Trabajos de Geología, Universidad de Oviedo, 30 : 331-336 (2010)

Analogue modelling of deepwater fold and thrust belts: dynamic interactions with syntectonic sedimentation

J. E. WU[1*], K. R. MCCLAY[1], F. DESPINOIS[1], M. WOOLLARD[1], R. EVANS[2], L. ISA[2] AND S. JANAI[2]

[1]*Fault Dynamics Research Group, Royal Holloway University of London, Egham, Surrey, UK.*

[2]*M. Sc. Tectonics, Royal Holloway University of London, Egham, Surrey, UK.*

[*]*e-mail: jonnyw@es.rhul.ac.uk*

Abstract: Fold and thrust belts developed in deepwater environments have generally been subjected to greater net sedimentation and different sedimentation patterns compared to subaerial or shallow marine environments. In this study, the effects of syn-kinematic sedimentation on fold and thrust belt evolution have been evaluated by varying the rates and patterns of syn-contractional sedimentation in 2D analogue models of simple thrust wedges. All models produced critically-tapered Coulomb wedges with topographic slopes of 7-10º. Increased rates of syn-kinematic sedimentation caused greater thrust spacings, increased the total wedge height and wedge length, and generally decreased the number of major thrust structures. Progradational sedimentation caused conspicuous out-of-sequence movement in thrusts at the rear of the model thrust wedge and frontal thrusts became buried and inactive. Aggradational sedimentation caused the rapid and sequential burial of thrusts, rendering them inactive and forcing the deformation to the front of the wedge. The geometries of the front of the Nankai accretionary complex, offshore Japan, and the offshore Niger Delta, Gulf of Guinea, compare well with models in this study and demonstrate that the addition of sedimentation during shortening of fold and thrust belts may dramatically affect the style of deformation as well as the timings and amounts of fault displacements in such systems.

Keywords: analogue modelling, fold and thrust belts, sedimentation, Niger Delta, Nankai.

The observation that many thin-skinned (e.g. no involvement of crystalline basement) fold and thrust belts have a tapered wedge geometry (Chapple, 1978) led to the development of the critically-tapered Coulomb wedge model (Davis *et al.*, 1983; Dahlen, 1990). In this model, a horizontal compressive force applied to a Coulomb material causes it to deform internally until the combined slopes of the basal detachment and the upper surface reach a 'critical taper' angle. With additional shortening, the critical taper is maintained through the synchronous accretion of new material in the foreland to the front of the wedge and internal deformation within the wedge. This model has been used to successfully explain the geometries of many natural fold and thrust belts including Taiwan, the Nankai Trough, and the offshore Niger Delta (Davis *et al.*, 1983; Bilotti and Shaw, 2005).

Surface processes involving erosion and sedimentation have been shown to exert significant control on the evolution of fold and thrust belts by steepening (e.g. supercritical) or lowering (e.g. subcritical) the topographic slope of a wedge relative to the critical taper (e.g. Beaumont *et al.*, 1992). Analogue models of fold and thrust belts (e.g. Beaumont *et al.*, 1992; Storti and McClay, 1995; Nieuwland *et al.*, 2000; Bonnet *et al.*, 2007) have demonstrated that surface processes caused dramatic effects including out-of-sequence thrusting, reductions in the number of thrust structures, increases in thrust ramp angles, and changing the interplay between basal accretion and frontal imbrication.

In deepwater fold and thrust belts such as the Nankai accretionary complex, offshore Japan (Fig. 1a) and the offshore Niger Delta, Gulf of Guinea (Fig. 1b), an understanding of the effects of surface processes is particularly important for predicting their evolution and the thrust fault geometries and activites. Deepwater erosion rates appear to be at least an order of magnitude lower compared to subaerial environments (Mitchell *et al.*, 2003). Depositional patterns in deepwater systems can vary between 'progradational' sedimentation, where turbidity current and debris flow processes bypass the upper slope and deposit material in the lower slope and basin floor, and 'aggradational' sedimentation, where hemipelagic processes deposit material evenly across the deepwater margin (e.g. Stow and Mayall, 2000; Weimer and Slatt, 2007).

