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Scale effects and rheologic constraints in ramp-flat thrust models

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Abstract: Dynamic models for the interactive development of ramp-flat thrust styles are studied in centrifuge experiments. Plastilina simulates the competent strain-hardening behaviour of sandstones and carbonates, while viscous or plastic bouncing putties represent incompetent evaporites and shales. The models exhibit various fault-fold geometries; e.g. *fault bend folds, footwall synclines, wedge faults* as structural expressions of ductile ramp-flat accommodation. Depending on the rheological stratification, the ramps change shape and length as slip accumulates along the fault surfaces in flowing surroundings.

A ductile fault bend folds develops in a single competent layer detached above a rigid base, with or without a soft cover. The load imposed by the overthrusting hangingwall generates a footwall synform in case the yield limit of the material is exceeded. In models where the competent single layer is underlain or sandwiched between stiff ductile strata the initial straight ramps change shape to wedge faults. These exhibit footwall synforms that mirror the hangingwall antiforms. Hangingwall blocks that overthrust soft ductile strata get injected by the substratum material beneath the ramp. The ramp-flat structures simulated in the models may give valuable insight in assessing the rheology of rocks deforming under similar conditions in nature.

Introduction

Geological mapping in overthrust terranes, for over a century (Willis, 1890; Heim, 1921) has shown the intimate association of thrusts/folds. The relative importance of folding-faulting styles are largely controlled by the rheological stratification in a stratigraphic column. At less than crustal scale the modes and kinematics of fold-fault interaction can vary greatly, and their interrelationships has received wide attention. Since the early days of geology it has been well-known that thrusts may develop from pre-existing folds, by shearing out of middle limbs of antiform-synform pairs (Heim, 1921; Willis, 1890). However, the mechanics of thrusting where faulting preceeds folding are not well-understood. In the current literature, these are variously named; *fault bend folding* (e.g. Suppe, 1983), fault propagation folding (Jamison, 1987; Geiser, 1988) and decollement folding (Jamison, 1987), all based on the initial Rich (1934) concept which suggested that overthrust faulting localises in mechanically weak rocks, parallel to bedding (e.g shales) and steps upwards in mechanically strong rocks (e.g carbonates).

A radically different view was invoked by Gretener (1972) who suggested that a competent layer could act as a stress guide and fail when the strength limit of the material is exceeded and subsequent transfer of movement would take place to weaker horizons. In field examples, Burchfiel et al (1982) have shown localisation of thrust ramps in competent dolostone layers in southern Nevada rather than the underlying weaker rocks. Eisenstadt & De Paor (1987), while accepting the initial nucleation of thrust ramps in comptent members argued that the flats develop in incompetent members as a result of fault tip line migration both up-and down section from multiple source ramps.

Here dynamic models for the interactive development of ramp-flat thrust styles are presented. The models assume initial nucleation of a thrust ramp in a competent brittle member (simply by inducing a ramp in the initial model design) and study the subsequent ramp-flat accommodation after the material has acquired ductile properties, in flowing environments (most probably caused by changes in temperature and pressure conditions or mineral transformations subsequent to faulting). Alternatively, the ramps could be simple old planes of weakness without implying any cause for their origin. In such situations slip along fault surfaces may take place simultaneoulsly as flow and folding accumulates in the surroundings, controlled by the rheological stratification. Such faults in ductile environments are known as stretching faults (e.g. Means, 1989).

Figure 1, a to e shows various ramp/flat accommodation styles encountered in the earth that might reflect ductile accommodation, ranging from fault bend folding to overthrusts emanating from ductile decollements to wedge faults.

In the sections below a number of dynamic models for the interrelationships between fold and fault geometries are presented and discussed.

