PERGAMON

Journal of Structural Geology 23 (2001) 593–600

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Influence of uniform basement extension on faulting in cover sediments

Tim Harper[a], Haakon Fossen[b,*], Jonny Hesthammer[c]

[a]*Geosphere Ltd, Netherton Farm, Sheepwash, Beaworthy, Devon EX21 5PL, UK*
[b]*Department of Geology, University of Bergen, Allegt. 41, N-5007 Bergen, Norway*
[c]*Statoil, N-5020 Bergen, Norway*

Received 6 December 1999; revised 1 June 2000; accepted 6 June 2000

Abstract

Numerical predictions are compared with the results obtained from sandbox experiments intended to reproduce the effects of uniform basement extension. For mechanically homogeneous or uniformly layered sediments that are not strain-softened, faults are *not* expected to develop during uniform basement extension. Even in heterogeneous or strain-softening sediments subject to uniform basement extension, the only faults to develop reveal an irregular and uncharacteristic distribution of displacements along the fault plane. It is inferred that minor and inevitable gradients in strain rate are the most important reason why faulting was observed in the sandbox models.

Irregularities such as topographic variation can also lead to faulting. Numerical experiments show that with increasing thickness of a basal elastic layer (rubber membranes in sandbox models) faulting of the cover sediments can cause the strain in the underlying elastic "basement" layer to become non-uniform.

Faulting during uniform basement extension is controlled by irregularities particular to each example, and thus does not give rise to a characteristic structural style in the overlying sediments. Thus, sandbox experiments of this type cannot be used as templates for structural interpretation except for the rare case when the initial distribution of sediment and basement material properties are known and their influence is explored from extensive numerical experimentation.

1. Introduction

Our understanding of geological deformation is continuously enhanced by means of field analysis, numerical simulation and physical modelling. As for the latter, sandbox experiments have proved to be a useful tool in the investigation of structural development during extension as well as other deformation types. The extensive use of sandbox experiments to investigate extensional faulting has been summarised by Ishikawa and Otsuki (1995). These authors, innovatively applying strain gradients in sandbox experiments, showed that half grabens tended to develop in the presence of a strain gradient. In contrast, drawing on the results of previous modelling, Ishikawa and Otsuki (1995) concluded that horst and graben structures tended to develop in the presence of a homogeneously (uniformly) extending basement (uniform bulk extension/pure shear).

Recent sandbox experiments intended to reproduce uniform basement extension are described by McClay and Ellis (1987a,b), Vendeville et al. (1987) and Vendeville and Cobbold (1988). In these experiments, the base of the moving wall of the sandbox was connected to the base of the fixed wall by a rubber membrane. The rubber membrane is referred to as "basement". During all of these experiments, horst and graben systems evolved with end results strikingly similar to seismically imaged structures in natural rift systems. In particular, the structures produced by McClay and Ellis (1987a,b) were remarkably similar to extensional structures in the North Sea, some of which contain very large accumulations of hydrocarbons (e.g. the Gullfaks structure; Fossen and Hesthammer, 1998). Some of the sandbox results are thus of major economic as well as academic interest. In particular, accurate description of the tectonic "boundary conditions" is an essential pre-requisite of predicting subseismic structure by modelling the structural history of a reservoir.

It should be noted that uniform stretching of a basement (rubber sheet) that remains flat during extension is unrepresentative of most geological settings. A basement unit is always mechanically heterogeneous, with pre-existing weak faults and shear zones and weak, tilted layers. Strain is expected to concentrate on such basement structures and influence fault growth in the sedimentary cover. Rotation of basement blocks is inevitable, and contradicts the assumption of a flat basement throughout the strain history. Some of

* Corresponding author.
E-mail address: haakon.fossen@geol.uib.no (H. Fossen).

0191-8141/01/$ - see front matter
PII: S0191-8141(00)00107-3

these sources of non-uniform basement deformation are eliminated if the basement–cover interface is represented as a low-angle detachment fault. However, in this case the detachment is better modelled as a low-friction slip surface rather than an extension-controlling "rubber sheet". The aim of this paper, however, is not to model a specific geologic example, but to examine the effect of uniform basement extension which, as noted above, has provided apparently important results in the past. In pursuing the primary objective of determining the geological relevance of the structural styles observed in previous sandbox analogues, the investigation serves also to emphasise that uniform basement extension is geologically improbable.

Below we present numerical experiments and compare the numerical predictions with the results obtained from the sandbox experiments intended to reproduce the effects of uniform basement strain. In particular, the numerical analyses suggest that the uniform extension condition described by McClay and Ellis gives rise to essentially homogeneous strain (no major faults). Consequently, we emphasise that, despite the remarkable similarity of structure developed in the sandbox experiments of McClay and Ellis and those of field examples such as Gullfaks, such structural arrangements should not be interpreted to result from uniform basement extension. To the contrary, they could be interpreted to be partly a consequence of inhomogeneous basement extension. Such structural arrangements would be more consistent with the conclusions of Ishikawa and Otsuki (1995).