In this study, the effect of syn-kinematic sedimentation on fold and thrust belt evolution were evaluated by varying the rates and patterns of syn-contractional sedimentation in 2D analogue models of simple contractional wedges. Results of the models were compared to cross-sections through natural deepwater fold and thrust belts.

Methods

A series of four experiments were run in a glass-sided deformation box that was 30 cm wide, 100 cm long and 20 cm deep. The base of the apparatus was horizontal and covered with a low-friction textile that formed the basal detachment surface. To create a simple critically-tapered Coulomb wedge, a rigid, moving horizontal backwall shortened the sandpack at an average rate of 30 cm h^{-1}. In each experiment, the pre-kinematic sandpack consisted of a 2.25 cm-thick horizontal layered sequence of coloured sand over a 0.25 cm-thick basal detachment layer of glass beads. During the experiments, syn-kinematic sedimentation was added every 1 cm of shortening after the initial 10 cm of contraction. The syn-kinematic sedimentation rate was varied by adding increased sand thicknesses from 0.5-1 mm for the 'low' sedimentation rate to 1-2 mm for the 'high' sedimentation rate after each 1 cm shortening increment. The

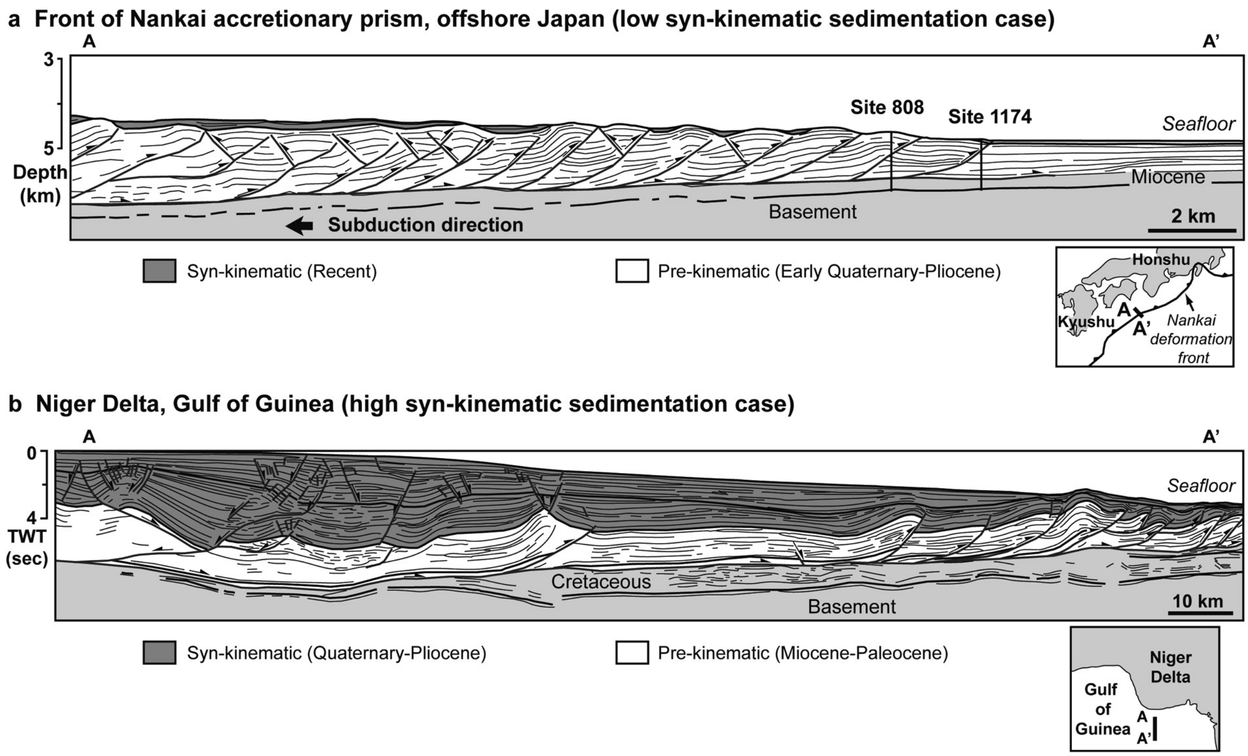

Figure 1. (a) Re-interpretation of frontal zone of the Nankai accretionary complex, offshore Japan, from a prestack depth-migrated seismic line in Hills *et al.* (2001), (b) interpretation of a regional time seismic section from the eastern lobe of the Niger Delta, Gulf of Guinea (after Ajakaiye and Bally, 2002).

pattern of syn-kinematic sedimentation was also varied from 'progradational' deposition, where sediment was only added on to the frontal slope of the wedge, to 'aggradational' deposition, where sediment was added evenly over the entire wedge. The progressive evolution of the models was monitored using high resolution digital photography through the glass sidewalls of the apparatus. At the end of the experiment, the thrust wedge models were preserved and serially sectioned.

Analysis and results

The contraction of all four models produced critically-tapered Coulomb wedges with topographic slopes of 7° to 10° above the horizontal basal detachments (Fig. 2). The Coulomb wedges were typically formed by 4 to 6 forward-vergent, imbricate thrust systems with minor back-thrusts associated with each major forward-vergent thrust. Fault-propagation folds were formed at the tips of each major thrust fault (Fig. 2). In each experiment, the maximum wedge height at the rear of the model tended to stabilize between 7 and 9 cm (Fig. 3a), whereas the wedge lengths tended to increase in a semi-linear fashion, producing a 'saw-tooth' pattern in the graph of wedge length against shortening (Fig. 3b).

Model 1 – No syn-kinematic sedimentation

In this model a typical imbricate fan of six forward-vergent thrusts formed in a forward nucleating sequence (T1 to T6) and produced a critically tapered wedge with a topographic slope of 10° at the front of the wedge (Fig. 2a). Several small-displacement back-thrusts were formed at the leading edges of each major thrust T1 to T6 with the formation of an asymmetric anticline at the thrust tip near the upper surface of the model. Synchronous thrust activity was observed during the shortening of this model with active deformation focused towards the front of the model during its evolution.

