Mechanical decoupling and basal duplex formation observed in sandbox experiments with application to the Western Mediterranean Ridge accretionary complex

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Abstract

Sandbox experiments of accretionary wedges were performed incorporating a thin weak layer of micro glass beads. The impact of heterogeneous sedimentary input on wedge mechanics, evolution and mass transfer was investigated. We report the first experimentally documented growth of basal duplexes. These occurred for high basal friction conditions, with restricted output of the lower section. The upper and lower sections were completely decoupled due to the intervening layer of glass beads, with frontal accretion occurring in the upper section simultaneously with basal duplex formation and underplating of subsequent generations of duplexes. IMERSE multichannel seismic reflection data from the Western Mediterranean Ridge (WMR) image Tertiary clastics beneath a thick section of Messinian evaporites. The base of the evaporites is identified as the primary décollement for deformation in the frontal part of the accretionary complex. Constriction of the channel of subducting Tertiary sediments, as well as internal deformation observed as arcward-dipping reflectors argue for basal underplating and/or two different active décollements. We propose an evolution of the WMR in accordance with the sandbox experimental results. A weak mid-level detachment (base of evaporites) combined with a strong basal detachment produce mechanical decoupling and basal accretion of toeward-verging duplexes. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The growth and evolution of submarine accretionary wedges at convergent margins can be described in terms of the critical taper model (Davis et al., 1983; Dahlen, 1984, 1990; Lallemand et al., 1994). This concept assumes that marine sediments entering a trench and then being underthrust or scraped off from the lower plate and accreted against the upper plate may be described as a frictional Coulomb material analogous to a sand wedge in front of a moving bulldozer. For the submarine case, the mechanical state is a function of internal and basal (i.e. at the décollement) friction angles, pore pressures, and cohesion. In accordance with the Mohr–Coulomb approach, the mechanical properties of the décollement, which marks the plate boundary (Moore, 1989), govern the mass transfer modes present in the whole accretionary complex controlling the style of deformation and the relative amount of accretion, subduction and underplating (Kukowski et al., 1994; Gutscher et al., 1998a).

Many insights into the systematics of growth and deformation of accretionary wedges have been gained from carefully designed analogue sandbox modelling (Malavieille, 1984; Mulugeta, 1988; Byrne et al., 1993; Kukowski et al., 1994; Gutscher et al., 1998a). In accretionary wedges the backstop against which ongoing accretion occurs may be an older accretionary wedge (e.g. off Alaska, von Huene et al., 1998) or a faulted probably continental crystalline body (e.g. off Peru, Byrne et al., 1993; Kukowski et al., 1994). In either case the backstop is stronger than the sediments forming the modern accretionary wedge. Consequently in analogue modelling, backstops made of wet sand or rock powder, both of which are stronger and more cohesive than dry quartz sand, have been found to realistically simulate different types of convergent margins backstops (Byrne et al., 1993; Kukowski et al., 1994; Gutscher et al., 1998b).

In some accretionary systems it has been shown through seismic images (e.g. Moore et al., 1991; von Huene et al., 1996, 1998) that sediments are subducted beneath the entire backstop and through studies of the isotopic composition of arc magmas (Morris et al., 1990; Kita et al., 1993) that sediments are subducted even into the mantle. Therefore, the removal of material from the experimental apparatus has to be considered when simulating mass transfer in the frontal part of a convergent margin. This has been done by introducing a ‘subduction window’, an opening at the base of the hinterland side of the apparatus, in studies of the Peruvian (Kukowski et al., 1994) and Alaskan (Gutscher et al., 1998b) margins.

A systematic series of experiments with different boundary conditions (Gutscher et al., 1998a) has revealed that the different styles of mass transfer are a function of basal friction and the ratio of input to output. However, in all of these previous experiments, the incoming section was homogeneous, whereas in nature the sediments entering a subduction zone may have quite variable mechanical properties. This can dramatically affect the style of deformation. For instance, in convergent margins (e.g. Nankai or Barbados), the level of the décollement is controlled by the varying mechanical properties of the different lithologies within the incoming sediment pile (Taira et al., 1992; Moore et al., 1998); variations in the mechanical properties along the layer can thus lead to changes in the level of the décollement. In the case of the Mediterranean Ridge for example, it has been argued that near the deformation front the décollement occurs at the base of the Messinian evaporites, but that further arcward the décollement is deeper at the level of the Aptian shales (Ryan et al., 1982; Reston et al., 2002a).

