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Experimental designs to model along-strike fault interaction

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Abstract: We review the different designs and results of various previous models simulating the along-strike interaction between laterally offset faults, focusing on the formation of pull-apart basins in between strike-slip faults or relay zones located between laterally offset normal faults.

The design of most models traditionally includes the use of a basal sheet, whose edge acts as a velocity discontinuity onto which faults nucleate (Faugère and Brun, 1984; McClay and Ellis, 1987; Vendeville, 1991). One drawback of such design is that the location and orientation of faults in the relay zone are conditioned by the shape of the edge of the basal sheet. An improved version of this design by Sims et al. (1999) using a strong viscous basal layer also forces faults to follow the basal velocity discontinuity. Using a third design by Le Calvez and Vendeville (1996), faults can freely propagate above a thin, weak viscous layer but fault blocks cannot subside or rotate in response to deformation. We introduce a new design in which although fault location is controlled by small instabilities at the brittle-ductile interface, faults can freely propagate along strike after they have nucleated. This design also allows fault blocks to subside, rise, or rotate in response to deformation. The main advantage of such design is that it forces the faults to form at a predetermined location. The ridges are high enough (about one 20th of the brittle-layer thickness) to act as instabilities that trigger the nucleation of the main two faults, which thereby form with an initial lateral offset. But the ridges are low enough so that, once faults have formed in the brittle layer the fault planes act as dominant instabilities and freely propagate along strike. Because this design provides much more freedom for fault interaction within the relay zone and for fault-block rotation, results significantly differ from those of previous models.

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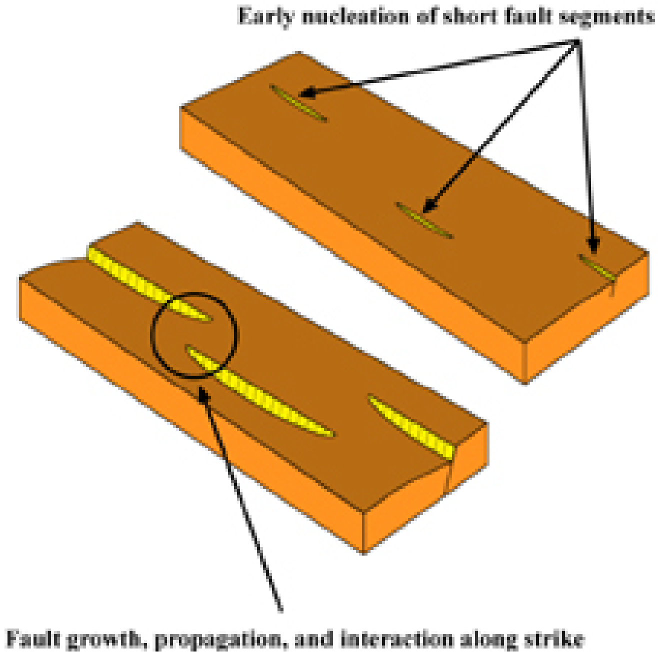
Introduction

Field outcrop studies and detailed interpretation of 3-D seismic data indicate that faults in nature and at various scales (e.g., at the scale of the upper continental crust or that of the sedimentary cover) typically have sinuous traces and that long faults are composite zones made of coalesced, shorter fault segments. During the early stages of extension of a brittle layer, short fault segments form (Fig. 1). Their location and distribution are either random or may be clustered by the presence of preexisting zones of weakness. With continued extension, each short fault segment propagates along strike (Fig. 1). Analytical and numerical simulations of crack growth and propagation (Pollard and Aydin, 1984; Olson and Pollard, 1991; Pollard, 2000) have shown that the tips of a propagating crack or fault change the local stress regime. Studies have also shown that when the tips of two cracks or faults propagate close to one another, the cracks or faults start to influence each other's growth (Willemse, 1997). Thus, normal faults do not propagate along strike forever but tend to terminate along strike by linking with other faults, thereby forming relay zones connecting the two faults (e.g., Gibbs, 1984; Pollard and Aydin, 1984; Larsen, 1988; Morley et al., 1990; Peacock and Sanderson, 1991; Zhang et al., 1991; Trudgill and Cartwright, 1994; Dawers and Anders, 1995; Hooper and More, 1995; Davies et al., 1997; Koledoye et al., 2000). Likewise, in areas subjected to a strike-slip regime, strike-slip faults are rarely made of a single, straight and continuous plane. The main fault is commonly made of segments that are laterally offset. Depending on the fault's sense of slip and on the type of offset, linkage between such fault segments can lead to the formation of local transtensional (e.g., pull-apart basins), or transpressional (e.g., restraining bends) zones.

Figure 1. Nucleation of randomly distributed faults



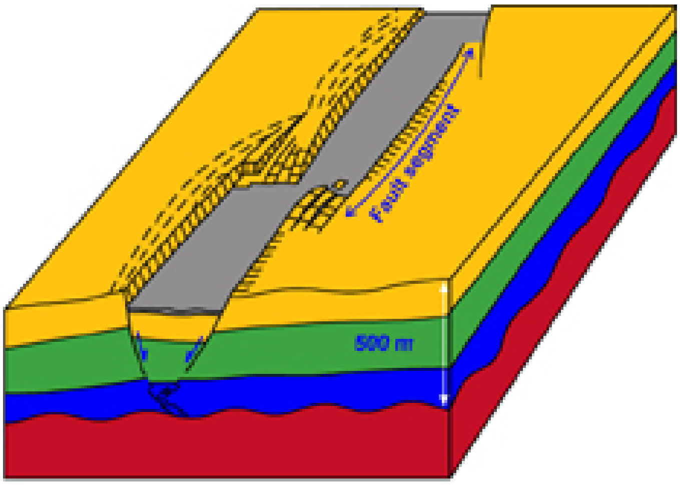
Cartoon illustrating the nucleation of randomly distributed faults followed by their propagation along strike.

Whether regional tectonics involves strike-slip or extension, along-strike propagation of laterally offset faults leads to the formation of short transition zones or relay zones, in which the strains and displacements associated with one fault are transmitted to another fault. Because the stress regime in such relay zones can greatly vary in space, the trends and dips of fault planes and of strata in relay zones, pull-apart basins, and restraining bends can greatly vary within short distances. Field mapping of outcrop data usually does not provide much information about the third dimension (depth). Although 3-D seismic data may cover the three dimensions, their clarity is damaged by the fact that pull-apart basins and relay zones often comprise steeply-dipping reflectors (fault planes and stratigraphic horizons) that lower seismic resolution. Furthermore, neither outcrop nor 3-D seismic analysis can directly provide reliable information about the evolution of such structures through time, which is the reason why a significant number of researchers have turned to forward modeling to analyze and predict the evolution of relay zones and pull-apart basins through time. Because 3-D numerical modeling is still technically challenging, most researchers have relied on experimental (physical) modeling. Such physical experiments have focused on strike-slip (e.g., Faugère and Brun, 1984; Sims et al., 1999) or on extensional (Vendeville, 1991; Le Calvez and Vendeville, 1996) regimes.

Characteristics of the Natural Prototype

In this article, we restrict our focus on faults (i) affecting a brittle layer overlying a proportionally weaker ductile layer (e.g., continental upper/lower crust, or brittle sedimentary cover overlying a viscous décollement; e.g., Fig. 2) and (ii) forming in response to regional extensional or strike-slip tectonic regimes. The following discussion does not apply to second-order faults that form within larger fault blocks in response to bending, folding, or distortion of larger fault blocks (e.g., in the hanging wall of normal faults; Dawers and Anders, 1995).