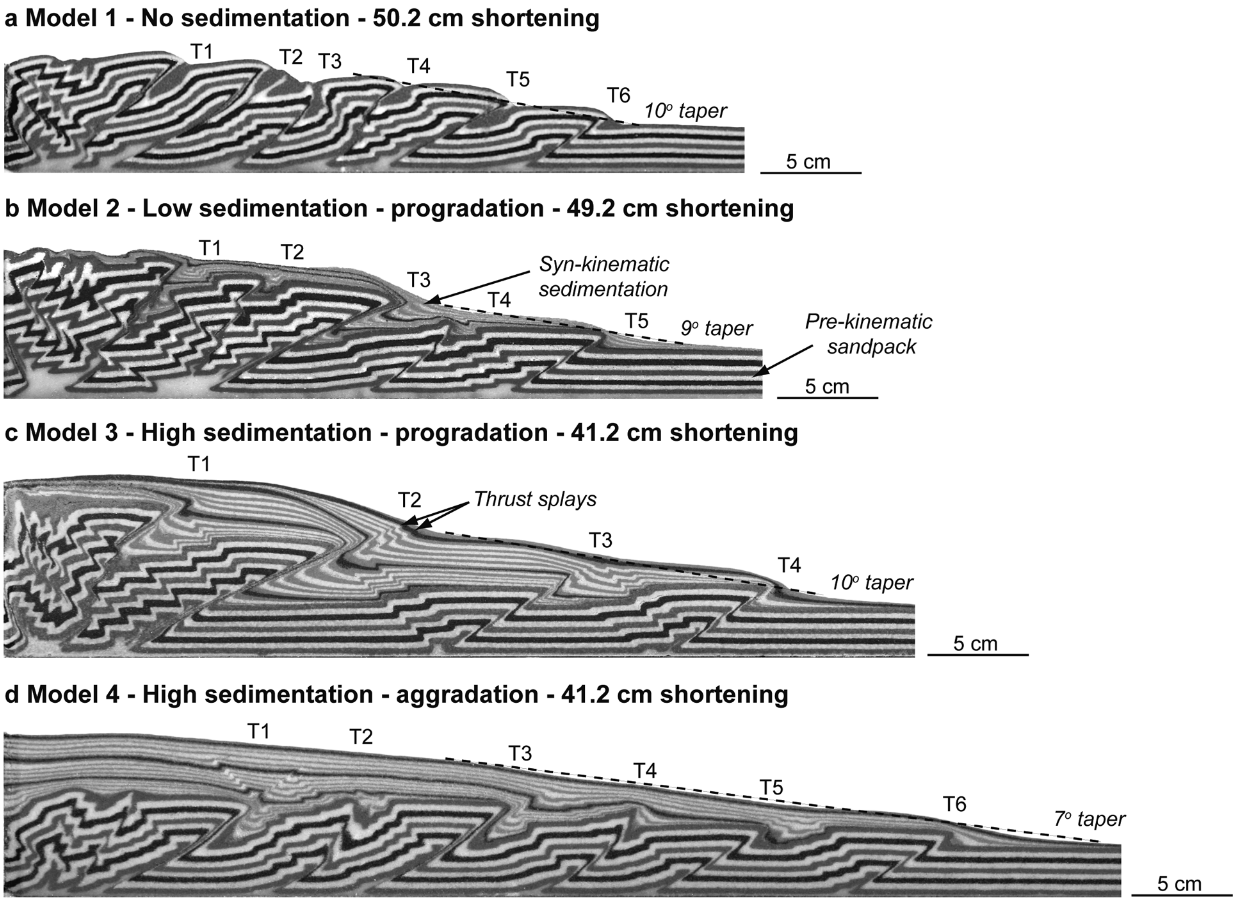

Figure 2. (a-d) Comparison of internal vertical sections taken at the centre of each model at the end of experiment. Major forethrusts (T1, T2, etc.) numbered in the sequence of nucleation.