The Experimental Models

Model set-up , purpose and procedure

The models were intended to address two questions: 1) What is the scale effect of ramp-flat thrust accommodation,

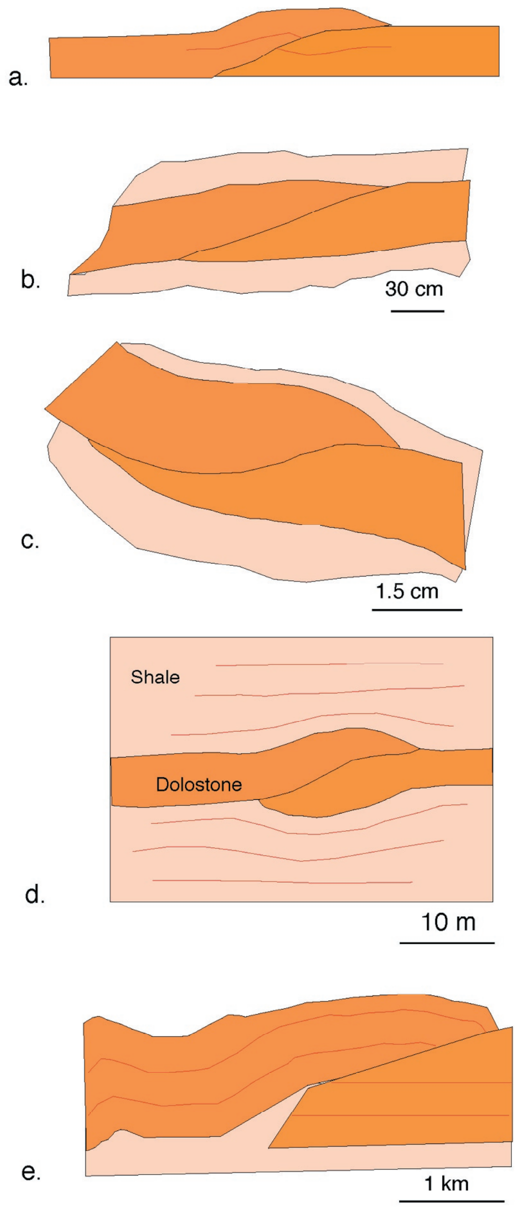


Figure 1. Ramp-flat accommodation styles in relatively competent layers: a) Geometric fault bend fold model (e.g. Suppe, 1983). b) and c) in a sandstone layer in the Bloomsburg formation, W Virginia, U.S.A (modified from Cloos, 1961). d) in Kimmeridge Bay (Ramsay, 1992). e) Mt.Terry anticline (Suter, 1981).

and 2) How does ramp-flat accommodation progress in flowing environments. The models were prompted by the need to explore other alternative solutions of fault-fold interaction than the concept of Rich (1934) of stair-case thrust propagation which has dominated the geological literature. Because, the focus here is on the mechanics of ramp/flat accommodation subsequent to faulting in flowing environments, ramps with a 30º inclination angle (with respect to the maximum stress) were first induced in competent single layers and it is modelled here how these layers accommodate slip in ductile surroundings. A 30º inclination for the ramp was chosen because ramps usually develop at this angle in frictional plastic materials). The models were end-loaded in a centrifuge spinning at 800 *g* (Fig. 2). This level of acceleration was chosen to scale strength for gravity (see discussions later) and hence prevent gaps from developing while slip accumulated along the ramp sufaces.

The models represent layered materials arranged in different stratigraphic successions, with nearly initial constant thickness/width ratio (≈0.2) of the hangingwall blocks (Figs. 4 to 8). In a first arrangement the scale effect of ramp-flat accommodation was investigated by deforming models under normal gravity, and alternatively in a centrifuge (Fig. 4a). In a second set-up (Fig. 5a), a competent layer with an induced ramp and overlain by ductile strata of various competence was detached above a rigid base. In a third arrangement (Fig. 6a) the competent block was detached above ductile layers of various competence. This set-up was intended to study the geometry of ramp-flat accommodation emanating from ductile decollements. In a fourth set-up the plastilina hangingwall-footwall pairs were embedded in ductile strata of various competence (Fig. 7a). All models were deformed in plane strain in the transport direction. In the tests a rigid base lubricated with liquid soap provided a through-going decollement.

Materials

Plastilina simulated the behaviour of competent sedimentary rocks such as sandstones and limestones. Stress-strain curves for plastilina show strain-hardening plastic behaviour (Fig. 3a), at the confining pressures used in the centrifuge (0-2 MPa). The yield strength of plastilina increased with confining pressure in the range $\approx 10^4$-10^5 Pa. Creep viscosities after yielding varied in the range 10^7-10^8 Pa s, depending on strain rate. This material has the appropriate stress and strain-dependent rheological properties to simulate the deformation of sedimentary rocks at deeper levels in the crust (e.g. Hoshino et al., 1972).