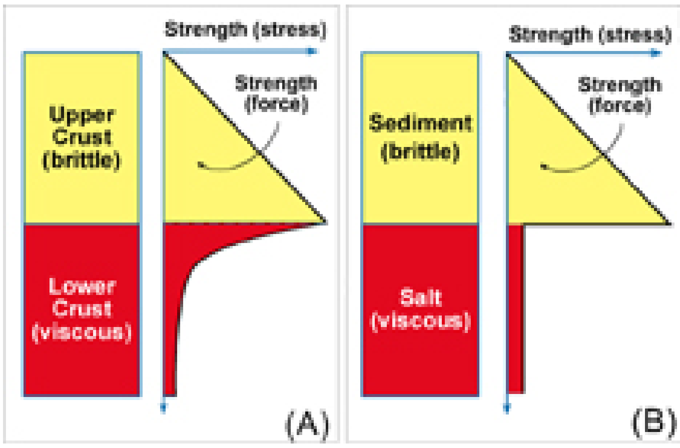
Figure 2. Graben relay in a brittle sedimentary cover



Example of graben relay in a brittle sedimentary cover detached above viscous evaporites (Trudgill and Cartwright, 1994).

Properly modeling a geologic system requires incorporating into the experimental model the main mechanical elements and boundary conditions characteristics of the natural prototype after appropriate scaling. Our prototype comprises a brittle layer resting on a weaker, viscous layer (Fig. 3) that may be denser (e.g., the lower continental crust) or less dense (e.g., an evaporitic layer). The weak, viscous layer may be thick, representing the lower crust or a thick evaporitic layer, or it may be thin, representing a detachment horizon located beneath a sedimentary cover. If the viscous layer is thick, fault blocks in the brittle layer should be free to subside or rise isostatically in response to tectonic thinning or thickening, or to syntectonic sediment deposition. Fault blocks can also freely rotate around both horizontal and vertical axes. By contrast, if the viscous layer is thin, block rotation around a vertical axis only can occur.

Figure 3. Simplified strength profiles



Simplified strength profiles for (A) the lower/upper continental crust, and (B) a brittle sedimentary cover above viscous evaporites.

Ideally, the best way to model the interaction between faults as they propagate along strike is to construct large brittle-viscous models, in which faults nucleate at randomly distributed locations, then propagate along strike. In practice, this approach is however technically difficult. On one hand, having a model in which many faults can nucleate randomly requires that the model width and length be large compared with the thickness of the brittle layer. On the other hand, the brittle layer needs to be thick enough so that the resolution in cross sections is high enough to provide detailed information on the 3-D geometry of the relay zone. In other words, appropriate modeling of along-strike fault interaction would require very large models, well beyond the size that is usually available in most modeling laboratories.

A more practical approach chosen by modelers has been to design experimental set-ups that (1) force faults to nucleate at predetermined locations while (2) allowing faults to propagate along strike and interact in relay zones. The risk associated with such designs is that the set-ups used to force the main two faults may also drastically influence the geometry and location of faults in the relay zones. In other words, the geometry of the relay zone is too much constrained by the imposed boundary conditions, rather than is the result of free interaction between the two offset faults as they propagate along strike. The experimental designs chosen by most authors (Faugère and Brun, 1984; Vendeville, 1991; Sims et al., 1999; and Le Calvez and Vendeville, 1996) involve the use of a basal plate that forces faults to form along its edges, which act as velocity discontinuities triggering the formation of faults in the overlying brittle layer. In some experiments, the brittle layer rests directly on the basal plate. In others, a viscous layer is intercalated between the basal plate and the brittle layer.

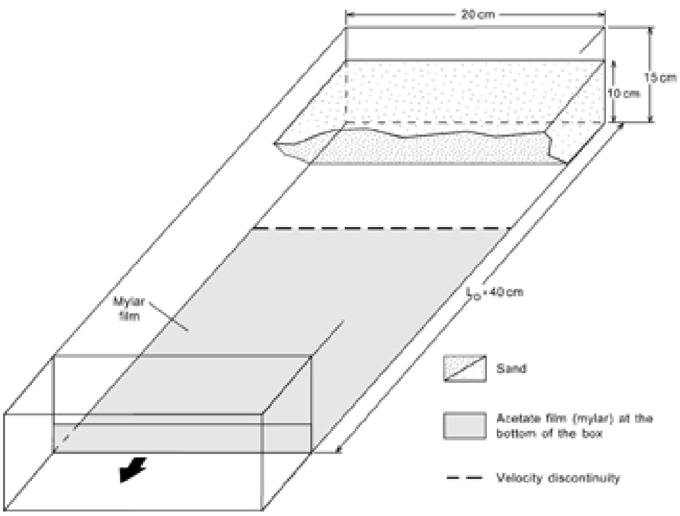
In the following section, we review the models' designs and results for each type of set-up, as well as discuss their appropriateness (1) in terms of mechanical properties and boundary conditions and (2) in reference with the natural prototype. We then introduce a radically new design (Le Calvez and Vendeville, 1999), in which faults are not triggered by a basal plate and can freely propagate along strike.

Brittle Models (basal plate + brittle cover)

Model set-up

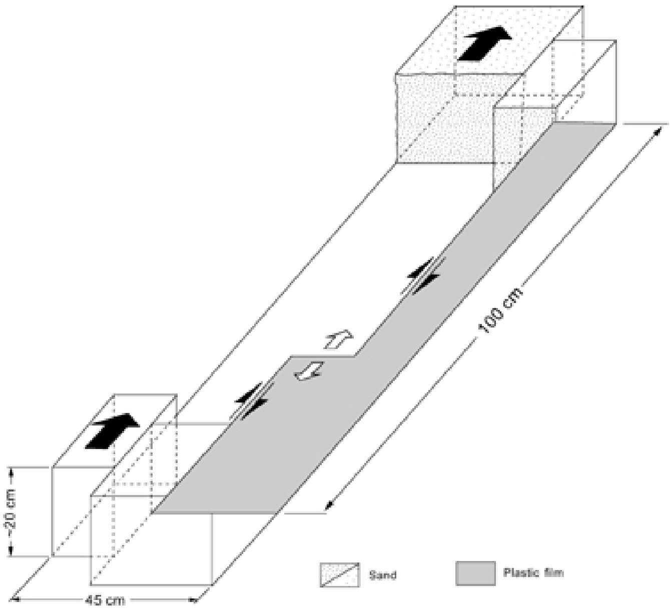
This type of set-up has been used to model 2-D extensional systems (McClay and Ellis, 1987; Faugère and Brun, 1984: Fig. 4), relay zones between offset normal faults (Vendeville, 1991: Figs. 7 and 8) and pull-apart basins located between offset strike-slip zones (Faugère and Brun, 1984: Figs. 5 and 6). In all experiments, a thin sheet of non-stretchable acetate plastic was placed on the model's rigid base. One end of the plastic sheet was attached to a moving wall. The models were built entirely of layered dry sand, having low cohesion and an angle of internal friction near 30˜. One part of the sand layer rested on the plastic sheet. The other part, where the sheet was absent, rested directly on the rigid base.

Figure 4. Experimental set-up



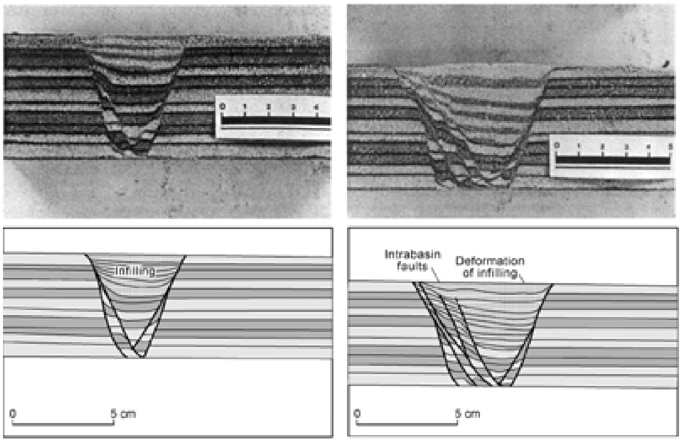
Experimental set-up used by Faugère and Brun (1984) to model pure extension using a sand layer resting on a basal plastic sheet.

