deformation of the accretionary body in front of a buttress can be forward modeled applying a sandbox technique. However, in most former models the buttress was modeled as a hard, non-deformable member and sand was accreted against a landward or seaward dipping rigid stationary buttress (Byrne et al., 1988; Mulugeta 1988; Lallemand et al., 1992). To achieve more realistic conditions, Byrne et al. (1993) used a deformable backstop made of wet sand. Considering the tectonic deformation in the buttress off Peru, we introduced a deformable buttress (compacted rock powder) in the sandbox modeling. Furthermore, we scaled the models after observations in seismic records across the Peruvian margin to replicate features observed in nature and we allowed material to leave the system through a 'subduction window' to simulate that in nature a certain amount of material is transported to greater depths.

In this paper we report the results of our sandbox modeling. A main objective of our models was to test
Tectonic history of the Peruvian margin

Four seismic lines (1017, 1018, CDP-1, HIG-14) covering about 30 km along the Peru margin near 12° S show the accretionary wedge and the buttress (Fig. 1). Line CDP-1 from the Nazca Plate Project and Shell 1017 were processed in the time domain to a pre-stack migration in preparation for ODP drilling on leg 112 (von Huene and Miller, 1988). HIG-14, which was also a part of the drilling transect (Moore and Taylor, 1988), was post-stack time migrated. The Shell line 1018 is also very close to the main drilling sites. Because of this proximity and because the Shell data are of fairly high quality, both Shell lines were pre-stack depth migrated at GEOMAR (von Huene and Pecher, unpublished data).

From early wide-angle seismic data (Hussong and Wipperman, 1981) it was known that seismic velocities of 5 km s⁻¹ and greater characterize upper plate rocks landward of the first 10 km of the margin. In seismic reflection records, coherent reflections were visible along boundaries above and below a high velocity wedge, but incoherent events characterized its interior. Rocks recovered from outcrops at the edge of the shelf and along the lower slope indicated that the area of incoherent reflections could represent equivalents of the schists and gneisses that are exposed in the coastal mountains. After drilling leg 112, these rocks were observed from a submersible in outcrops at the foot of the margin in Chiclayo Canyon (Sosson et al., 1992). During leg 112 a shallow water Eocene sandstone which is known to rest unconformably on the metamorphic rock cropping out at the edge of the shelf was recovered from two sites on the lower slope near 12° S. The unconformity is seen in all multi-channel seismic records across the continental shelf and is inferred to extend onshore. This regional unconformity, now up to 5 km below sea level, was a subaerial erosion surface in pre-Middle Eocene time (von Huene, Suess et al., 1988) because the shallow water continental origin of the sandstone on the unconformity makes it unlikely that the underlying basement is an Eocene deep water accretionary wedge. Minor deformation affects the thin tapered part and only extensional deformation of the basement is observed to cut the basement from the middle slope landward (Fig. 2). These observations indicate that the wedge-shaped buttress is a relatively rigid body probably composed of metamorphic rock similar to that in the coastal massif (Kulm et al., 1988).
One aim of our study was to test this kinematic interpretation physically with sandbox experiments.

**Sandbox experiments**

**Model concept**

Modeling the evolution of an accretionary wedge with the sandbox technique is based on the assumption that the frontal part of a subduction zone, i.e. the accretionary wedge, the underplated sediment and the frontal part of the buttress, behaves as a Coulomb material (Davis et al., 1983; Dahlen, 1984). Thus the scale-independent Coulomb theory can be applied. Dahlen (1984) derives an exact solution for the critical taper a uniform wedge for the case of a non-cohesive material. The mechanical state of the accretionary wedge is, for a given rock density, a function of only four parameters, the internal and basal pore pressures and friction angles, but not of time or temperature. However, natural rocks are cohesive materials. Dahlen et al. (1984) showed that the Coulomb theory can be extended to cohesive materials with cohesion, $C_0$, as the fifth of the parameters which characterize the state of stress in a critically tapered wedge.
Construction of the model experiments

The experiments were carried out using a glass-sided rectangular box (Malavieille, 1984). The oceanic crust is represented by a plastic plate which can be bent to model the geometry of a subduction zone. On its surface, materials such as sticky paper or a Mylar sheet are fixed to simulate different basal frictions. The main difference between our experiments and previous work is the use of a deformable backstop made of compacted rock powder (rock sawdust), which means that the frontal part of the buttress is also assumed to behave as a Coulomb material. In the first experiment, a curved plate was used.