2. Modelling faulting in geological materials

Certain aspects of fault initiation and propagation in geological materials are sometimes misunderstood in structural geology. For example, the belief that local weaknesses, such as grain boundaries or microcracks, are required for fault initiation in a deforming continuum is not uncommon. Such weaknesses, present in physical models but usually not in numerical models, have no significant effect on the style of faulting. Failing to recognise this fact can lead to an unfounded preference for sandbox results relative to the output of numerical models. Consequently, we restate some of the fundamental conclusions drawn by previous workers that lucidly explain localisation during shear deformation.

Localisation is the spontaneous formation of zones of concentrated deformation. Cundall (1990) explained that the possibility for localisation arises when one or more stress components at any location in a continuum are able to decrease with increasing strain. The strain then tends to be concentrated at this location. Cundall (1990) listed three ways in which the stress at a point can decrease with increasing strain: (a) large geometric distortions—buckling of a thin beam is an extreme example of this; (b) material softening, by which the intrinsic material becomes weaker, e.g. a dilatant material becomes looser and hence weaker; and (c) a change in stress state such that at least one component decreases. Cundall (1990) developed this third effect, "stress state softening", emphasising that it can occur even when a material is getting stronger (hardening). These effects occur in a deforming continuum and do not rely on the presence of pre-existing flaws, discontinuities or other form of heterogeneity.

Heterogeneity is a typical characteristic of geological materials. It can affect the locus of initiation of a shear band in that localisation occurs in the immediate vicinity of a hard or soft "inclusion" (Desrues, 1990). Nevertheless, the overall style of deformation is independent of microscale heterogeneity.

Examining the potential for modelling fault genesis in an initial continuum, Cundall (1990) investigated the influence of element size and loading rate on the results, and also large strain effects. Poliakov et al. (1993) reviewed the suitability of the FLAC algorithm used here for simulating sedimentary rock behaviour. Readers requiring a more detailed description of the processes of localisation than the brief comments given here are referred to Jenkins (1990), Poliakov et al. (1993), Vermeer (1990), Mühlaus and Vardoulakis (1987) and Rudnicki and Rice (1975). The paper by Poliakov et al. (1993) also includes a discussion of shear band formation in numerical models including the mesh-dependence when modelling strain-softening materials.

3. Description of the numerical method and conditions used here

Numerical experiments were conducted using the geomechanical code FLAC 3.4 (Fast Lagrangian Analysis of Continua; Itasca Consulting Group Inc., 1998). FLAC is an explicit, plane strain finite difference method, which uses Lagrangian analysis, and explicitly solves the dynamic equations of motion. The stresses, velocities and displacements at each grid point are calculated for each time step. Incremental displacements are added to the coordinates so that the grid moves and deforms with the material it represents (the Lagrangian formulation). Each element in FLAC behaves according to a prescribed linear or non-linear stress/strain law in response to the applied forces and boundary conditions. Linear elastic or elastic-perfectly plastic properties were used in the present experiments.

FLAC is able to model the development and evolution of shear bands. This is partly because FLAC is formulated using the dynamic equations of motion that are damped to achieve static or pseudo-static solutions (i.e. the kinetic energy that accompanies shear band formation is released and dissipated in a physically realistic way). The thickness of the shear bands depends upon the smallest width that can be resolved by the grid. Almost invariably, this width is much greater than the actual size of a shear band (fault) in a brittle material. Numerically developed shear bands may vary in thickness from one zone if the band is parallel to grid axes, to 3–4 zones if the band is inclined. This effect bears similarities to sandbox experiments, where the relatively large grain size results in shear zones rather than discrete faults.

Advantages of such numerical experiments over physical models include the complete control of boundary conditions, the absence of scaling problems and complete control of each step during the deformation history. The current experiments were conducted using FLAC in large strain mode directly at the true scale of a representative North Sea-type reservoir sequence (initially 2 km pre-compaction thickness and 10 km in length).

In most cases the sediments were represented as a homogeneous sand with the following properties: shear modulus = 3×10^7 Pa; bulk modulus = 1×10^8 Pa; buoyant density = 1000 kg/m^3; cohesion = 0; friction = 35°; tensile strength = 0. In one additional experiment, two clay layers were included with the following properties: shear modulus = 1×10^8 Pa; bulk modulus = 3×10^8 Pa; buoyant density = 1000 kg/m^3; cohesion = 8×10^3 Pa; friction = 15°; tensile strength = 0. With certain exceptions the sediments were modelled as neither strain-softening nor as strain-hardening, i.e. elastic–perfectly plastic, Mohr–Coulomb material. Properties of the elastic basement layer are given in Appendix A. Although a strain-softening material is more prone to produce shear bands, as noted above, Cundall (1990) emphasised that "faults" can develop naturally in FLAC and other models without the need to invoke complications such as strain-softening.

Reference points for recording of the history of displacements and shear stresses were equally spaced inside the model 1.5 km above the base and at the base, as shown in Fig. 1a.