Figure 5. Experimental set-up



Experimental set-up used by Faugère and Brun (1984) to model pull-apart basins.

Figure 6. Cross sections in a model by Faugère and Brun

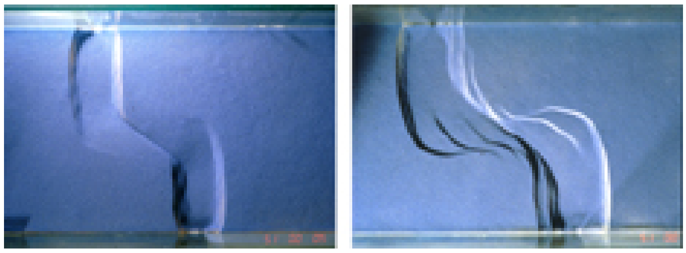


Photographs and line drawing of cross sections in a model by Faugère and Brun (1984) showing the graben asymmetry, including the presence of one permanent faults (right-hand side) and transient faults (left-hand side).

Model results

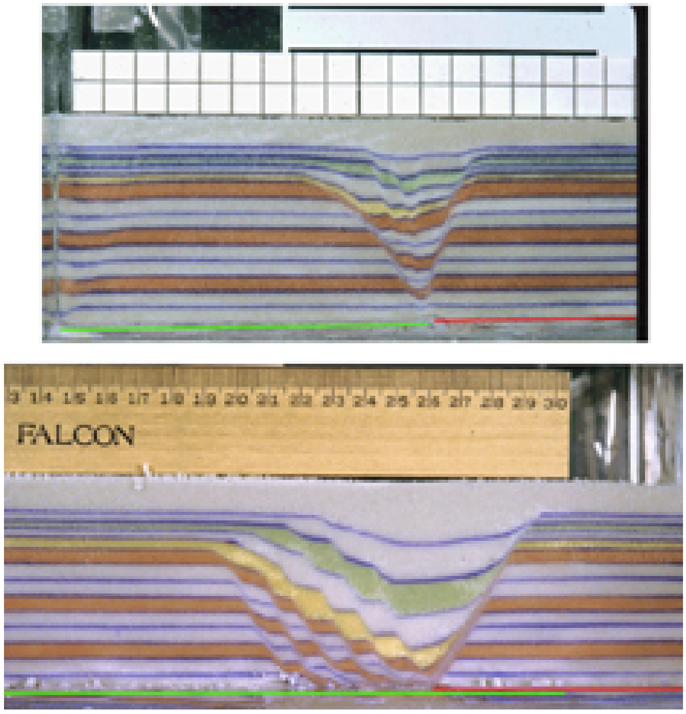
Deformation was induced by pulling the moving endwall and thereby pulling the attached acetate sheet. The purely extensional models evolved as follows. First, a pair of normal faults nucleated above the edge of the basal plate (the velocity discontinuity). The fault located above the moving sheet remained active throughout the entire experiment. This fault and its footwall remained attached to the moving basal sheet. On the other side, the fault located above the rigid model base ceased to slip once the velocity discontinuity moved farther away. A new fault nucleated above the velocity discontinuity and split the triangular graben block. This process was repeated during additional extension, as faults above the rigid model base slipped only for a short period, while their base was near the velocity discontinuity. In experiments having no concurrent sedimentation, the graben block became smaller until the two halves of the original sand layer became disconnected. In experiments having syntectonic sedimentation filling the graben trough, new faults on the fixed side formed continuously above the velocity discontinuity. The overall resulting geometry was that of an asymmetric graben: above the basal plastic sheet, one permanent fault rooted at depth on the velocity discontinuity and its footwall remained continuously attached to the moving basal sheet; above the fixed model base, the graben was bounded by a series of transient faults younging toward the velocity discontinuity, each fault remaining active only shortly. The sense of asymmetry was directly related to the geometry of the basal sheet, with the permanent fault located above the sheet. Flipping the side where the basal sheet lay led to an opposite sense of asymmetry.

Figure 7. Model by Vendeville



Overhead photographs of a model by Vendeville (1991) simulating graben relays. Extension was E-W.

Figure 8. Cross-sections in a model by Vendeville



Cross-sections in a model by Vendeville (1991) simulating graben relays. Top: N-S cross section intersecting one graben. Bottom: E-W cross section intersecting the relay zone. Note that all faults root at depth on the velocity discontinuity.

This simple 2-D geometry was further developed into 3-D set-ups by Faugère and Brun (1984) to model pull-apart basins and by Vendeville (1991) to model relay zones between extensional grabens (Figs. 7 and 8). In these set-ups the edge of the basal plastic sheet was dog-leg shaped, having (1) for pull-apart basins, two edges parallel to the lateral walls (thus inducing strike-slip movement) linked by one transverse edge perpendicular to the direction of displacement, or (2) for extensional relay zones, two edges perpendicular to the lateral walls (inducing local extension) linked by one transverse edge parallel to the direction of displacement, As in the purely extensional models, the active faults always nucleated on the basal velocity discontinuities. Strike-slip faults nucleated on top of the edges parallel to the lateral walls, whereas normal faults nucleated on top of edges perpendicular to the imposed motion. In both models, extensional structures were the first structures visible from top views, whereas strike-slip zones appeared later, which suggests that more strain was required for strike-slip zones to form. Also, all faults rooted at depth along the edges of the basal sheet (Figs. 6 and 8), whether these faults were parallel or perpendicular to the direction of imposed displacement. Although faults at depth rooted on the velocity discontinuity, their surface traces did not strictly follow the geometry of the basal sheet. Fault planes were curved in both plane view and cross section. The extensional regions of the models were characterized by asymmetric grabens whose sense of asymmetry was directly related to the geometry of the basal sheet.