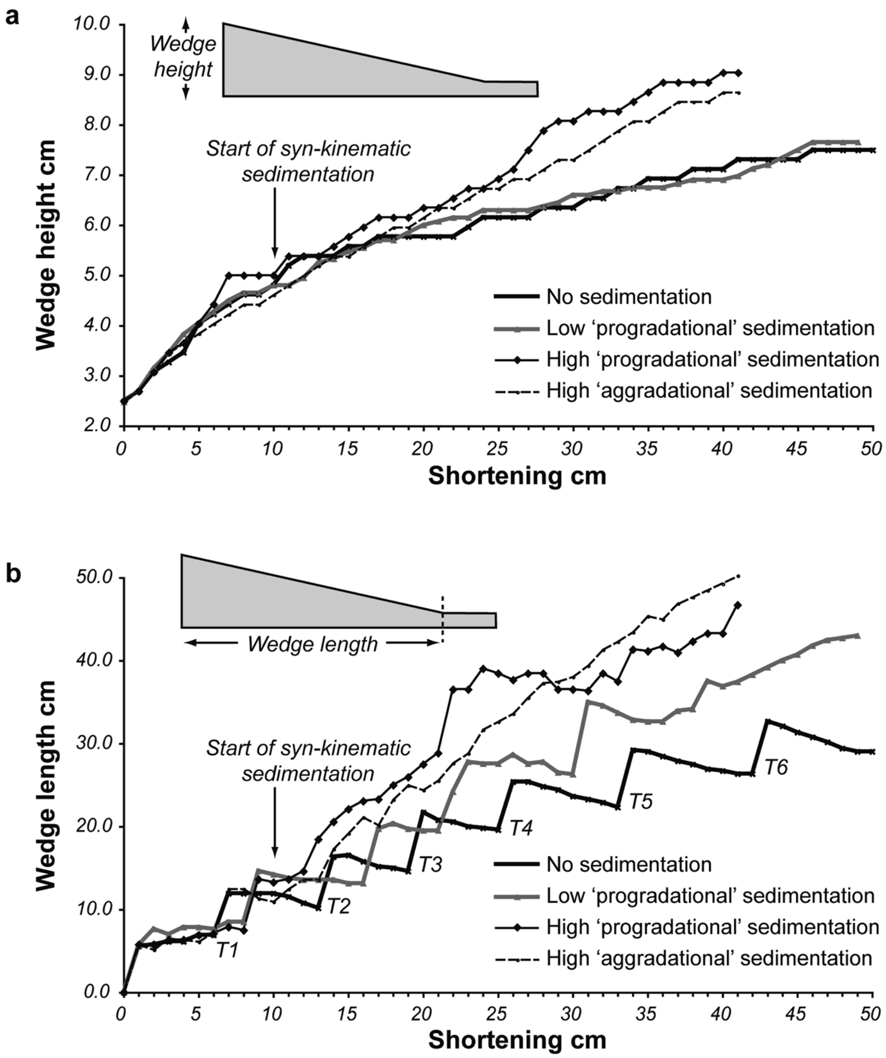

Figure 3. Comparison of (a) wedge height against shortening, and (b) wedge length against shortening. Major forethrusts (T1, T2, etc.) of 'no sedimentation' model are numbered in the sequence of nucleation.

Model 2 – Low syn-kinematic progradational sedimentation

In this model progradational syn-kinematic sedimentation was added to the frontal part of the critically tapered Coulomb wedge at a rate of 0.5 mm per 1 cm of shortening for every increment after an initial contraction of 10 cm. Five forward-vergent major thrusts (T1 to T5) were formed in a general forward-nucleating sequence, resulting in a final critical wedge taper of 9-10° at the front of the wedge (Fig. 2b). In this model, there was one less major thrust than in Model 1 and the major thrusts propagated through the syn-kinematic layers. Thrusts T1 and T3 also exhibited some out-of-sequence movement, producing an over-steepened slope particularly above the trace of fault T3. As in Model 1 backthrusts were associated with each major thrust and formed tip line folds (Fig. 2b).

Model 3 – High syn-kinematic progradational sedimentation

In this model the progradational syn-kinematic sedimentation was added to the frontal part of the critically tapered Coulomb wedge at a rate of 1-2 mm per 1 cm of shortening for every increment after an initial contraction of 10 cm. After 41.2 cm of shortening four major forward-vergent thrusts (T1 to T4) were formed in a forward-nucleating sequence and formed a critically-tapered Coulomb wedge with a surface slope of 10° at the front of the wedge (Fig. 2c). Numerous high-displacement backthrusts formed associated with