In this paper we use the results of sandbox modelling to investigate the effect of two décollement levels on the geometric evolution of the accretionary system. To simulate the shallower décollement, we incorporate a thin layer of micro glass beads in the incoming section; the deeper décollement is controlled by the height of the subduction window. The results have implications for geodynamic models for the evolution of the Mediterranean Ridge.
2. Tectonic evolution of the Mediterranean Ridge

The Mediterranean Ridge (Fig. 1) is an accretionary complex resulting from the convergence between the African and Eurasian plates at a rate of about 3.8 cm yr\(^{-1}\) (Le Pichon et al., 1995). In 1993 and 1994, cruises with the German RV Meteor, the French RV Nadir and the Italian seismic vessel OGS Explora (Hieke et al., 1994; Mascle et al., 1994; IMERSE Working Group, 1997) collected OBH wide-angle, swath bathymetry, gravity and magnetic data together with grids of multichannel reflection seismic lines. IMERSE profile 5 across the ridge (Reston et al., 1999a) collected OBH wide-angle, swath bathymetry, gravity and magnetic data together with grids of multichannel reflection seismic lines. IMERSE profile 5 across the ridge (Reston et al., 1999a), which runs close to PRISMED profile 03 (Chaumillon et al., 1996; Chaumillon and Mascle, 1997) is most suitable to characterise the structure of the Western Mediterranean Ridge (WMR, Fig. 2) because it is not affected by the subduction of asperities (von Huene et al., 1997) and closely parallels the direction of convergence at a location where convergence is almost normal to the margin.

Five units can be identified within the incoming section beneath the Abyssal plain (Reston et al., 1999a). These are, from the oldest up, the basement (unit 1), presumed to be oceanic crust; a series of highly reflective sediments, interpreted as Mesozoic carbonates (unit 2); less reflective layered sediments, interpreted as clastics of Late Mesozoic to Tertiary age (unit 3); the Messinian evaporitic sequence (unit 4); and the Pli-Quaternary (unit 5). Along profile 5 (Fig. 2), the frontal slope dips at about 1.2\(^{\circ}\) and, regionally, varies between 0.9\(^{\circ}\) and 2.3\(^{\circ}\) along strike, while the plate boundary dips at about 1\(^{\circ}\). At the toe of the wedge, the position of the décollement, long a matter of debate (cf. Ryan et al., 1982; Le Pichon et al., 1982, Kastens et al., 1992), is now thought to lie at the interface between the unit 3 clastics and the overlying unit 4 Messinian evaporites (Reston et al., 1999b). Beneath the upper slope...
Fig. 2. Interpretation of a seismic section (in time) through the Mediterranean Ridge accretionary wedge based on the results of the IMERSE project and in particular profile 5A (Reston et al., 1999a). See text for details of the tectonic interpretation.
a series of NE-dipping thrust slices have been interpreted as slices of the pre-Messinian clastics (unit 3) which have been underplated by duplexing (sensu lato) as the décollement cuts down to deeper levels (probably the top of unit 2) to the NE. These thrust slices are underlain (Reston et al., 1999a) by a little deformed sheet of pre-Messinian sediments of units 2 and 3.

The structures identified in IMERSE profile 5A have been explained (Reston et al., 1999a) by an evolutionary model (Fig. 3) for the WMR starting with the formation of the first basal duplex after the end of the Messinian where the décollement cuts up toward the SW from the top of the Mesozoic carbonates (unit 2) to the top of the Tertiary clastics (unit 3, Fig. 3a). After several basal duplexes were formed during the Pliocene (Fig. 3b), a long sheet of the Tertiary clastics has been underthrust beneath the underplated duplexes (or subcreted in terms of Reston et al., 1999a), which at the present reaches as far as the NE edge of the basal duplexes (Fig. 3c). The disruption of the top of this underthrust package may indicate the early stages of breakup leading to the formation of the next generation of underplated duplexes.

3. Sandbox experimental set-up and experiments with homogeneous input

To perform sandbox experiments to study the growth and evolution of convergent margin accretionary complexes, we use a glass-sided box in which a 240-cm-long PVC plate, on top of which dry quartz sand with an internal friction of $\mu = 0.57$ is sprinkled to simulate the incoming
sediment section, is dragged underneath a deformable buttress made of material comprising a higher cohesion than sand, e.g. a mixture of mortar and sand or rock powder (Kukowski et al., 1994; Gutscher et al., 1996). Depending on the size of the initial buttress, the thickness of input and the style of mass transfer, the apparatus allows for shortening of 100–170 cm. While the untreated plate comprises low basal friction ($\mu_b$ is about 0.30), sticking double-sided adhesive tape to it, which then is carefully completely covered with a thin layer of sand, results in a considerably higher basal friction, which is significantly larger than 0.5 (Gutscher et al., 1996).