The following are the main types of experiments performed with cover sediments above a uniformly extending basement surface: 1) extension of a homogeneous sand sequence; 2) extension of homogeneous sand with two clay layers; 3) extension of a sand sequence with heterogeneous mechanical properties and two homogeneous clay layers; 4) extension of a sand having an initial density heterogeneity; and 5) extension of strain-softening sand. Experiments were also conducted of the extension of homogeneous sand above a non-uniformly extending basement.

4. Results

4.1. Extension above a uniformly stretching basement

To reproduce the second experimental series of McClay and Ellis (1987a), or the first series of Vendeville et al. (1987), a 100 m thick elastic layer at the base of the sequence was overlain by 1.9 km thick Mohr–Coulomb material with properties as outlined above (Fig. 1a). The elastic layer corresponds to the rubber sheet in the sandbox models, whereas the Mohr–Coulomb material corresponds to the sand. The base of the model, i.e. immediately below the rubber membrane, is a frictionless (roller) boundary. Uniform basement extension was obtained, as a result of the uniform, linear nature of the elastic layer. Additional comments on the influence of the sediment deformation on the uniformity or of the deformation on the elastic membrane (basement) are given in Section 4.4.

No significant structures developed during the stretching history, which was taken to 100% extension (Fig. 1b). The very minor variation of cumulative shear strain shown may be an artefact relating to the model boundaries (in comparison, the models by McClay and Ellis (1987a,b) produced a total of 50% extension). The resulting homogeneous incremental, as well as finite, strain is confirmed by monitoring the rate of extension of the individual reference points at the base of the model (Fig. 1a and Fig. 2a) and by shear stress histories of the sedimentary cover (Fig. 1a and Fig. 3a). The finite deformation state is seen to be homogeneous pure shear, as opposed to the heterogeneous strain produced in the sandbox experiments. The mechanical explanation for the homogeneous finite strain is directly related to the uniformity of the strain of the uniform elastic basement. Fig. 4 shows a detail of the state of the sediments shown in Fig. 1b. It is evident that there are dipping bands of sediment at yield but that these bands become diffuse (broader) at depth in the vicinity of the basement. Outside these bands, yield at an earlier (post-consolidation) phase of the extension is indicative of the evolving nature of the pattern of incipient shear bands, none of which becomes a concentrated zone of shear strain.

An additional experiment was performed, where a sequence had an elastic layer at the base with an elastic modulus 10 times less than that of all the other models (i.e. very much softer). The result of this experiment (not shown here) is similar to the one above, implying that softening the modulus of the elastic layer has no effect on the result.

An additional uniformly stretching basement experiment was performed. This experiment was similar to the one described above, except that two clay layers were introduced in the upper half of the model (properties listed above). The purpose of this run was to investigate the effect of such heterogeneity on the deformation.

The distribution of cumulative shear strain (Fig. 1c) is very similar to that obtained for homogeneous sand. Hence, it appears that normal lithological (rheological) stratification does not change the observations from the first experiment, i.e. that the extensional strain above a uniformly extending basement is homogeneous and thus fails to produce structures.

4.2. Extension above a non-uniformly stretching basement

Having noticed that a uniformly extending basement fails to produce structures in its cover, an experiment was