Discussion

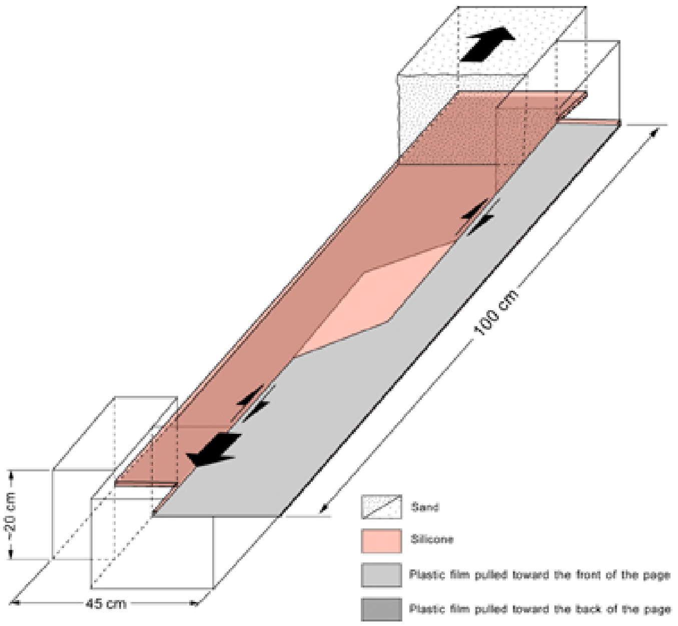
Although the above models successfully formed linked strike-slip and extensional fault zones, their applicability to the natural prototype is limited by several observations. First, every active fault formed above the basal velocity discontinuity, including within the relay zone or in the pull-apart basin. The geometry of the transverse edge of the basal sheet entirely controlled the location of faults in the transition zone. In other words, the location and geometry of structures in the interaction region (pull-apart basin or relay zone) results from the nucleation and upward propagation of faults from the velocity discontinuity, rather than the result of interaction between the two main offset faults. Indeed, changing the orientation of the transverse velocity discontinuity changed the structural pattern within the relay zone or pull-apart basin. Second, the mechanical properties of the models were not properly scaled equivalents of the natural prototype. In nature, the brittle layer rests on a weaker viscous layer. In the models, the brittle layer overlay a stronger rigid base (model’s base or basal plate) onto which it remained effectively attached during deformation. The only part of the brittle layer that deformed was narrow, triangular in cross sections, and confined to the area located immediately above the velocity discontinuity (graben or strike-slip zone). Third, the use of an extensional velocity discontinuity has one structural inevitable side effect, asymmetry. One side of the graben is bounded by one permanent fault, whereas the faults on the other side are continuously replaced by younger faults. Fourth, designs using a basal plate do not allow fault blocks to rise or subside isostatically. The base of the brittle layer remains flat and horizontal, bounded to the model's base. Overall, the main flaw of these experimental designs is that although the experiment is meant to elucidate how faults interact along strike, its very design entirely dictates the resulting structural pattern. This flaw is particularly well illustrated by the fact that although the goal of the pull-apart experiments was to investigate the formation of transtensional faults in response to motion along two strike-slip faults, the transtensional structures in the model formed before the strike-slip faults formed.

Brittle-Viscous Models (basal plate + strong viscous layer + brittle cover)

Model set-up

This set-up (Fig. 9) was designed by Sims et al. (1999) to alleviate some of the main flaws of pull-apart models using a basal sheet, especially the rooting of fault planes into the transverse velocity discontinuity. Like Faugère and Brun (1984), Sims et al. (1999) used a basal plastic sheet, on edge of which was attached to a mobile wall. On the other side, the sheet's edge was dog-leg shaped and comprised two edges parallel to the lateral walls (to induce strike slip) linked by a transverse edge oblique to the direction of imposed displacement. Unlike the previous models, where the brittle layer rested directly onto the model's base and basal plastic sheet, Sims et al.'s model comprised a thin (0.5 to 1.0 cm), tabular layer of viscous silicone polymer located between the base and the brittle layer and covering the entire model area. Because the applied deformation rate was high (10 cm.h-1) the viscous layer was strong enough to allow for some amount of coupling between the basal sheet and the brittle layer and therefore induce the formation of two laterally offset strike-slip zones in the brittle layer.

Figure 9. Experimental set-up used by Sims



Experimental set-up used by Sims et al. (1999) to model pull-apart basins using a sand layer, a strong basal viscous layer, and a basal plastic sheet.

Model results

In all experiments, faulting initiates as Riedel R shears oriented sub-parallel to the oblique, transverse edge of the plastic sheet (Fig. 10). Formation of the Riedel R shears is closely followed by antithetic, Riedel R' shears and synthetic P shears linking with the R shears to form fault-bounded horses in strike-slip duplexes. The duplexes rotate clockwise, synthetic to displacement along the primary strike-slip faults. Formation of linear D shears follows the formation of antithetic R' shears. Basin subsidence begins with local formation of normal faults, the onset of dip slip on existing R and R' shears, or both (Fig. 10). Normal displacement varies along strike to create asymmetric sub-basins with basin asymmetry switching side along strike. Large basins are elongate and bound on one side by a strike-slip faults and normal faults on the opposite sides, or by strike-slip fault and normal or oblique-slip faults on the opposite sides (Fig. 11). The basin floor has a trapdoor geometry, where the basin is bounded on all but one side by faults, with the remaining side operating as a hinge. Cross sections (Fig. 10) indicate that the main faults formed above or near the basal velocity discontinuities.

Figure 10. Overhead photograph and cross sections in a model by Sims et al. (1999). The overhead photograph shows the first faults whose traces are parallel to the underlying velocity discontinuity. Cross sections also show that faults form near the basal discontinuity (arrows).

Discussion

Sims et al. (1999)'s design represents an improvement of previous designs because it incorporates the presence of a viscous layer beneath the brittle cover. Ideally, the viscous layer may be considered as an analog for the ductile lower crust or for an evaporitic décollement at the base of the sedimentary cover. However, the high deformation rate used during these experiments makes this viscous layer much stronger than what a properly dynamically scaled analog for either the lower crust or a stratigraphic décollement would be. In order to properly simulate such viscous layers, the model would have to be deformed at a much lower rate. The quandary faced by modelers is twofold. In order to transmit localized strain from the basal sheet to the brittle layer, the basal viscous layer must be strong enough, hence deformed at a high strain rate. Whereas in order to properly simulate a décollement or the lower crust deformed at typical geological strain rates, the model must be deformed at rates so low that the viscous layer would effectively fully decouple the brittle sand layers from the model's base. Practically, such decoupling by the weak layer would not transmit the velocity discontinuity from the model's base to the overlying brittle layer, which would therefore deform in response to the movement of the end-walls and sidewalls only, rather than to the movement of the basal plate. As a result of the high strain rate, the models by Sims et al. (1999), like those by Faugère and Brun (1984), deform first by formation of faults located above the transverse velocity discontinuity. The transition zones between the two strike-slip faults forms before the strike-slip faults themselves (Fig. 10).

In addition, most faults form above or near the basal velocity discontinuities, including above the transverse boundary (Fig. 10). According to this scheme, the set-up, once again, constrains not only the location of the two offset strike-slip faults, but also that of the faults in the accommodation zone. There, faults do not form solely in response to the interaction between the offset strike-slip faults: instead, their location and orientation match those of transverse edge of the underlying basal sheet.

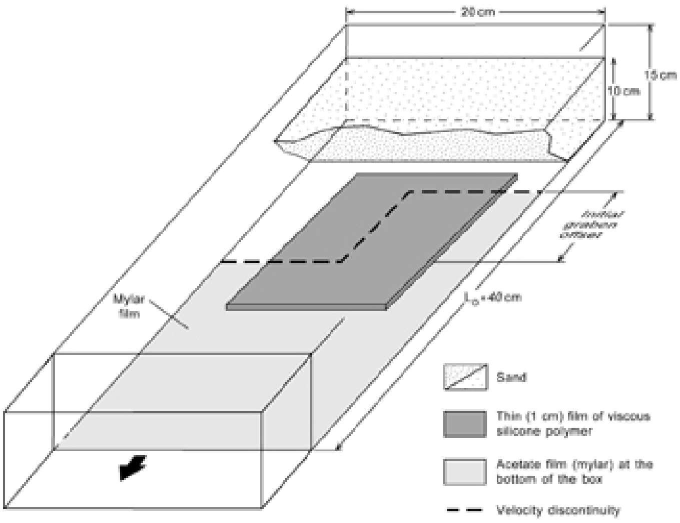
Finally, because the basal viscous layer was thin and strong, the amount of vertical subsidence and uplift of the base of the brittle layer remained limited, which makes these models applicable to geological settings involving thin décollements only, and not analogous to lower-upper continental crust.

Brittle-Viscous Models (basal plate + weak viscous layer + brittle cover)

Model set-up

This set-up (Fig. 11) was designed by Le Calvez and Vendeville (1996) as an attempt to combine the advantages of (1) a basal velocity discontinuity to localize offset faults and (2) the cushioning effect of a low-strength viscous layer to allow faults to propagate and interact freely. This set-up was tested only for relay zones between normal faults.