Two bouncing putties were used to represent the matrix materials. In one, DC-3179 bouncing putty (Hailemariam & Mulugeta, 1998) was mixed with sand to represent a relatively stiff matrix (hardened putty, 1 in Figs. 3 b and c). In the other, the same material was softened by admixing with aolic acid (softened putty, 2 in Figs. 3 b and c). These simulate ductile strata of various competence in nature, such as evaporites and shales. At room temperature and strain rate in the range 8×10^{-3} to 1.6×10^{-2} s^{-1}, the viscosity of the DC 3179 sand mixture varied in the range $\eta \approx (1.7\text{-}3.3)\times10^5$ Pa s with a power-law exponent ($n \approx 1.2$). For the same strain rate range the viscosity of the softened DC mixture varied in the range $\eta \approx 3\times10^{3.5\pm0.5}$ Pa s with a power-law exponent ($n \approx 2$). Thus, both matrix materials show strain-rate softening behaviour (Fig. 3c).

Scaling

Dynamic modelling of ramp-flat accommodation in a centrifuge required scaling of strength for gravity. This was necessary because strength is a fundamental property at shallow levels in the lithosphere. A major problem in

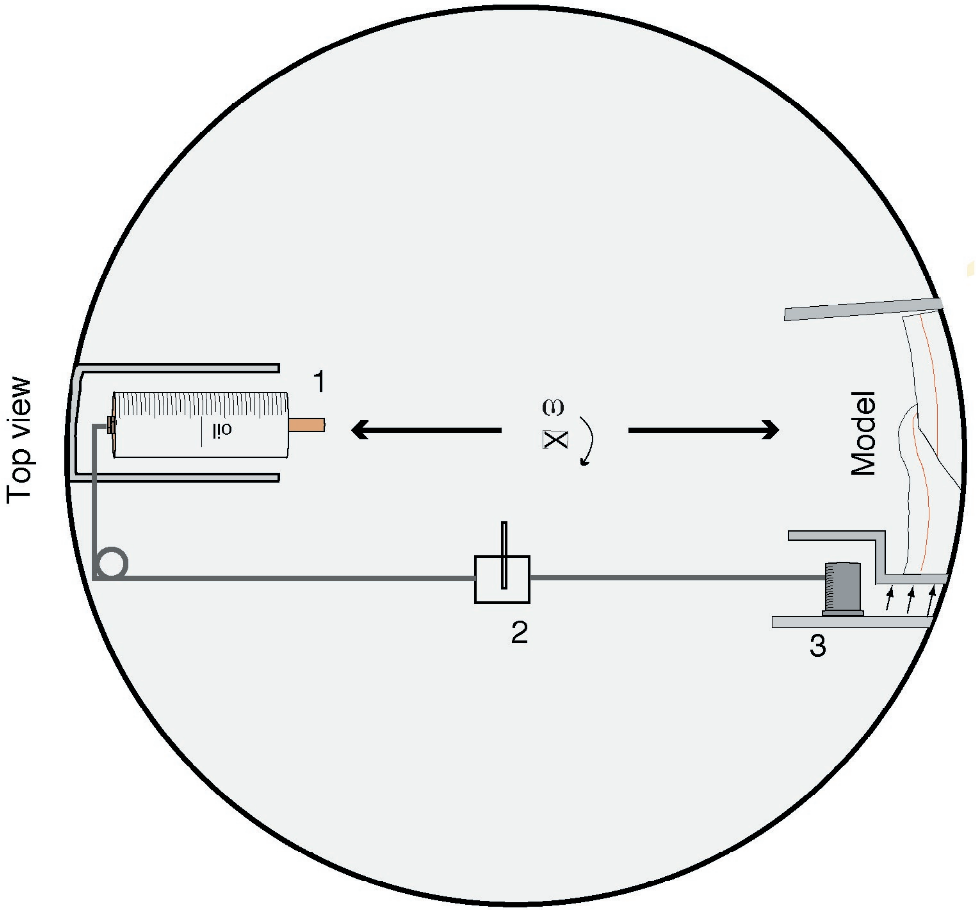


Figure 2. Diagrammatic representation (not to scale) of top view of a hydraulic squeeze-box used to deform models in a centrifuge. 1. Hydraulic cylinder. 2. Magnetic valve used to switch on and off the compression. 3.Telescopic cylinders pushing the rear wall of a squeeze-box.