We constructed the model geometry matching the angular relations observed in the seismic records. Scaling was such that 1 km in nature was equivalent to about 1 cm in a model (scale factor \( \approx 10^3 \)). Subduction was simulated by dragging a lower plate at a specified angle beneath the buttress. The thickness of incoming sediments was scaled according to the thickness of sediments near the trench observed in the seismic records. Material balance was controlled by constructing a fixed window ('subduction window') at the 'landward edge' of the model box through which subducted sand is allowed to exit with the moving plate from the model. The thickness of coherent reflections was assumed to represent the height of the subduction window.

Lallemand et al. (1994) compiled the mechanical parameters for many examples of convergent margins. However, there are no measurements available for the Peruvian subduction zone. In our first two experiments, which will be described in detail in the following section, we used different basal frictions. Thereby we tested which parameter set better matches observations to give a first constraint for the mechanical properties of the Peruvian continental margin.

In both experiments the buttress was constructed of darkly coloured rock powder (rock sawdust) from a Miocene sandstone which was carefully compacted during construction. Thin, light marker horizons of the same material were repeatedly inserted to mark any deformation occurring during the experiment visible. The oceanic and slope sediments were modeled using dry, fine-grained (<300 μm), differently coloured eolian quartz sand. The mechanical properties of both materials were measured giving \( \rho_{bu} = 2300 \text{ kg m}^{-3} \), \( C_{\partial bu} = 130 \text{ Pa} \), \( \mu_{bu} = 0.6 \) for the sawdust, \( \rho_s = 1900 \text{ kg m}^{-3} \), \( C_{\partial s} = 20 \text{ Pa} \), \( \mu_s = 0.57 \) for the sand. \( \mu \) is scale-independent and \( \sim 0.6 \), a reasonable value (Lallemand et al., 1994), cohesion scales to \( \sim 13 \text{ MPa}, 2 \text{ MPa} \), respectively which are again reasonable values (Hoshino et al., 1972).

As indicated in the seismic lines, the buttress in the first experiment had an initial taper of 20° and the slope had a taper of 9° (Fig. 4a). Sedimentation in the trench axis was simulated by adding material during the course of the experiment on top of an originally 0.5 cm thick section of material representing pelagic and hemipelagic sediments and initial trench-fill. In this experiment, double-sided adhesive tape was attached to the moving plate giving a basal friction \( \mu_b \) of 0.5. During the first 30 cm of convergence, an increasing amount of sand was added in the trench axis to simulate material supply from the continental plate. As a result of this, the ratio \( R \) of incoming to outgoing material changed from \( R = 2 \) to \( R = 3 \). No more material was added to the trench axis, and \( R \) decreased to about \( R = 1 \) after 80 cm of convergence and then remained constant.

The construction of the second model was designed to answer questions raised by the interpretation of the first experiment and especially to investigate the role of the subduction channel. During this experiment no material was added to the trench as it became clear from the first experiment that the material input could be simulated without constant sedimentation in the trench axis. A critical parameter is the height of the subduction channel in seismic records, which is uncertain because of its great depth (12–15 km). An error of 100–200 m might have a significant effect on the results in a sandbox model. To test this, the thickness of incoming material was the same as that of the subducted material during the whole course of the experiment (\( R = 1 = \text{const.} \)).
Results of the sandbox experiments

First experiment

The first experiment was started with a slope angle $\alpha = 10.5^\circ$ and a dip angle $\beta = 8^\circ$ (Fig. 4a), which should give a stable initial taper according to Coulomb theory. During the run of the experiment, the rigid lower plate was dragged a total of 105 cm, taking a photograph for documentation every 5 cm. Several times during the first stages of this experiment, sand was added to the trench to match a possible effect of an increase in sediment volume just after the subduction of the Nazca Ridge.

During the first 20 cm, the slope angle decreased to about $8^\circ$ in the ‘arcward’ part of the model wedge and then remained constant. Consequently, the taper also changed, matching the critical taper for a basal friction of 0.5 (Lallemand et al., 1994). In this stage, the buttress, especially at its toe, underwent additional compaction. Thus the bending of the toe of the buttress due to frontal accretion induced shortening in the upper part of the buttress and caused the formation of conjugate thrusts in the sandy cover (Fig. 4c).

During the first 30 cm of convergence, material was accreted only beneath the buttress, which resulted in uplift and a decrease in the thickness of the trenchward part of the buttress. After more than 35 cm of convergence, the formation of the frontal accretionary wedge and duplexes began.

To accommodate the shortening, several nearly parallel backthrusts dipping $43^\circ - 45^\circ$ towards the toe developed in the buttress. As the input of material continued, sediment was partly accreted in front of the buttress, partly below it. Material leaving the experimental box through the subduction window originated mostly from the subducted sand, but also to a small amount from the buttress. This resulted in the formation of faults nearly perpendicular to the backthrust in the lower part of the buttress near the rigid backstop. The deforming buttress was tilted arcward and uplifted by the growing wedge beneath it (Fig. 5).