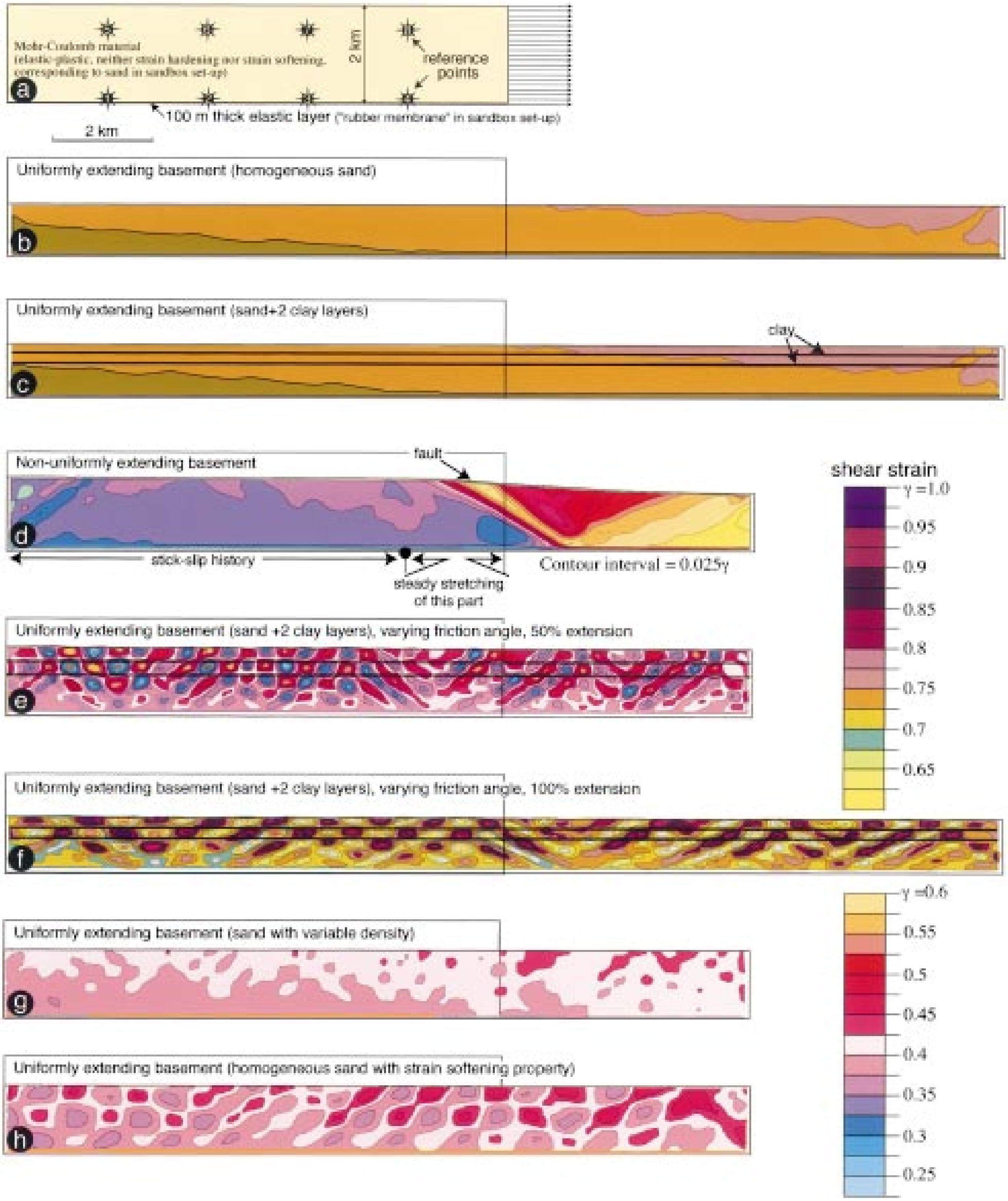

Fig. 1. (a) Initial set-up of the experiments, showing the constant velocity applied to the right-hand side of the model and reference points for the measurements shown in Figs. 2 and 3. (b) Cumulative shear strain after 100% extension of the homogeneous sand sequence above a uniformly extending basement. No localisation (faulting) is evident, simply a gentle gradient of cumulative shear strain. (c) Cumulative shear strain for the model of homogeneous sand including two clay layers. Note that the distribution of cumulative shear strain is similar to (b) and that the clay layers clearly demonstrate the lack of structure. (d) Experiment where the elastic layer (rubber membrane of McClay and Ellis, 1987a,b) was extended irregularly. A right-dipping fault is particularly well developed in the right-hand side of the model. (e) Result after 50% extension of a two-clay layer model similar to (c), but with heterogeneity (varying friction angle throughout the sand). Note localisation of shear strain to create conjugate structures with irregular displacement distribution; (f) same as (e) but after 100% extension. The result is similar to (e) with additional homogeneous pure shear. (g) Cumulative shear strain after 50% uniform extension of sediments of density varying with a standard deviation equivalent to ±5%. (h) Cumulative shear strain after 50% uniform extension of homogeneous strain-softening sand. See text for discussion.