scale-modelling under normal gravity is the requirement for model materials to be of extremely low-strength such as cohesionless sand, to mimic the deformation which takes place at a big-scale in nature. However, this restriction on model materials imposed by scaling can be overcome by deforming models in a centrifuge (e.g. Hubbert, 1937; Ramberg, 1981). Here, a hydraulic squeeze-box operating in a centrifuge (Mulugeta, 1988) was used to study various ramp-flat accommodation styles in rheologically stratified model systems (Figs. 4 to 7).

For a general 2-dimensional system, and neglecting inertia, the local stress equilibrium equation may be written as equation 1a.

$$d\sigma_{ij}/dx_j + \rho g_i = 0 \qquad \textbf{(1a)}$$

The various quantities in eq. 1a may be written in a non-dimensional form (where primes denote non-dimensionalisation) as scale model ratios (eq. 1b).

$$\sigma_r/x_r\rho_r g_r(d\sigma'_{ij}/dx_j) + \rho'(g_i) = 0 \qquad \textbf{(1b)}$$

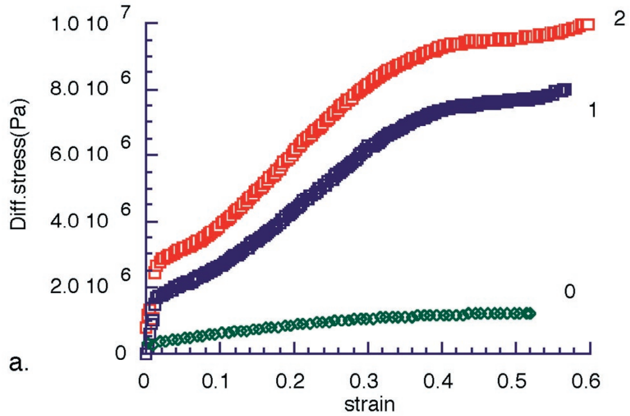
where $x_r = (x_j)_m/(x_j)_n$, $\rho_r = \rho_m/\rho_n$; $g_r = g_m/g_n$; $\sigma_r = (\sigma_{ij})_m/(\sigma_{ij})_n$ are scale ratios of length, density, acceleration and stress, respectively. The subscripts n and m denote nature and model, respectively and i,j are cartesian components.

The first term on the left-hand side of eq. 1b expresses the balance between strength and gravity induced stresses. Dynamic similitude is satisfied in case this ratio remains invariant in model and prototype. Moreover, the value which this dimensionless stress ratio acquires determines the style of ramp-flat accommodation. For example, when this ratio is much bigger than one; or $\sigma_r/x_r\rho_r g_r >> 1$, gravity plays no or little role in hangingwall accommodation. In the reverse case, when $\sigma_r/x_r\rho_r g_r << 1$ gravity dominates the style of hangingwall accommodation. In case $\sigma_r/x_r\rho_r g_r \approx 1$, there is a near balance between yield stress and gravity stress.

If the value of the dimensionless strength to gravity induced stress ratio is the same in nature as in experiments; $x_r = \sigma_r/\rho_r g_r$. If in a model an acceleration of N times gravity is applied then the acceleration ratio $g_r = N$, the scale factor for linear dimensions is then (eq.1c):

$$x_r = \sigma_r/\rho_r N \qquad \textbf{(1c)}$$

In the centrifuge tests (e.g. Fig. 4c) scaling based on eq. 1c amounted to 1cm:0.5km, i.e using N= 800 and a yield strength of 10 M Pa for the prototype rocks e.g.