During the course of the experiment, an out of sequence thrust (top décollement) developed just beneath the buttress (Fig. 4). Basal shear was partitioned between this ‘top décollement’ and the ‘basal décollement’ between the sand and the rigid lower plate. Between the top décollement and the buttress material originating from the moving plate was underplated. Above the top décollement, no movement occurred (Fig. 4d–f).
The first duplex was fully developed after a convergence of 50 cm. During the formation of a new duplex, the slope angle changed, reaching a minimum when a new fault originated, resulting in a periodicity of the specific steps of duplex formation which is documented in several distinct steps of different steepness along the slope in the three-dimensional view of the frontal part of the accretionary structure (Fig. 6a). Subsequent duplexes were progressively more closely spaced. Not all faults were active at the same time or during the whole course of the experiment, so that movement occurred at one time only in connection with the two or three latest duplexes. After the maximum convergence of 105 cm at the end of the experiment, seven duplexes had been built (Fig. 6b). The movement along the out of sequence thrust stopped after about 60 cm of convergence and the shape and amount of underplated material remained constant. This might be a consequence of the change in the amount of material remained constant. This might be a consequence of the change in the amount of input, which was no longer in excess of the output at the subduction window. After the development of a duplex was completed, no more movement occurred along the bounding faults.

Summarizing the main features observed during this experiment, we point out that the backward tilting of the buttress occurred as soon as enough underthrust sand was built beneath it, which is a function of greater input than output (Fig. 5). The thickness of the material accreted beneath the buttress increased continuously. The top décollement marks the boundary between accreted and underplated sediment.

The buttress undergoes shortening and tilting at its trenchward edge. Despite the contraction of the buttress the accretionary wedge grows at its seaward edge such that the accretionary advance is about twice the contraction of the buttress after a dragging distance of 105 cm (Fig. 6).

Second experiment

The initial geometry of this experiment was scaled to a more refined model from an early MIGPACK pre-stack depth migration version of line 1018 (Klingelhöfer, 1992) with $\alpha = 11.5^\circ$ and $\beta = 4.5^\circ$ (Fig. 7a).

The seismic record shows sediments 800 m thick entering at the trench axis and sediments of various thickness being subducted to a greater depth, but we do not know the history of subduction. Therefore, one major objective of this experiment was to investigate the effect of trench sediment supply versus its disposal by subduction. For this reason, the incoming material had the same height (8 mm) as the subduction window. Both heights were held constant during the experiment. The coefficient of basal friction was lower ($\mu_b = 0.43$). This was achieved by attaching a Mylar sheet on top of the moving plate.

In the early stages of this experiment, the trenchward edge of the buttress was compacted, shortened and thickened due to compression. Its leading edge was also tilted and a small amount of sand was accreted below it (Fig. 7b), concurrent with accretion in front of the buttress. Seaward verging faults in the sandy cover developed above the buttress’ leading edge due to the shortening. The buttress was involved in the underthrust sequence such that a major thrust ate its landward part. Schlieren-like accumulations of the light coloured sand in the dark sand indicate internal deformation and faulting within the accretionary wedge (Fig. 8).

During the experiment, the wedge steadily grew at a nearly constant taper. The material removed through the subduction channel was almost all from the buttress. Thus an upper part of the continental slope with a slope angle of about $12^\circ - 13^\circ$ above the landward part of the buttress can be distinguished and a more gentle lower continental slope above the critically tapered trenchward part of the buttress and the accretionary wedge. However, the volume of the whole model accretionary complex remained almost unchanged during the run of the experiment, reflecting the balance between the input and removal of material. The wedge itself grew steadily while the slope angles remained constant. Accretion began immediately at the trench axis and was compensated by erosion from the base of the buttress. This experiment indicates that accretion and tectonic erosion can occur simultaneously but at different locations if there is a certain amount of material being subducted and if distributed shear occurs along the plate boundary. However, this material flux has to be tested carefully by...
Fig. 6a, b. Photographs showing in detail the accretionary wedge in a an early stage and b a late stage of the first experiment.

comparison with data and observations in nature because these processes are forced to a certain amount in sandbox experiments.