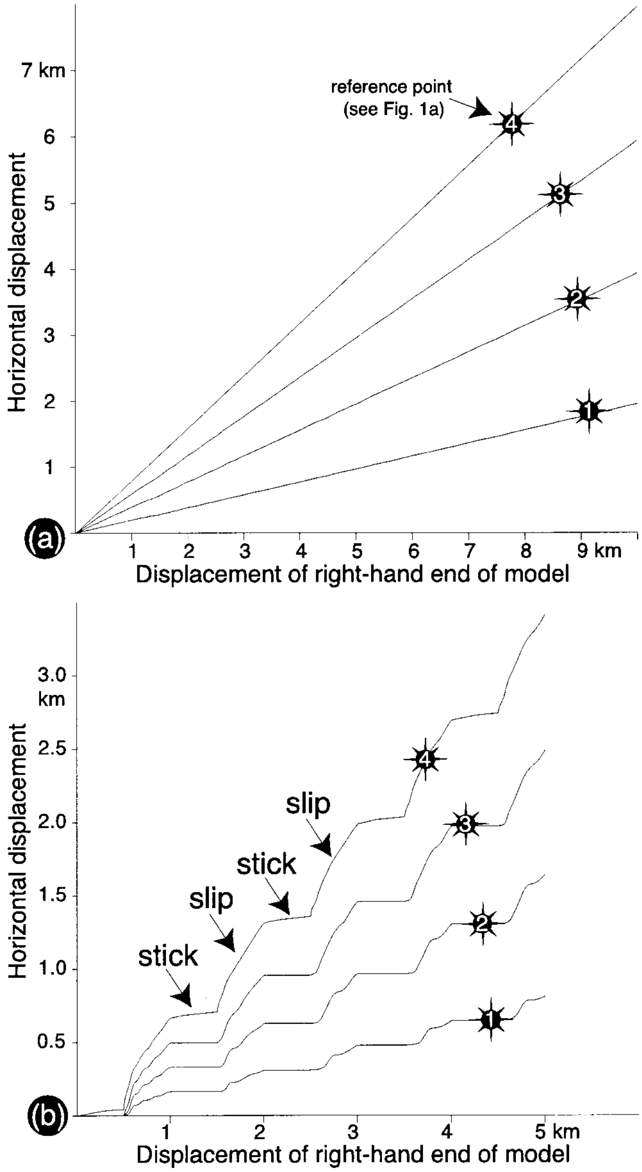

Fig. 2. Horizontal displacement versus the displacement of the right-hand end of the sequence for (a) the experiment with homogeneously extending basement, and (b) the experiment where the elastic layer was extended irregularly. The lines represent the displacement of the reference points shown in Fig. 1a. Note that the rate of extension is almost perfectly linear in (a) and step-like non-linear in (b).

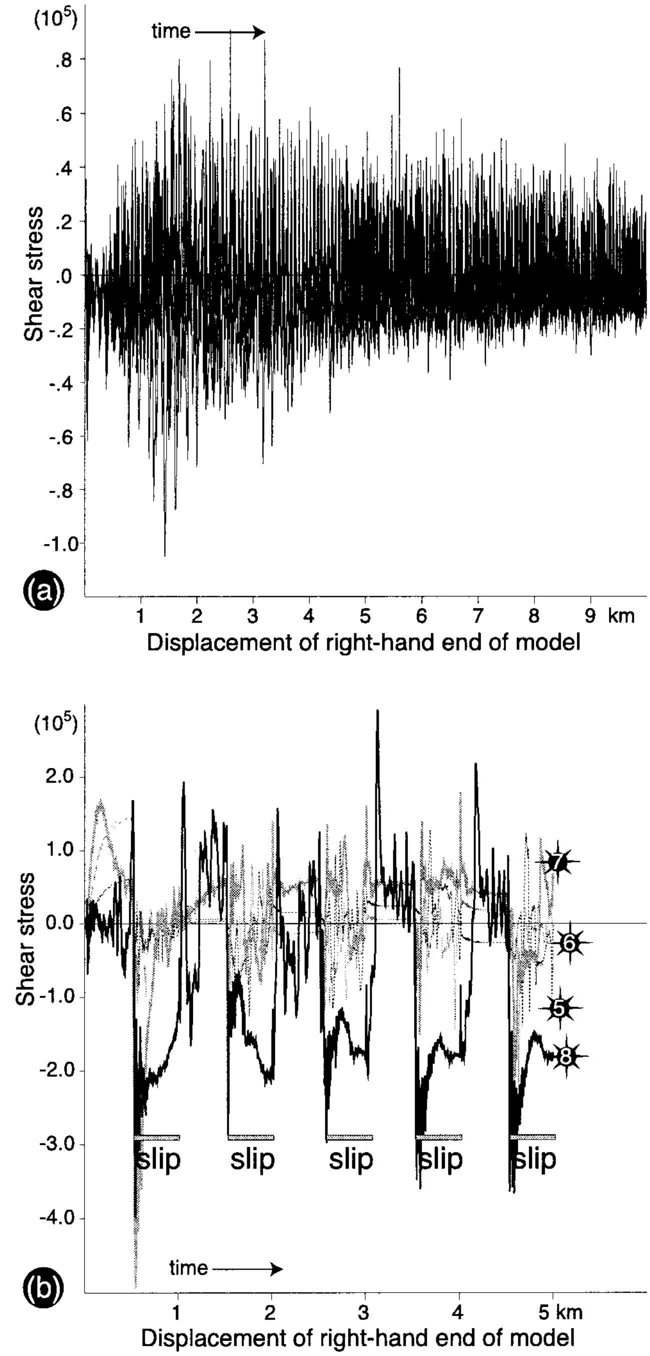

Fig. 3. Shear stress histories of the reference points shown in Fig. 1a for (a) the experiment with homogeneously extending basement, and (b) heterogeneously-extending basement. In (a) the shear stresses oscillate as the deformation progresses, but the fluctuation is essentially centred about zero and individual reference point curves are indistinguishable. In (b) the fluctuation of shear stress corresponding to the stick-slip increments is clearly portrayed. The strongest fluctuations (thick black line) occur in the vicinity of the reference location 8 in the model (see Fig. 1a). The negative shear stress corresponds to the right-dipping fault nucleated from the sticking point. The oscillatory nature of the shear stress reflects the nature of the FLAC formulation and the boundary conditions applied in this modelling. The dynamic equations of motion are included in the formulation with inertial terms and the generation and dissipation of kinetic energy. Increments of work are done on the sedimentary pile at each time step corresponding to the constant velocity boundary condition.

performed in which the elastic layer (rubber membrane of McClay and Ellis, 1987a,b and Vendeville et al., 1987) was subjected to heterogeneous extension. The 8 km on the left of the elastic layer was alternately prevented from extending and allowed to extend. A stick-slip behaviour of the elastic layer was thus modelled. The right-hand 20% of the sequence was allowed to extend continuously and homogeneously, but a point located one-fifth from the right end of the model was assumed to be subject to stick-slip behaviour (Fig. 1d). The 80% to the left of this stick-slip point alternately stretched or experienced constant strain. In this case, only 50% extension was modelled. The simple