thrusts T1 and T2 whereas only two small-displacement back-thrusts were associated with the two frontal thrusts T3 and T4 (Fig. 2c). Thrust T2 displaced conspicuous out-of-sequence movement. Tip-line thrust splays formed at the tip of thrust T2. The two frontal thrusts T3 and T4 effectively became buried by the high volume of syn-tectonic sedimentation late in the shortening of this model.

Model 4 – High syn-kinematic aggradational sedimentation

In this model the aggradational syn-kinematic sedimentation was added to the whole of the critically tapered Coulomb wedge at a rate of 1-2 mm per 1 cm of shortening for every increment after an initial contraction of 10 cm. This increased the wedge height at the back of the model, effectively pushing the deformation front further into the foreland. After 41.2 cm of shortening this resulted in six, more widely-spaced, forward-vergent thrusts (T1 to T6) that formed a critically-tapered Coulomb wedge with a surface slope of 7° at the front of the wedge (Fig. 2d). However, each of the individual forward-vergent thrusts had significantly less displacement compared to the equivalent thrusts in Models 1 and 3 (cf. Figs. 2a, 2c and 2d). Fewer small-displacement backthrusts were formed in association with the main thrusts (Fig. 2d). In this model, the thrusts were rapidly and sequentially buried by the high rate of syn-tectonic sedimentation such that they were 'shut down', forcing the deformation to the front of the wedge. In this model, the growth stratal patterns formed by the syn-kinematic units clearly demonstrate the forward breaking sequence of thrust nucleation and relative timing of thrust activities (Fig. 2d).