Underplating did not occur, a result which is fundamentally different to that of the first experiment. This might be due to the fact that the top décollement runs through the buttress, which was eroded. The absolute position of the uppermost décollement is a function of the basal friction (Lallemand, 1992); the relative position in relation to the buttress also depends on the thickness of material accreted beneath the buttress, the different position of the top décollement, which again is a function of basal friction. If we open the subduction window, the
Fig. 7a–d. Interpretative line drawings of a initial configuration and several steps during the run of the second experiment: b after 35 cm; c after 75 cm; and d after 110 cm of dragging of the lower plate

thickness of the removed layer increases as the basal friction decreases. In other words, with a high basal friction as in the first experiment, the thickness of the removed layer is more or less equivalent to the height of the window, whereas in the second experiment with a low basal friction the thickness of the removed layer is about twice the height of the window. This is supported by the observation that the removed layer constituted almost only sand in the first experiment, but sand and rock powder in the second. This means that if there is low basal friction, there is a great potential for tectonic erosion so that material removal is dominantly constrained by the height of the subduction window. The processes controlling the height of the subduction window and, therefore, the amount of material which can be transported to greater depths are only very poorly understood in nature. Here, physical modeling may be helpful in detecting the controlling processes and parameters.

From this experiment it can be shown that the basal friction coefficient and the ratio of incoming to removed material are the parameters dominantly controlling the shape and growth of the accretionary wedge. Here, the basal friction determines the deformation behaviour of the buttress, whereas the input to removal ratio controls the growth rate of the wedge and the total change in volume.

Discussion

The sandbox experiments scaled geometrically from seismic images of the subduction zone off Peru at 12° S showed that the tectonic reconstruction proposed from seismic and geological data (Fig. 3) is consistent with the development of an accretionary wedge as modeled in a physical approach. The shape of the stable buttress obtained in the sandbox models shows a great similarity to what can be imaged in the seismic records as well as some structures such as back-thrusts. This indicates that applying the Coulomb rheology for the frontal part of a convergent margin may be realistic and may give a first constraint for the mechanical parameters of convergent margins. Therefore, from physical experiments we can learn something about the fundamental principles of accretion and erosion, and then try to constrain a kinematic evolution for a specific case.

Hussong and Wipperman (1981) proposed that the vertical movement of the trenchward part of the continental crystalline rocks (= buttress) in the Peruvian continental margin is a consequence of the thickening of material from the oceanic plate in the early stages of convergence. Comparing the observed structure of the Peruvian continental margin with the final stages of the sandbox models, the first experiment seems to match the observations more closely than the second. A value of basal friction of > 0.45 simulates the natural processes better.

The simultaneity of accretion and erosion as observed in the second sandbox model poses the question of whether this is also reasonable and possible in nature. There is some evidence that both mechanisms were active simultaneously along the Peruvian continental margin. The Lima Basin, located on the middle part of the slope, subsided from about 5 Ma ago to at least 2 Ma ago, as interpreted from foraminiferal data (von Huene, in press). The subsidence is inferred to be caused by the removal of material at the plate boundary. Therefore, although still hypothetical, accretion in front of the buttress and tectonic erosion at the back are not in conflict with observations and inferences about the processes at the plate boundary.

The experiments have revealed the ratio of incoming to removed material as one of the most crucial parameters controlling the mechanics of a subduction zone. Basal friction is another dominant parameter controlling distributed shear in a layer along the plate boundary. However,
the thickness of the subduction channel in nature and its role with regard to mass balance are poorly known. An associated question is the effect of changing the ratio of incoming material to material removed by subduction to greater depths. Similarly, the conditions conducive to underplating need quantification. We suggest that underplating can only take place if the ratio $R$ is significantly larger than unity and if basal friction is sufficiently high, so that the out of sequence thrust will be located beneath the buttress. Before being able to derive a complete model of the growth of an accretionary wedge in response to constraints from material supply, further systematic experiments are needed.

Seismic imaging and numerical modeling (Shi et al., 1990) have shown the importance of fluid transport within an accretionary wedge. Fluid pressure is a function of the hydraulics of the rocks present and controls the shear strength. This parameter is absent from sandbox experiments and must be considered through numerical modeling. However, with numerical modeling it is not possible to model the dynamic evolution of an accretionary wedge. Here, sandbox modeling is a good tool to derive constraints for mechanical parameters that can be entered into numerical models for fluid transport. Thus a combination of different modeling techniques constrained by good geophysical data could be a key to understanding the dynamic transport processes taking place in subduction zones.

Acknowledgements We kindly thank the Deutsche Akademische Austauschdienst (DAAD) and the Ministère des Affaires Etrangères Français for financial travel support to conduct the experiments in the Laboratoire de Géologie Structurale of the Université de Montpellier II within the French German PROCOPE program. Fundings of experiments came from the French Program ‘Dynamique et Bilan de la Terre’, CNRS-INSU-DBT contribution No. 80713. We also thank Marc Sosson and an anonymous reviewer for their valuable suggestions.

References

Fig. 8a, b. Photographs showing a an initial and b the final stage of the second experiment

“This is a short but fascinating paper. This sort of modeling is not easy to do well, but the authors have succeeded admirably. The importance of the relative size of the subduction window has never before been addressed as well as in this paper, the simultaneous accretion and erosion is another very important result.” Anonymus reviewer