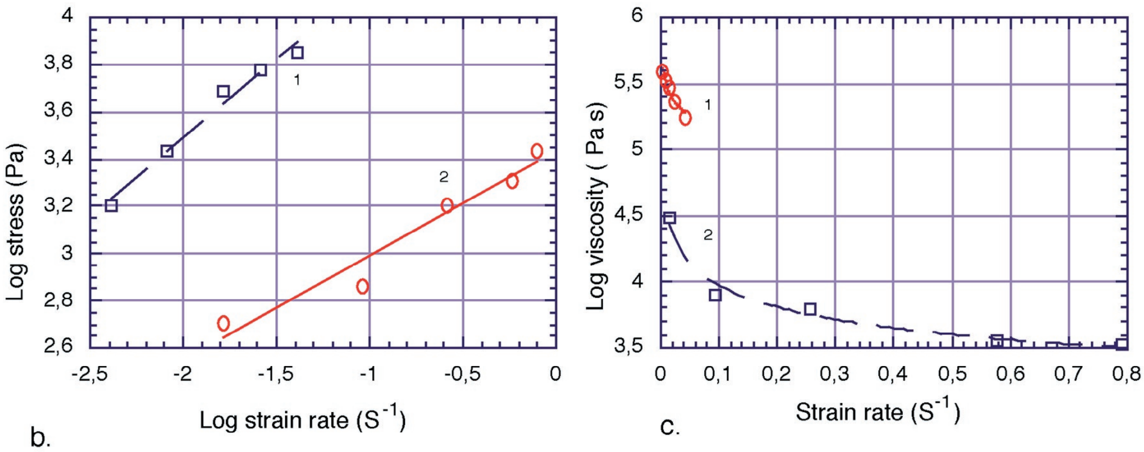


Figure 3. a) Stress-strain behaviour of plastilina at different confining pressures (0, 1 and 2 in MPa, respectively). b) Stress-strain rate behaviour of hardened (1), and softened (2) DC 3179 dilatant compound, used to simulate the incompetent surroundings in nature. c) Viscosity versus strain rate curves showing the strain rate softening behaviour of the incompetent surroundings.

sandstone, limestone in nature (e.g. Hoshino et al., 1972) and an average prototype density for sediments (e.g. sandstones, limestones) of 2.4 gm/cm^3. For the model material (plastilina, Fig. 3a), a yield strength of 10^5 Pa and a density of 1.7 gm/cm^3 was used. However, it must be realised that the scaling discussed above is approximate as the yield strength of both rocks and the model materials vary depending on strain and confining pressure. In the section below a number of dynamic models simulating ramp-flat accomodation styles are illustrated and discussed.

Experimental Results

The experimental models exhibited a wide spectrum of ramp/ flat thrust accommodation styles mainly controlled by scale-effects and the rheological stratification, as discussed below.

The scale effect of ramp-flat accommodation

In a first model (Fig. 4a) a single plastilina block with induced ramp was detached from a rigid base to simulate the scale effect and rheological control of ramp-flat thrust accommodation. This was done simply by end-loading models with similar initial set-up but under different g-values i.e. under normal gravity and alternatively in a centrifuge (cf. Figs.4 b & c). In the model end-loaded under normal gravity, because strength was not properly scaled for gravity, the hangingwall block translated forward without bending and unbending to the form of the footwall. As a result void spaces developed during translation above fault bends.

By comparison in the centrifuged model (Fig. 4c), the special geometric features of ductile fault bend folding developed from the necessity of making geometric adjustments in the hanging wall to conform to the shape of the underlying flat-ramp-flat footwall. This required a yield stress of the hanging wall blocks in near balance with the gravity stress. In this particular model, because the footwall was deformable a footwall synform developed in response to the load imposed by the advancing hanging wall.