Discussion

The results of this series of simple thrust wedge experiments clearly demonstrate the dynamic interaction between syn-contraction sedimentation and the geometries and activities of thrust fault systems in critically-tapered Coulomb wedges. All of the model wedges were formed by imbricate fans of forward-vergent thrusts (Fig. 2). The number of thrust faults progressively decreased with increased progradational syn-kinematic sedimentation as described in the experiments of Storti and McClay (1995). However, with strong aggradational syn-contractional sedimentation there was less displacement on each individual major thrust in the wedge system and thrust activity was rapidly halted as the wedge was buried with syn-kinematic sediments.

The critical taper model is useful for explaining these interactions as thrust wedges without syn-contractional sedimentation (e.g. Fig. 2a) can only attain the critical taper angle through thrust imbrication. In contrast, thrust wedges with sedimentation (e.g. Fig. 2b, 2c and 2d) can attain the critical wedge taper through a combination of thrust imbrication and passive sedimentary infill, thereby requiring less imbrication to achieve the same taper angle.

Thrust wedge heights and wedge lengths were also strongly affected by different patterns of syn-kinematic sedimentation (Fig. 3). High rates of syn-kinematic sedimentation effectively increased the wedge size and forced deformation to step outwards to the front of the wedge as well as switching off thrusts as they became buried. Thrust activities associated with no sedimentation or low rates of syn-kinematic sedimentation displayed a strong 'sawtooth' pattern in the graphs of wedge length vs. contraction (Fig. 3b). During periods where deformation was focused primarily on a group of thrusts the wedge length decreased (negative slopes in the graphs in figure 3b) whereas the nucleation of a new thrust rapidly increased the wedge length as deformation stepped forward into the foreland. In contrast, for experiments where the rates of syn-kinematic sedimentation were high, this cyclic 'sawtooth' behaviour was suppressed – particularly for the aggradational Model 4 (Fig. 3b).

In order to compare the geometries and internal structures of naturally occurring thrust wedges in deepwater settings two examples were selected (Fig. 1). In the Nankai accretionary prism example, the cross-section across the foremost section of the prism, where the rates of syn-kinematic sedimentation appear to be low (Fig. 1a; Hills *et al.*, 2001), shows a well-ordered array of forward-vergent thrust faults with minor backthrusts – similar in structural styles to Models 1 and 2 (Figs. 2a and 2b).

Figure 1b shows a regional cross-section from part of the deepwater fold belt offshore Niger delta. Here the rates of syn-kinematic sedimentation appear to be very high so that the fold belt is completely buried. In this cross-section, the imbricate thrusts that form the Coulomb wedge are widely-spaced, have small displacements, and are completely buried i.e. 'shut off' by the syn-kinematic sedimentation in a very similar manner to that found in Models 3 and 4 (Figs. 2c and 2d). Backthrusts, which developed in the model thrust wedges but are not seen in this section, are prevalent in cross-sections from other areas of the Niger Delta (e.g. Bilotti and Shaw, 2005).

The natural examples show similarities to the geometries of the experimental wedges described in this paper and demonstrate that the addition of syn-kinematic sedimentation during shortening of fold and thrust belts may dramatically affect the style of deformation as well as the timings and amounts of fault displacements in such systems. Further detailed comparative experiments are warranted to investigate these effects in more detail. Other experiments are planned that also incorporate syn-tectonic erosion.