Figure 11. Experimental set-up used by Le Calvez and Vendeville



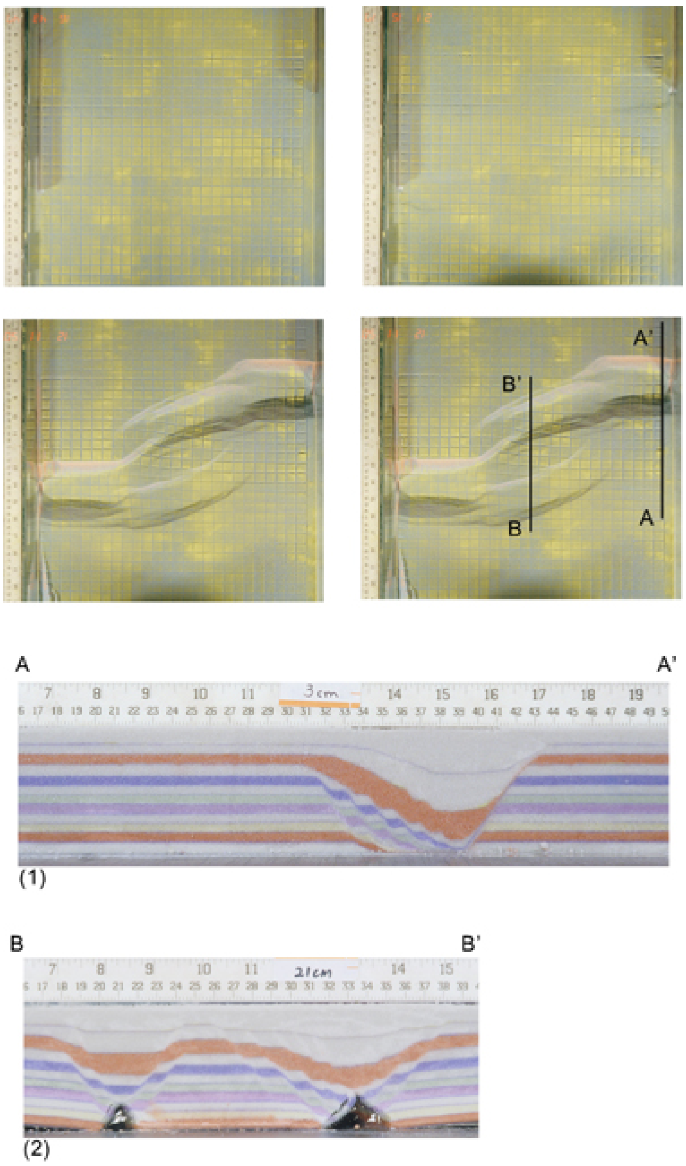
Experimental set-up used by Le Calvez and Vendeville (1996) to model graben relays using a sand layer, a weak basal viscous layer, and a basal plastic sheet. Note that only the center of the model comprises the weak viscous layer.

Like Faugère and Brun's, and Sims et al.'s models, this set-up required the presence of a dog-leg shaped velocity discontinuity at the model's base. As in Sims et al.'s model, the design involved a thin viscous layer below the base of the brittle layer. However, the viscous layer was located only in the central part of the model and the deformation rate was low enough (2 mm.h-1) to allow for full decoupling between the model's base and the brittle layer. According to this design, the lateral parts of the model did not comprise a viscous layer: the brittle layer lay directly on top of the velocity discontinuity. This design forced normal faults to form at predetermined location (hence with predetermined offset) in the lateral parts of the model. After normal faults formed in the lateral areas, they propagated along strike into the model's center, the area underlain by the weak viscous layer and in which faults could freely propagate irrespective of the location of the velocity discontinuity below the viscous layer.

Model results

In all experiments, grabens formed first in each lateral part of the box, where the viscous layer is absent (Fig. 12). The graben faults rooted at depth on the velocity discontinuity. Like in experiments by Faugère and Brun (1984), the grabens were asymmetric and bounded on one side by one permanent fault, and on the other side by transient faults.

Figure 12. Model by Le Calvez and Vendeville



Overhead photographs and N-S cross sections in model by Le Calvez and Vendeville (1996). Faults form first in the lateral regions of the model, where the lubricating basal viscous layer is absent, then propagate along strike into the mode's center, above the lubricating viscous layer. Grabens are asymmetric in the lateral parts (Cross section 1), and symmetric in the model's center (Cross section 2).

Each graben then propagated along strike toward the center of the model, where the thin viscous layer decoupled the brittle layer from the model's base. Unlike in the lateral parts of the box, where the viscous layer is absent, grabens in the center tended to be more symmetric (Fig.12). Unlike in experiments conducted using the two previous set-ups (e.g., Faugère and Brun, 1984; Vendeville, 1991; and Sims et al., 1999), the faults' traces and location in the model's center did not follow the velocity discontinuity located below the viscous layer. The low displacement rate allowed the viscous layer to fully decouple the brittle layer from the model's base in the center. Varying the shape of the velocity discontinuity, where the viscous layer was present did not change the grabens' geometry in the central area.

Results show that fault orientation and linkage vary with varying the amount of graben offset. Grabens having small offset propagate perpendicularly to the direction of regional extension and fault slip gradually decreases along strike, toward the model's center. With additional extension and syntectonic sedimentation, faults eventually hard-link. Grabens having moderate offset widen as they propagate toward each other and faults trend oblique with respect to the direction of extension. Faults soft-link and fault slip gradually decreases along strike. Displacement is transferred between overlapping faults by distorting fault ramps in the intervening blocks. Where graben offset is initially large, fault displacement is not transferred by soft-linked faults and distorted ramps. Instead, a new transtensional graben forms oblique to the direction of regional extension, and acts as a transfer structure between the two offset grabens. The formation of a new oblique transfer structure reflects a critical size for the rock volume between offset grabens (hence the graben offset) above which soft linkage and block distortion alone cannot accommodate deformation.

Discussion

The main flaw with the two previous model designs was that the presence of a transverse velocity discontinuity dictated the location, orientation, and sense of asymmetry of faults in the overlying brittle layer. The design by Le Calvez and Vendeville (1996) circumvents this flaw by effectively insulating the brittle layer from the transverse velocity discontinuity located in the model's center. Because faults could freely propagate along strike, the interaction between the two offset grabens was controlled solely by their mutual influence on each other's stress state.

Mechanically, this design also respects the main rheological characteristics of the natural prototype: the model comprises a strong brittle layer overlying a weaker viscous layer. However, this design does not incorporate some of the boundary conditions proper to the natural prototype. Because the viscous layer is thin, isostatic rise or subsidence of the faults blocks remained severely limited.