Fig. 4. Perspective view of the experimental apparatus. The PVC plate is dragged to simulate convergence. Blow-up shows the incoming section.

Fig. 5. (a) Sandbox experiment with low basal friction after 65 cm of convergence. Input: 3.3 cm, output: 0.5 cm (cf. Gutscher et al., 1998a, Fig. 5c). (b) Sandbox experiment with high basal friction after 90 cm of convergence. Input: 2.5 cm, output 1.0 cm.
Previous model experiments with homogeneous sand as input have demonstrated that low basal friction leads to the development by frontal accretion of a small tapered wedge of regularly spaced imbricate thrust slices. Thrust slice spacing is a linear function of thickness of the incoming section (Gutscher et al., 1998a). The same remains valid if a layer, e.g. consisting of micro glass beads, which is weaker than sand, however, stronger than the basal interface, is incorporated in the incoming section (Fig. 5a). High basal friction, on the other hand, produces a cyclic behaviour (Fig. 5b) alternating between frontal accretion and underthrusting of long, nearly undeformed layers (Gutscher et al., 1996), which finally are underplated beneath the buttress. These experiments clearly show that underthrusting and underplating only occur in the case of high basal friction (Kukowski et al., 1994; Gutscher et al., 1996), which has been verified by means of a force balance analysis (Gutscher et al., 1998b). Thus, in the case of high basal friction, the relative position of the active décollement is transient, whereas in the case of low basal friction it remains always on top of the PVC plate (i.e. at the base of the incoming layer) which is the weakest interface in the experimental set-up.

4. Results of sandbox experimental work including a weak layer in the incoming section

Observations from Nankai and the Mediterranean Ridge as described above suggest that even quite a thin layer of a weak sediment may change mass transfer modes and deformation styles dramatically. These observations led us to incorporate a relatively thin layer (1–2 mm thick) of a granular material weaker than sand in the incoming section. Micro glass beads are a very suitable analogue material as they are a Coulomb material and their density and size are almost the same as those of dry sand, however due to their close to perfect roundness their coefficient of internal friction is about 23% smaller (μ_int = 0.44), with cohesion almost negligible.

For the experiment shown in detail here, we chose a high basal friction in order to make the layer of glass beads the weakest component of the materials used and because we wanted to test if and how underplating occurred when working in a mechanically heterogeneous system. Experiments done later with comparable boundary conditions showed that the observation of decoupling and basal duplex formation as described below could be repeated several times (Kukowski et al., 1997). Adhesive tape was used as the basal interface. Alternating layers of coloured, well-sorted quartz sand to a total thickness of 1.2 cm, a 2–3-mm-thick layer consisting of micro glass beads, and finally a ca. 1.5-cm-thick sand layer were sprinkled on top of the basal plate (Figs. 4 and 6a). The buttress was made of dry, compacted mortar, which has a significantly higher cohesion (S_0 ≈ 150 Pa) than sprinkled sand (S_0 ≈ 20 Pa) to simulate stronger material. Cohesion and size are scaled with a factor of 10^5 (Kukowski et al., 1994; Gutscher et al., 1996). The subduction window was set to a height of 0.7 cm such that part of the section is ‘subducted’. The presence of the subduction window forces a décollement to develop at the height of the window, so that the subducted section is significantly thinner than the incoming section, and crucially (as far as this experiment is concerned) is also thinner than the section beneath the micro beads.

The result of this experimental configuration is that the frontal and basal part of the accretionary complex are decoupled. The thin micro glass-bead layer serves as décollement for the accretionary wedge evolving in front of the buttress. The regional slope measured between the deformation front and the (oldest) thrust slice adjacent to the buttress is a straight line dipping at about 8–9° throughout the experiment, as predicted for a low cohesion Coulomb material. The slope angle at the toe of the youngest thrust slice varies between 7° and 12°. The formation of thrust slices occurs regularly resulting in eight slices after 50 cm of convergence (Fig. 6d) and 17 slices after 100 cm of convergence (Fig. 6f) which gives an average spacing of 5.9 cm, implying a thickness of about 1.75 cm for the frontally accreting section (cf. Fig. 6, Gutscher et al., 1998a). This places the décollement of the frontal accretionary wedge at the base of the layer of glass beads.
The regional slope angle of the frontal wedge is higher than observed in the sandbox experiment with low basal friction, which was 5–6° (Gutscher et al., 1998a). During the frontal accretion phase in high basal friction experiments, on the other hand, slope angles between 10° and 15° have been observed (Gutscher et al., 1998b). When putting a Mylar® sheet ($\mu_b = 0.43$) on top of the PVC plate in a sandbox experiment also using homogeneous sand as incoming section, the development of a frontal accretionary wedge with a taper of about 9° was observed (Kukowski et al., 1994), similar to the frontal taper observed in our experiment. This implies a similar basal friction to that of the Mylar sheet consistent with the development of the décollement at the base of the micro glass beads ($\mu_b = 0.44$).