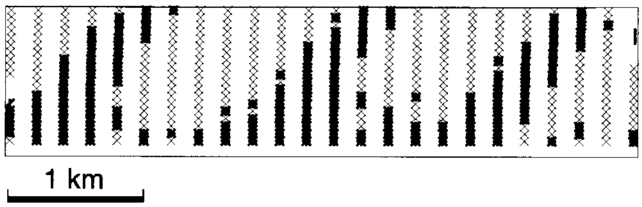

Fig. 4. Detail of the uniformly extending basement experiment shown in Fig. 1b. Thick black marks denote yield while thin-lined crosses denote an elastic state (at yield in the past). Left-dipping bands of yielding material (incipient faults) become broad and diffuse in the vicinity of the elastic layer at depth, which prevents fault development. This pattern illustrates the mechanical reason why faults do not develop above uniformly extending basement.

stick-slip model presented here is only one example out of an infinite spectrum of non-uniformly extending basement modes.

The result (Fig. 1d) is considerably different from the other experiments in that the deformation is clearly heterogeneous. Cumulative shear strain varies markedly throughout the right-hand side of the model, where a high-strain zone indicates an ~35° right-dipping fault. The location of this fault coincides with the left limit of an increased rate of thinning of the deforming sediment, and the fault has nucleated from the point in the elastic layer at which sticking was imposed.

The history of displacements, as portrayed in Fig. 2b, reveals the stick-slip effect involved. The corresponding shear stress histories are plotted in Fig. 3b. The fluctuation of sense of shear stress corresponding to the stick-slip increments is clearly shown. The strongest fluctuations occur in the vicinity of the easternmost reference location (reference point 8). The negative shear stresses portrayed in Fig. 3b correspond to the right-dipping fault nucleated from the sticking point. This fault is the only clearly developed fault shown in Fig. 1d (the left-dipping structure is a broad rather than concentrated feature).

4.3. Influence of heterogeneity and topographic irregularity

Additional modelling was conducted with a sediment heterogeneity randomly imposed as a normal distribution of sediment properties. A normal (Gaussian) distribution of either clay friction angle, clay cohesion or sand friction angle, or a combination of these, was applied randomly throughout the zones of the model as an initial condition. The most heterogeneous examples resulted from imposing a standard deviation of the clay friction angle of 2° (± 13.3%) or of 2° (±5.7%) to the sand friction angle. Examples of the results are shown in Fig. 1e and f, which resulted from applying a standard deviation of 2° to the sand friction angle to achieve a random distribution of sand strength. The sand friction angle was thus varied with a standard deviation of ±5.7% of the mean friction angle of 35°.

This condition resulted in considerable heterogeneity, conducive to relatively large local shear strains. Because the heterogeneity is a function of grid size (100 × 100 m) the scale of the property variation is large. The larger the scale the more pronounced any incipient faults, so this large scale tends to exaggerate the formation of incipient faults induced by heterogeneity. The results (Fig. 1e and f) are plotted at the same contour interval as the other figures in this paper for ready comparison. After 100% extension, the maximum strain of the heterogeneous sediment is 40% greater than the maximum strain of the homogeneous sand, reflecting the localisation associated with heterogeneity. Hence, this result confirmed that heterogeneity can cause shear bands to initiate in sediment overlying a uniformly extending basement.

Comparison of Fig. 1e (50% strain) and Fig. 1f (100% strain) indicates that the faults induced by heterogeneity do not develop in the same manner as those induced by inhomogeneous basement extension (Fig. 1d). Because of the random distribution of material properties, the shear displacements were irregular and atypical of the usual displacement distribution recorded on extensional faults. The fact that the structures in Fig. 1e and f are almost identical in spite of large differences in finite strain indicates that the faults did not significantly propagate from 50 to 100% extension. Faults may initiate because of heterogeneity but do not propagate in perfectly plastic material for these basement conditions. Similarly, a standard deviation of pre-consolidation sediment density corresponding to ±5% in the modelled 2 km of sand, resulted in only weakly developed shear bands which did not develop into well-defined shear bands penetrating from top to bottom of the sand (Fig. 1g). This indicates that variation of the sand density in the shear box is not likely to have been the cause of the structures reported by McClay and Ellis (1987a,b).