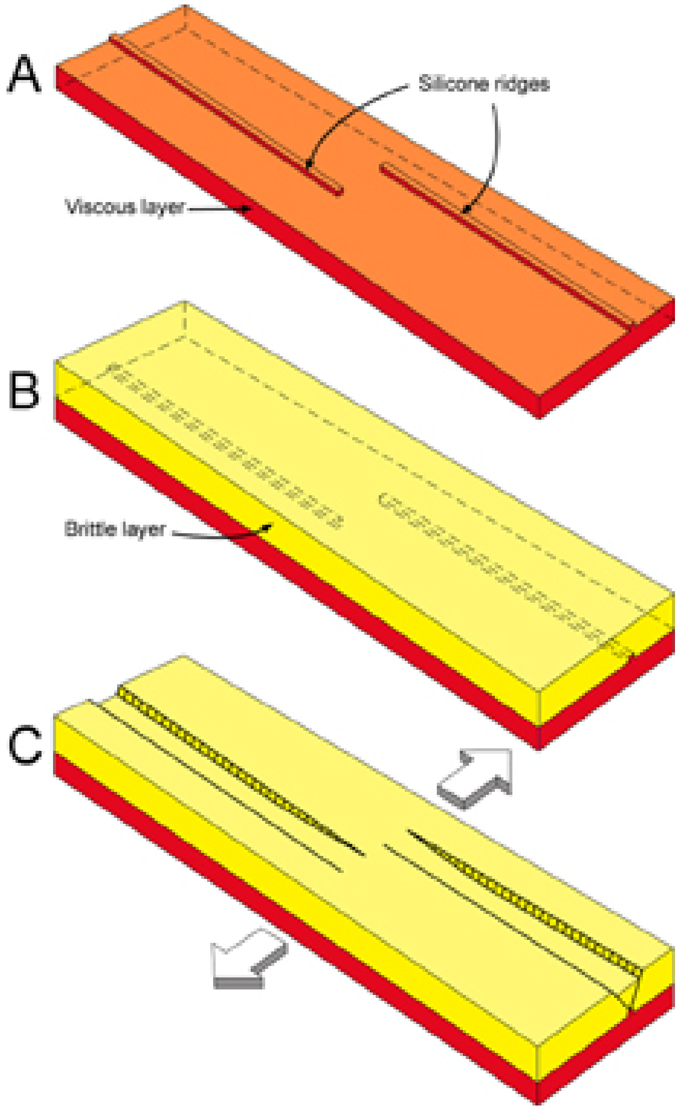
Furthermore, the influence of the velocity discontinuity in the lateral areas of the model imparted some asymmetry to the grabens. Although grabens tend to become more symmetrical as they propagate along strike above the lubricating viscous layer, the asymmetry in the lateral areas is likely to affect the fault pattern and evolution even in the model's center.

Brittle-Viscous Models (thick viscous layer + brittle cover)

Model set-up

This design (Fig. 13) departs radically from the three above designs because it does not rely on the presence of a basal velocity discontinuity (Le Calvez and Vendeville, 2000). Instead of propagating localized deformation from the base upward into the brittle layer, this design allows to make the brittle layer locally weaker in order to trigger faults or grabens at predetermined location. This set-up was used only to model relay zones between offset grabens. It has not yet been tested on experiments simulating pull-apart basins between offset strike-slip faults.

Figure 13. Experimental set-up used by Le Calvez and Vendeville



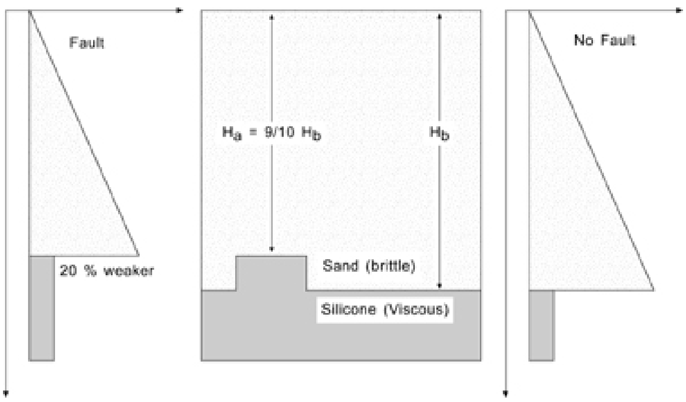
Experimental set-up used by Le Calvez and Vendeville (2000) to model graben relays using a thick layer of viscous silicone overlain by a thick sand layer. Two narrow ridges of silicone at the base of the sand layer trigger nucleation of two offset grabens.

The models were constructed and deformed in a large box (152-cm long and initially 50-cm wide; Fig. 13). The models comprised a 2.0-cm-thick layer of Newtonian transparent viscous silicone polymer (El Polymer NA, a Polydimethyl Siloxane manufactured by Wacker Silicones, U. S., whose properties have been described in detail by Weijermars in 1986) (density of about 950 km.m-3 and effective viscosity of about 6 x 104 Pa.s at a strain rate of 10-4 s-1), representing the salt layer (or lower continental crust for crustal-scale models), overlain by a thick (i.e., 5-10 cm) layer of dry sand (angle of internal friction of 25° to 30°, low cohesion, and density ranging from 1500 to 1700 kg.m-3), representing the brittle sedimentary overburden (or upper crust for crustal-scale models). After deposition of the viscous layer and before deposition of the sand layer, two long and low ridges of silicone (about 0.5-mm high and 1-cm wide) were laid on top of the viscous layer. The sand cover was therefore locally thinner (by 5 or 10%) above the silicone ridges (Fig. 14). Each one of the two ridges extended across half the model's length. The ridges were parallel to the moving walls used to impose extension, and were laterally offset. The amount of offset between the ridges varied between experiment in order to test its influence on the deformation pattern in the relay zone.

Bases of scaling theories were thoroughly described by Hubbert (1937, 1951).

Deformation was imposed by slowly moving the two endwalls at a low displacement rate (0.5 mm.h-1). As the two endwalls moved apart, the model spread under the effect of its own weight and deformed by thin-skinned extension. The viscous layer flowed while the brittle cover faulted. In the absence of silicone ridges, faults in the brittle layer would have nucleated either randomly or, more likely, close to the moving walls. However, because the brittle layer was initially locally thinner, hence weaker, above the silicone ridges, normal faults formed there (Fig. 14). The silicone ridges acted as triggers to nucleate the grabens at predetermined locations. Once the faults nucleated, the fault planes themselves controlled subsequent deformation because of the stress softening associated with faulting.

Figure 14. Schematic strength profiles



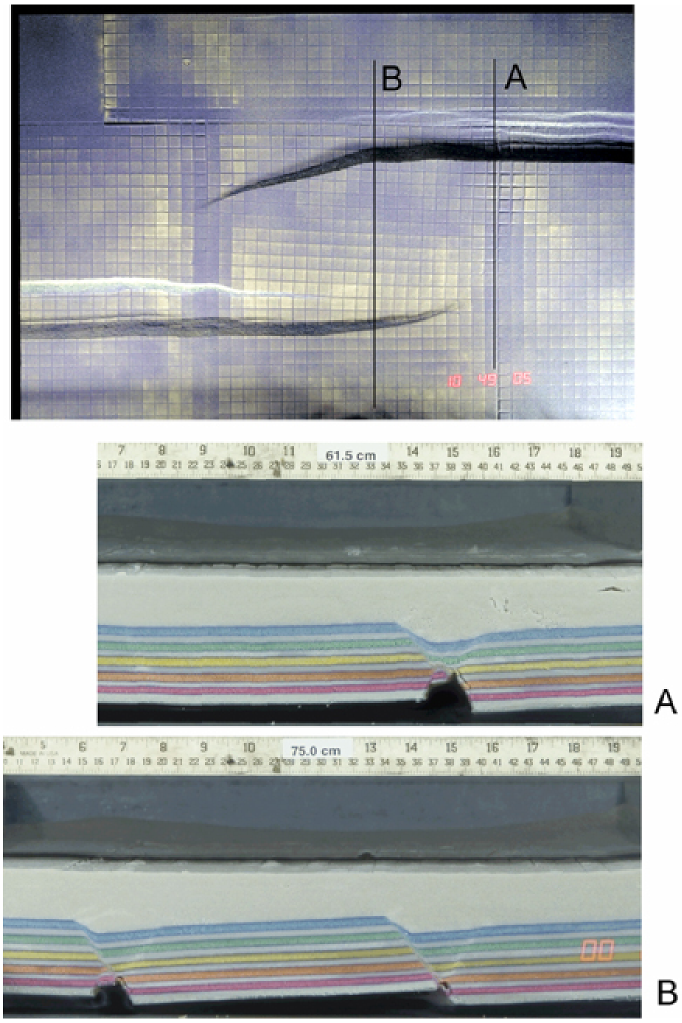
Schematic strength profiles illustrating that a silicone ridge (height: 1/10th of the sand-layer thickness) lowers locally the strength of the brittle layer by 20% and therefore nucleate faulting there.