Beneath the frontal accretionary wedge, the 1.2-cm-thick lowermost sand section is underthrust without being deformed and arrives at the frontal edge of the buttress. There it is shortened resulting in the formation of basal duplexes. After 50 cm of convergence five duplexes have been formed (Fig. 6d) and then are underplated beneath the buttress, which undergoes deformation and tilting, but is only slightly faulted. The formation of the next generation of duplexes then follows. After 70 cm of convergence (Fig. 6e), three second generation duplexes have been formed and after 100 cm of convergence, the second undeformed sheet is underthrust (as indicated by the red marker horizon in the lowermost sand section, Fig. 6f), underplating the second generation of duplexes. Thus a cyclic transfer process similar to that for frontal accretion with the high basal friction deformation mode (Gutscher et al., 1996, 1998b) takes place, except that it occurs not beneath the front of the wedge but in the region of underplating in front of the subduction window.

Glass beads are no longer incorporated in the undeformed sheet when arriving beneath the buttress. Either they remain at the base of the frontal wedge or are incorporated in the imbricate thrusts. This again clearly places the décollement at the base of the glass-bead layer in the frontal wedge (Fig. 7). Beneath the buttress, the subduct--
ing section is the lower portion of the lowermost sand section the top of which acts as a décollement. It more or less matches with the red marker layer (Fig. 7).

Throughout the experiment, the frontal part of the accretionary complex and the hinterland part including the buttress and the underplated portion remain completely decoupled. As soon as convergence is initiated, the décollement is located at two different ‘stratigraphic’ levels (Fig. 7): the base of the micro glass beads and further back near the deeper red sand layer at the height of the subduction window. The transfer of displacement between these two levels migrates during progressive deformation to produce the cycles of basal duplexing and underplating similar to those observed in high basal friction experiments. The boundary between the two styles of deformation roughly coincides with a change in the slope angle; arcward, the slope is significantly steeper and curved due to underplating underneath the buttress. The upper slope angle steepens quite abruptly to about 23° and remains stable throughout the whole experiment.

5. Discussion and implications for the WMR

Sandbox experiments with input consisting of layers with variable mechanical properties show that a distinct difference in internal friction of a material is alone sufficient to serve as a detachment level if sufficiently thick (which is 1–2 mm in a sandbox experiment). Formation of basal duplexes beneath the buttress is only observed if the detachment in the frontal part of the subduction complex is at a higher level than in the hinterlandward part and if basal friction is high. Experiments similar to the one described above, but with low basal friction did not produce the same pattern of structures. Instead these were dominated by frontal accretion of imbricate thrust slices, leading to wedges with slopes of 6 ± 0.5° together with basal erosion and development of an out-of-sequence thrust in case of the subduction window opened (Fig. 5a). Thus, a mid-level décollement may only be active if it is weaker than the basal detachment.

In both the interpretation of the IMERSE reflection seismic data and the sandbox experiment, the décollement is situated at a shallower stratigraphic level at the base of the actual accretionary wedge than hinterlandward of the zone of underplating (Fig. 8). Beneath the post-Messinian wedge, unit 3 seems to be completely incorporated in the basal duplexes and then underplated, as it is no longer observed beneath the pre-Messinian wedge (Fig. 2). The analogue for unit 3 in the experiment is the sand layer between the lowermost red marker layer and the base of the glass-bead layer (Fig. 7). The height of the subduction window in the experiment corresponds to the thickness of unit 2. The continuation and unchanged thickness of unit 2 down to beneath the Messinian forearc basin (Reston et al., 2002a) corresponds to the section which leaves the experimental apparatus (Fig. 8) and therefore justifies the application of a restrictive subduction window: the subduction window is thus necessary to simulate the subduction of these carbonates and the consequent landward deepening of the basal detachment.