The effect that strain-softening characteristics can have on the tendency for localisation was also explored, as shown in Fig. 1h. Here, the homogeneous sand of Fig. 1b (constant friction angle of 35°) was replaced by sand of an initial friction angle of 45° reducing to 35° after 10 mm shear displacement. The effect of this shear softening, recorded in Fig. 1h, may be compared with Fig. 1a. Some degree of shear banding is evident but, in common with the heterogeneous sediment (Fig. 1e, f, g), the shear bands do not develop a well-defined structure. Thus weakly-developed shear bands can form in sediments displaying either strain-softening behaviour or heterogeneity (of shear strength or pre-consolidation density) during uniform basement extension. Although the bands do not develop strongly, this does not preclude the possibility of better-developed structures arising from a combination of strength heterogeneity and shear softening, or other numerical mesh sizes (Poliakov et al., 1993). The resulting horst and graben style bears close similarities with the style developed in uniformly(?) extended sandbox models presented by McClay and Ellis (1987a,b) and Vendeville et al. (1987). However, since the distribution of such structures is a function of heterogeneity (as well as other factors), the results of such sandbox models cannot be used as templates for structural interpretation (e.g. McClay, 1995) unless the distribution of sediment material properties are known and their influence investigated by an exhaustive series of numerical experiments.

Mandl (1988) reported a numerical experiment whereby shear band formation was initiated by imposing a notch in the sediment sequence overlying uniformly extending basement. This implies that topographic irregularity can also cause fault initiation. Again, the results are of no value as structural templates without a supporting programme similar to that mentioned above.

4.4. Sediment-basement coupling

Uniform basement extension was achieved in our experiments by means of a linearly elastic layer at the base of the model. Preliminary numerical investigations of the influence of developing faults in the cover sediments revealed that the initially uniform extension of the elastic layer can become non-uniform if conditions in the cover sediment sequence are such that faults do after all develop in the cover. In our preliminary experiments this could be achieved by doubling the thickness of the elastic basement to 200 m rather than attempting to model a (relatively thin) membrane as used to represent the sandbox results which motivated this investigation. It was noted that if faulting in the cover can develop sufficiently to cause a local thinning of the basement layer, then the consequent local reduction in basement thickness simply led to a local increase of basement strain. Of particular interest, was that the local basement thinning was not stationary as extension progressed, such that the basement-cover coupling resulted in a quasi-periodic evolution of the geometry of deformation. Further exploration of this interesting behaviour was deemed beyond the scope of this investigation. Thus we infer that not only does a non-uniformity of basement extension give rise to faults in the overlying sediment but that the reverse also occurs, i.e. the sediment and basement are coupled. Because coupling was only observed when the thickness of the elastic layer in our models exceeded a certain value, we expect that the effect may not be observed in sandbox models using thin basal rubber membranes.

Note that the basement in these models was stronger than the cover in that no plastic yield criterion is included in the description of the basement constitutive behaviour—the basement simply remains linearly elastic for all applied stresses. It therefore follows from the results that the cover sediments can influence the basement rocks regardless of relative strength.

The numerical results reported by Mandl (1988) were achieved using a boundary condition whereby the basement displacements were forced to be uniform throughout the experiment. Our preliminary results thus suggest that such a boundary condition can yield misleading results.

5. Discussion

Uniform basement extension gives rise to essentially homogeneous strain of homogeneous sand. No significant structures are developed in this case unless the sand has strain-softening properties. Even with strongly strain-softening sand, only weakly developed faults with an atypical displacement distribution were generated during our experiments. Thus, the results of previous sandbox experiments intended to represent a uniform basement extension are misleading. Softening the modulus of the elastic layer makes no difference to the results, nor does inclusion of two clay layers. However, structure did develop when sticking of the elastic membrane was simulated.

It is inferred that the rubber membrane used in the experiments by McClay and Ellis (1987a,b) and Vendeville et al. (1987) did not extend uniformly during the course of their experiments. Mechanical heterogeneity of the sand might have played a part in the initiation of faults but any such heterogeneity-initiated faults are not likely to have propagated and formed prominent structures as seen in the sandbox experiments. We have no evidence that the sand was not strain-softened and, although improbable, the possibility that faulting initiated in response to heterogeneity and propagated in response to strain-softening cannot be entirely eliminated. The sand used in the physical experiments was loose and probably not strain-softened, but if a contribution to faulting by softening is nevertheless assumed, we note that the effect is shown here to be limited under conditions of uniform basement extension. As indicated by the experiment with homogeneous strain-softening sand (Fig. 1h), fault propagation with the assistance of strain-softening does not lead to well-developed concentrations of shear strain when controlled by uniform basement extension.

McClay and Ellis (1987a) report some early heterogeneous extension of the rubber sheet (10–15% extension), but we suspect that the rubber sheet may have extended heterogeneously also at higher extensions. The later heterogeneity of extension may not have been large, as it was not recognised.

These findings emphasise two important points; 1) minor heterogeneity of basement extension is sufficient to nucleate faults, and 2) although not the only influential factor, the location of such heterogeneity influences the position, spacing and dip direction of faults. These discoveries call for further numerical exploration of models with heterogeneously extending basements, where their sensitivity to variations in typical basement and cover heterogeneity, including typical lithological variations, should be the focus.

Where basement extension is entirely or largely uniform, as concluded by Ishikawa and Otsuki (1995), horst and graben style will predominate (where conditions have been suitable for faults to initiate and propagate). It is stressed, however, that the distribution of faults will be a function of the irregularities of basement extension, sediment properties (other than uniform layering) and topography. Relatively straightforward numerical modelling can be used to assess the influence of each of these.