The advantage of using this set-up is that although the ridges represented instabilities large enough to nucleate faults above them, these instabilities remained small compared with the fault planes. During subsequent extension faults are therefore free to propagate and interact freely, irrespective of the presence of the trigger ridges. Although the ridges are efficient initial triggers, the instabilities they represent are too small to affect deformation once fault planes have formed. On this regard, the role of the silicone ridges is comparable to weak nodes often inserted in finite-elements numerical simulation to localize faults of folds at chosen location.

Model results

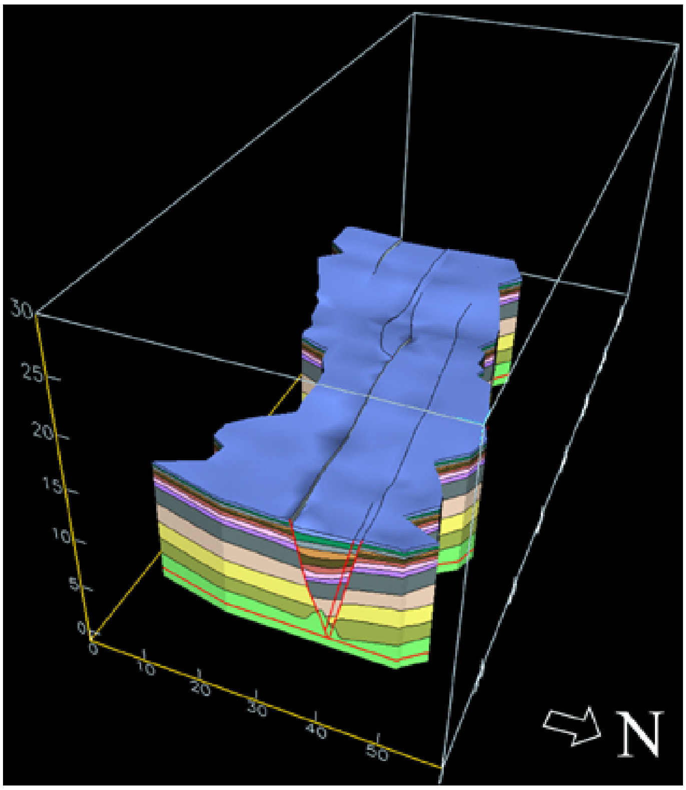
We conducted a series of 19 experiments using the above design. In this section, we present only a summary of the main results (Figs. 15 to 17). In all models, a graben nucleated on top of each trigger ridge. Each graben rapidly propagated along the entire length of the underlying ridge. During subsequent extension, the graben tips propagated along strike, beyond the tips of the underlying ridges. Depending on the amount of initial offset between the ridges (hence between the grabens), the grabens influence each other's propagation in various ways. Grabens having large imposed offsets progressively curved one toward the other and remained soft linked (Animation 1). The relay zone was wide and long (linearly proportional to the initial offset) and included fault blocks rotated around vertical and horizontal axes (Fig. 15). By contrast, faults bounding grabens having smaller imposed hard linked or even intersected one another, forming hourglass structures in the relay zone (Animation 2). The relay zone was narrow. In all models, the fault throw progressively decreased along strike, toward the relay zone (Fig. 16). Most grabens were symmetrical, with younger faults forming within the original graben block. Normal faulting thinned the graben floor, allowing the underlying viscous layer to respond isostatically by forming rising reactive diapirs (as described in Vendeville and Jackson, 1992). Like fault throw, the intensity of diapiric rise decreased along strike, toward the relay zone (Fig. 17).

Figure 15. Model of graben relay by Le Calvez and Vendeville



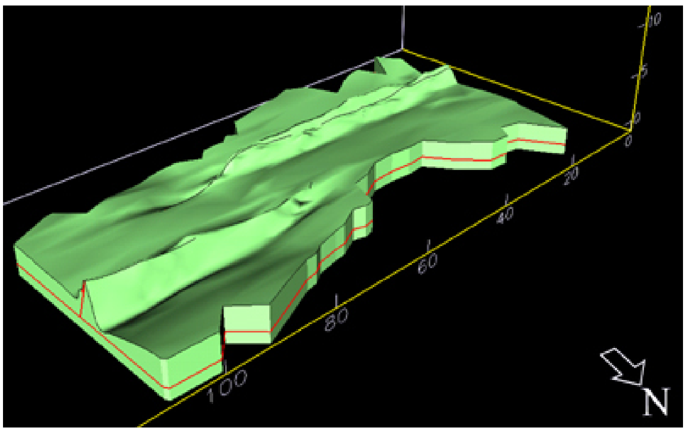
Overhead photograph and cross section of a model of graben relay by Le Calvez and Vendeville (1999). Cross sections: A: far from the relay zone; B: in the relay zone. Note that graben fault traces curve gently one toward the other, that fault slip progressively decreases toward the relay zone, and that the viscous layer rose diapirically beneath the grabens.

Figure 16. Model by Le Calvez and Vendeville



3-D visualization of a model by Le Calvez and Vendeville (1999) showing the entire model (viscous and brittle layers). Note the progressive change in fault throw along strike.

Figure 17. Model by Le Calvez and Vendeville



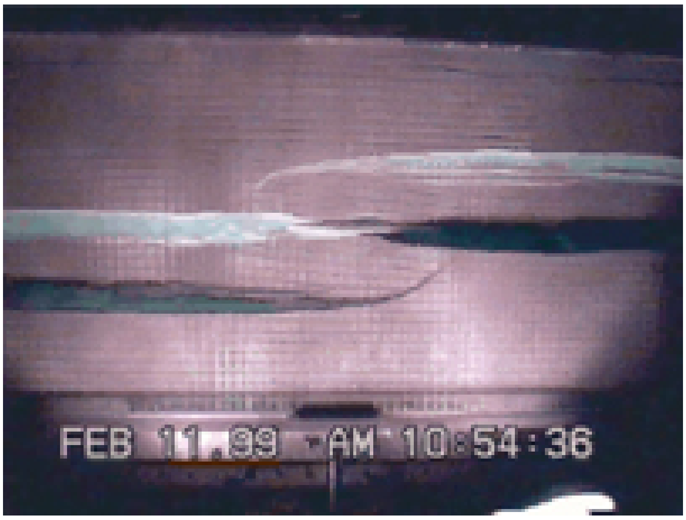
3-D visualization of a model by Le Calvez and Vendeville (1999) showing the top of the viscous layer and illustrating the progressive decrease in diapiric rise toward the relay zone.

Figure 17. Model simulation with large initial graben offset

Overhead view of model deformation through time showing soft-linked grabens (large initial graben offset).

Click on text to view animation.