Conclusions

The simple thrust wedge experiments clearly demonstrated a dynamic interaction between syn-contraction sedimentation and the geometries and activities of thrust fault systems in critically-tapered Coulomb wedges. All of the models produced critically-tapered Coulomb wedges with topographic slopes of 7-10º that were formed by imbricate fans of forward-vergent thrusts with associated, low displacement backthrusts. High rates of sedimentation generally caused a progressive decrease in the number of major thrust faults, a greater spacing between thrusts, and increased the wedge height and width of the thrust models. Progradational sedimentation caused conspicuous out-of-sequence movement in thrusts at the rear of the model thrust wedge whereas frontal thrusts became buried and inactive. Aggradational sedimentation effectively increased the wedge height at the rear of the wedge, forcing deformation to the wedge front, and causing the rapid and sequential burial of thrusts, rendering them inactive. The geometries of the front of the Nankai accretionary complex, offshore Japan, and the offshore Niger Delta, Gulf of Guinea, compare well with models in this study and demonstrate that the addition of sedimentation during shortening of fold and thrust belts may dramatically affect the style of deformation as well as the timings and amounts of fault displacements in such systems.

References

AJAKAIYE, D. E. and BALLY, A. W. (2002): Some structural styles on reflection profiles from offshore Niger Delta. In: *Course Manual and Atlas of Structural Styles from the Niger Delta. AAPG Continuing Education Course Note*, 41, 107 pp.

BEAUMONT, C., FULLSACK, P. and HAMILTON, J. (1992): Erosional control of compresional orogens. In: K. R. MCCLAY (ed): *Thrust Tectonics*, Chapman & Hall: 1-18.

BILOTTI, F. and SHAW, J. H. (2005): Deep-water Niger Delta fold and thrust belt modeled as a critical-taper wedge: The influence of elevated basal fluid pressure on structural styles. *AAPG Bull.*, 89, 11: 1475-1491.

BONNET, C., MALAVIELLE, J. and MOSAR, J. (2007): Interactions between tectonics, erosion and sedimentation during the recent evolution of the Alpine orogen: Analogue modelling insights. *Tectonics*, 26, TC6016.

CHAPPLE, W. M. (1978): Mechanics of thin-skinned fold-and-thrust belts. *Geol. Soc. Am. Bull.*, 89: 1189-1198.

DAHLEN, F. A. (1990): Critical taper model of fold-and-thrust belts and accretionary wedges. *Annu. Rev. Earth Pl. Sc.*, 18: 55-99.

DAVIS, D., SUPPE, J. and DAHLEN, F. A. (1983): Mechanics of fold-and-thrust belts and accretionary wedges. *J. Geophys. Res.*, 89: 1153-1172.

HILLS, D. J., MOORE, G. F., BANGS, N. L., GULICK, S. S. and LEG 196 SHIPBOARD SCIENTIFIC PARTY (2001): Preliminary results from integration of 2D PSDM and ODP Leg 196 LWD velocity data in the Nankai accretionary prism. *Eos Trans., Am. Geophys. Union*, 82: F1221.

MITCHELL, N. C., DADE, W. B. and MASSON, D. G. (2003): Erosion of the submarine flanks of the Canary Islands. *J. Geophys. Res.*, 108: 3.1-3.11.

NIEUWLAND, D. A., LEUTSCHER, J. H. and GAST, J. (2000): Wedge equilibrium in fold-and-thrust belts: prediction of out-of-sequence thrusting based on sandbox experiments and natural examples. *Geol. Mijnbouw*, 79: 81-91.

STORTI, F. and MCCLAY, K. R. (1995): Influence of syntectonic sedimentation on thrust wedges in analogue models. *Geology*, 23, 11: 999-1002.

STOW, D. A. V. and MAYALL, M. (2000): Deep-water sedimentary systems: New models for the 21st century. *Mar. Petrol. Geol.*, 17, 2: 125-135.

WEIMER, P. and SLATT, R. M. (2007): *Petroleum geology of deepwater settings. AAPG Stud. Geol.*, 57, 816 pp.