6. Conclusions

Our conclusions may be summarised as follows:

1. Well-defined faults do not form in layered but otherwise homogeneous sediments subject to uniform extension of the underlying basement.
2. Faults can initiate in heterogeneous sediments subjected to uniform basement extension in response to the heterogeneity. These faults do not evolve into clear fault structures in sediment that is not strain-softening. Strain-softening alone is not sufficient to give prominent structures under these conditions. We have not attempted to eliminate the possibility that heterogeneous strain-softening sediments subject to uniform basement extension could give rise to well-developed faults because the distribution of any such structures would also be a function of the irregularities (heterogeneity) that influenced fault initiation. Irregularities such as the topography can also lead to faulting.
3. Faults formed in cover sediments overlying an initially uniformly extending basement, in response to heterogeneity and/or topographic irregularity, can give rise to non-uniform basement extension by means of a coupling effect as extension progresses.
4. Uniform basement extension, in itself a geologically improbable condition, does not give rise to a characteristic structural style in the overlying sediments that can be used as a single structural template for interpretation purposes.

Acknowledgements

We thank Statoil for financial support. Peter Cundall kindly provided comments that helped us to clarify the paper. Detailed reviews by Bruno Vendeville and Steve McKinnon as well as comments by Ken McClay on an earlier version are also appreciated.

Appendix A. Experimental details

An initial 2000 zone grid was scaled to represent a 10 km long by 2 km deep section. The sides and base of the model were fixed normal to the boundary and free in the plane of the boundary (i.e. roller boundaries). The model was first consolidated under gravity as a linear elastic material. Excepting the zones immediately adjacent to the base of the model, the material was then given perfectly plastic, Mohr–Coulomb properties and further consolidated. The properties of the basal elastic layer were: bulk modulus = 1×10^8 Pa; shear modulus $= 0.64 \times 10^8$ Pa. The material was extended at a strain rate of 10^{-5} per calculation cycle by applying a constant velocity to the right boundary while the left boundary remained fixed. The effect of sticking of a basal membrane in a sandbox was investigated by sequentially and repeatedly imposing a zero velocity condition on basal gridpoints 2–80 for periods of 5000 cycles and then restoring the roller boundary condition.

References

Cundall, P., 1990. Numerical modelling of jointed and faulted rock. In: Rossmanith, A. (Ed.). Mechanics of Jointed and Faulted Rock. Balkema, Rotterdam, pp. 11–18.

Desrues, J., 1990. Shear band initiation in granular materials: experimentation and theory. In: Darve, F. (Ed.). Geomaterials, Constitutive Equations and Modelling. Elsevier, Oxford, pp. 283–310.

Ishikawa, M., Otsuki, K., 1995. Effects of strain gradient on asymmetry of experimental normal fault systems. Journal of Structural Geology 17, 1047–1053.

Itasca Consulting Group Inc., 1998. FLAC (Fast Lagrangian Analysis of Continua), version 3.4. ICG, Minneapolis.

Jenkins, J.T., 1990. Localization in granular materials. Applied Mechanics Review 43, 194–195.

Fossen, H., Hesthammer, J., 1998. Structural geology of the Gullfaks Field, northern North Sea. In: Coward, M.P., Johnson, H., Daltaban, T.S. (Eds.). Structural Geology in Reservoir Characterization. Geological Society Special Publication 127, pp. 231–261.

Mandl, G., 1988. Mechanics of Tectonic Faulting. Elsevier, Amsterdam.

McClay, K.R., 1995. 2D and 3D analogue modelling of extensional fault structures: templates for seismic interpretation. Petroleum Geoscience 1, 163–178.

McClay, K.R., Ellis, P.G., 1987aa. Analogue models of extensional fault geometries. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.). Continental Extensional Tectonics. Geological Society Special Publication 28, pp. 109–125.

McClay, K.R., Ellis, P.G., 1987bb. Geometries of extensional fault systems developed in model experiments. Geology 15, 341–344.

Mühlaus, H.-B., Vardoulakis, I., 1987. The thickness of shear bands in granular materials. Geotechnique 37, 271–283.

Poliakov, A.N.B., Podladchikov, Yu., Talbot, C., 1993. Initiation of salt diapirs with frictional overburdens: numerical experiments. Tectonophysics 228, 199–210.

Rudnicki, J.W., Rice, J.R., 1975. Conditions for the localization of the deformation in pressure-sensitive dilatant materials. Journal of Mechanics and Physics of Solids 23, 371–394.

Vendeville, B., Cobbold, P.R., 1988. How normal faulting and sedimentation interact to produce listric fault profiles and stratigraphic wedges. Journal of Structural Geology 10, 649–659.

Vendeville, B., Cobbold, P.R., Davy, P., Brun, J.P., Choukroune, P., 1987. Physical models of extensional tectonics at various scales. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.). Continental Extensional Tectonics. Geological Society Special Publication 28, pp. 95–107.

Vermeer, P.A., 1990. The orientation of shear bands in biaxial tests. Géotechnique 40, 223–236.