Figure 18. Model simulation with small initial graben offset



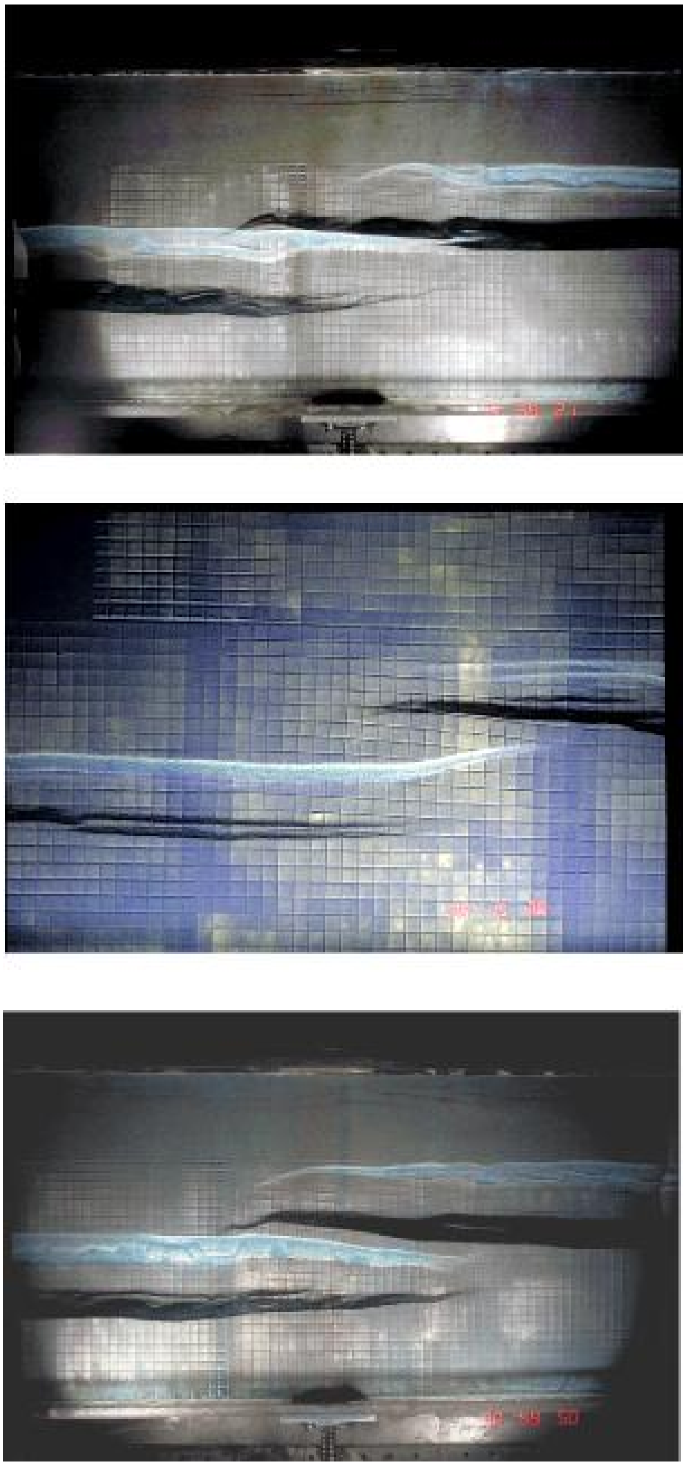
Overhead view of model deformation through time showing hard-linked grabens (small initial graben offset).

Click on text to view animation.

Discussion

This design differs from all other designs because it does not involve upward propagation of basal discontinuities from the model's base. Models have rheological and boundary conditions similar to those of the natural prototype. The model comprises a weak viscous layer overlain by a stronger brittle layer. Fault blocks can rise, subside, or rotate around vertical and horizontal axes in response to deformation. Once they have nucleated, the faults can freely propagate along strike. To be reliable, this design requires that the silicone ridges act as temporary instabilities that control the location of the first faults during their nucleation, while the ridges do not interfere with deformation once the faults have formed. We conducted several experiments to test for possible influence of the ridges after nucleation of the main faults. In nature, faults are expected to nucleate as short segments that subsequently propagate along strike.

Figure 18. Photographs of the model surface



Photographs of the model's surface for three experiments having similar graben offset and sand thickness but varying amounts of underlap or overlap (Le Calvez and Vendeville, 1999). A: 40 cm underlap; B: no overlap - no underlap; C: 40 cm overlap. Note that A and B deformed similarly but that the presence of a large overlap influences fault propagation and changes the geometry of the relay zone.

We therefore tested whether changing the length of the trigger ridges, which, to some extent, can be regarded as equivalent to the length of the initial fault segments in nature, could affect the deformation outcome. We conducted three experiments (Fig. 18) having identical characteristics (thickness, displacement rate, and amount of finite extension) but having silicone ridges of varying length. In one model (Fig. 18A), the ridges had a large underlap: their tips were 40 cm apart. In another model ((Fig. 18B), the tips of both ridges were aligned near the model's center. In a third model (Fig. 18C), the ridges overlapped by 40 cm.

The deformation patterns in the first two models (Figs. 18A and 18B: underlap and aligned ridge tips) are similar. In the model having in an underlap configuration (Fig. 18C), where the initial fault segments were short and far apart, faults first propagated along strike with a straight trace. Faults from the offset grabens started to interact and curve only once their tips had propagated beyond each other, past the model's center. This observation explains the similar pattern between models where the original ridges' tips were located far apart or were aligned (Figs. 18A and 18B). The ridges' tips did not interfere with the along-strike propagation of the graben faults.

By contrast, in the model in Figure 18C, the presence of overlapping ridges appears to have influenced fault propagation: instead of starting to interact near the model center (where the tips of the two offset grabens are aligned), the graben faults propagated in a straight manner up to the tips of the underlying ridges. The presence of overlapping ridges clearly influenced the deformation pattern in the relay zone. For this reason, our series of experiments used only set-ups where the trigger ridges were underlapping or had aligned tips.

Conclusion

Our review illustrates how similar types of structural settings have been modeled using various designs. Comparison between these experimental set-ups reveals the strengths and limits of each design (Table 1) and illustrates the progressive improvement in designing models whose geometric and rheological properties are analogous to those of the geological prototypes.

Table 1. Scaling parameters used for experiment J18, assuming a 200-m-thick source layer.

	Fungen et al. 1986	**Le Calvez and Vendeville, 1996**	**Sims et al. 1999**	**Le Calvez and Veneville, 2002**
The trace of the faults at the base of the brittle layer are not forced to follow a predetermined profiled (basal velocity discontinuity), outside / within the zone of transfer.	No / No	No / Yes	No / No	Yes / Yes
The base of the brittle layer is not forced to remain horizontal and rigid, outside / within the transfer zone.	No / No	No / Yes	Yes / Yes	Yes / Yes
Fault blocks are allowed to subside outside / within the transfer zone	No / No	No / Yes	Yes / Yes	Yes / Yes
The graben asymmetry is imposed by boundary conditions outside / within the transfer zone	No / No	No / Yes	No / No	Yes / Yes

In the above discussion, we have shown how the first set of models using a brittle layer resting directly above a basal sheet (Faugère et al., 1984; McClay and Ellis, 1987; Vendeville, 1991) controlled the location, orientation, and sense of asymmetry of faults in pull-apart basins or in the relay zones. The design by Sims et al. (1999) represents an improvement of this set-up by incorporating a basal viscous layer. This design, however still constrains too much fault location and orientation in the model. Although the third design by Le Calvez and Vendeville (1996) allowed to effectively insulate the brittle layer from the model base, it still does not permit significant fault-block vertical movements and rotations. The new set-up illustrated in this article represents only the latest step in the evolution of model design and will with no doubt be superceded by newer designs in the future. With this design, experimenters can confidently model the interaction of normal faults as they propagate along-strike during extension above a weaker viscous layer. The same design could easily be adapted to study fault interaction in different tectonic regimes, such as regional strike-slip or compressional deformation.

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