Experimental work clearly shows that also for the case with heterogeneous input the possibility of underplating is restricted to the high basal friction part of the accretionary complex. However, the style of mass transfer (i.e. underplating sheets versus underplating basally formed duplexes) varies, resulting in a different quantity of material accreted, underplated or subducted. The ratio of input to output was 4.3 in the experiment described in 4. In sandbox experimental work including a weak layer in the incoming section, 60% of the incoming material was accreted frontally, 17% underplated, and the remaining 23% subducted. This differs significantly from what would be expected in a homogeneous experiment with the same I/O ratio in both the high or low basal friction case (Gutscher et al., 1998a,b). The mechanism of decoupling allows for a wider ratio of frontally accreted to basally underplated material; material transfer ratios are directly related to the thickness of the layers beneath and above the weak layer.

The present-day structure of the WMR is best represented by the stage of the experiment after
70 cm of convergence (Figs. 6e and 8b) where the duplexes created by shortening beneath the buttress have been underplated due to underthrusting of the next undeformed sheet. Only a minor portion of the pre-Messinian sediments, i.e. unit 2, is subducting beneath the pre-Messinian wedge (Fig. 2). This portion would refer to the material which is allowed to leave the experimental apparatus through the ‘subduction window’.

When comparing the geometry of a submarine wedge and its subaerial laboratory analogue, the absence of fluid pressure which can dramatically change the mechanics needs to be considered (Davis et al., 1983; Dahlen, 1990). A taper of 8–18° in a laboratory subaerial wedge would refer to a submarine wedge with a taper of 3–8°. In the experiment we relate to the mechanics of the WMR, the dip of the downgoing plate was 2° and the
slope of the frontal wedge adjusted at about 8°–9°. This would be at the upper end of what would be a realistic subaerial analogue for the WMR; more realistic would be 2° or 3° less. To achieve a taper as small as this, the weak layer should have an internal friction equal or even lower than the lowest (polished PVC plate, with a basal friction coefficient of about 0.3) that can be modelled with the experiment set-up described. Further on, the role of the buttress in the experiment is different from that in nature (Fig. 8), however, this does not impair the validity of the mechanical processes observed.

The proposed mechanics of the WMR accretionary complex as following from the analogue experiment imply a change in basal friction across the ridge. The interface between unit 2 and unit 3 need to be of high friction which is realistic, unit 3 are believed to be clastics and unit 2 carbonates. The low regional taper of the WMR can best be explained (Reston et al., 2002b) by fluid pressures within a few percent of lithostatic (Dahlen, 1984) at the top of unit 3, that is beneath the impermeable Messinian evaporites dominating the frontal portion of the wedge. The arcward deepening of the décollement from the top to the base of unit 3 may be related to the absence of a thick sequence of evaporites further back in the WMR (the site of the pre-Messinian wedge). The lack of impermeable evaporites within the pre-Messinian wedge probably prevents high fluid pressures building up at the top of the clastics: instead, it may provide a pathway for the escape of fluids expelled during the compaction of unit 3 clastics (Westbrook and O’Neill, pers. commun.). Beneath the pre-Messinian wedge we suggest that the décollement occurs at inherently impermeable Aptian shales as proposed by Ryan et al. (1982) where high pore fluids may be maintained in the absence of evaporites. This does not however explain the cyclicity of basal duplexing and underplating observed beneath the WMR, which may indicate a transient hydraulic regime. However, this mechanism cannot be modelled in sandbox experiments but should be treated with coupled poroelastic numerical modelling.

6. Conclusions

In the sandbox experiment described above with heterogeneous input for the first time a complete decoupling of the mechanics of the frontal wedge and those of hinterland portion of the subduction complex including the buttress was observed. Decoupling is a function of high basal friction coinciding with the presence of a weak layer. The development of basal duplexes and underplating is controlled by the position of the weak layer relative to the subduction window (the deeper décollement). The weak horizon is completely incorporated into the imbricate thrusts. This clearly places the décollement at the base of the glass-bead layer in the frontal accretionary wedge which hinders the weak material from being subducted.

With this experimental configuration it was basically possible to simulate the evolution of the Mediterranean Ridge from the end of the Messinian up to the Present in accordance with a geodynamic model based on reflection seismic data. Key observations are the presence of two décollements at first and then the shift in the position of the décollement in a later stage (Fig. 8).

The results of the experiments discussed here and their applicability to a complex convergent margin reveals the great importance of material heterogeneity for the mechanics accretionary systems. Thin weak layers control the style of deformation, the level of the décollement and the mode of mass transfer. They serve as detachment level if their internal friction is lower than the basal friction. The presence of a thin weak layer provides a mechanism for the growth of an accretionary wedge complex by simultaneous efficient frontal accretion and basal underplating.

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