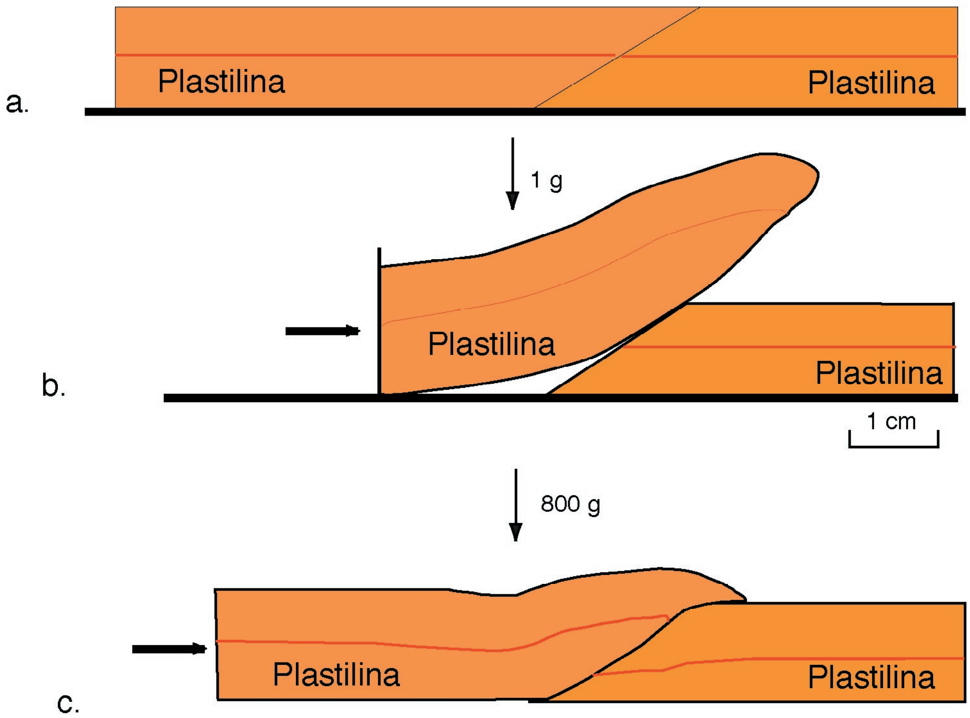


Figure 4. a) Initial set-up of a single plastilina layer detached above a rigid base. b) and c) represent deformed models under normal gravity and in a centrifuge, respectively.

Ramp-flat accommodation in a competent layer beneath ductile strata

Figures 5 and 6 show various 2-layer models which show how the initial ramps changed shape while slip accumulated along the flat and ramp sector, mainly controlled by the rheological stratification. In a first arrangement (Fig. 5a) the plastilina material, overlain by a soft (Fig. 5b) or stiff (Fig. 5c) non-Newtonian viscous material was detached above a rigid base. Slip along the rigid base and along the ramp caused the competent plastilina hangingwall to be driven into the overlying, less competent layer. The soft overburden material thinned above the ramp anticline and thickened in the area surrounding the anticline (Fig. 5b). In this model, because the base was rigid there was a physical continuity between the ramp and the flat gliding horizon, movement was accommdated in the manner of fault bend folding. Moreover, the load imposed by the advancing hangingwall created a footwall syncline.

By comparison, when the competent plastina layer was overlain by stiff ductile strata (Fig. 5c), the overthrust was small compared to the total shortening of the stratigraphic package. The stiff overburden material acted as a more or less rigid lid hindering forwards displacement along the ramp surface. In consequence the initial ramp became modified to a listric shape with deformation. In these two-layer models isostatic adjustment was not aided by a density instability because the overlying materials were less dense than the hangingwall/footwall plastilina blocks.

Ramp-flat accommodation above ductile substrates

In other rheologically stratified two-layer models (Fig. 6a), the same materials as the previous tests (Fig. 5) were used, except that the hangingwall/footwall plastilina blocks rested on ductile layers of various competence. In these models, as compared to the previous ones (Fig. 5 b and c) there was no direct physical continuity between the ramp surface and the flat basal decollement. When the hangingwall/footwall plastilina blocks overthrusted a weak viscous substratum (Fig. 6b), the soft material was mobile enough to get injected into the ramp during forwards transport of the hangingwall. In addition, forward transport of the hangingwall downflexed the footwall which created a shallower ramp along which movement of the hangingwall could easily be accommodated. In these models adjustment of the plastilina hangingwall/footwall blocks took place in the presence of buoyancy forces. The original 30^{o} ramp became rotated to near horizontal position during translation of the hangingwall above the footwall. Such a two-layer model where a soft substratum layer is transported from synclines to anticlinal core as the upper competent layer ramps up is supported by geological data. For example, salt and evaporite-cored anticlines beneath developing ramps are well known in the Appalachian plateau (e.g. Wiltschko and Chapple, 1977) and in the Jura (e.g. Suter, 1981; Jordan & Noack, 1992).

By comparison when the competent material was underlain by a stiff ductile layer (Fig 6c), the initial straight ramp became wedge-shaped with deformation. In addition, the overthrusting hangingwall accumulated

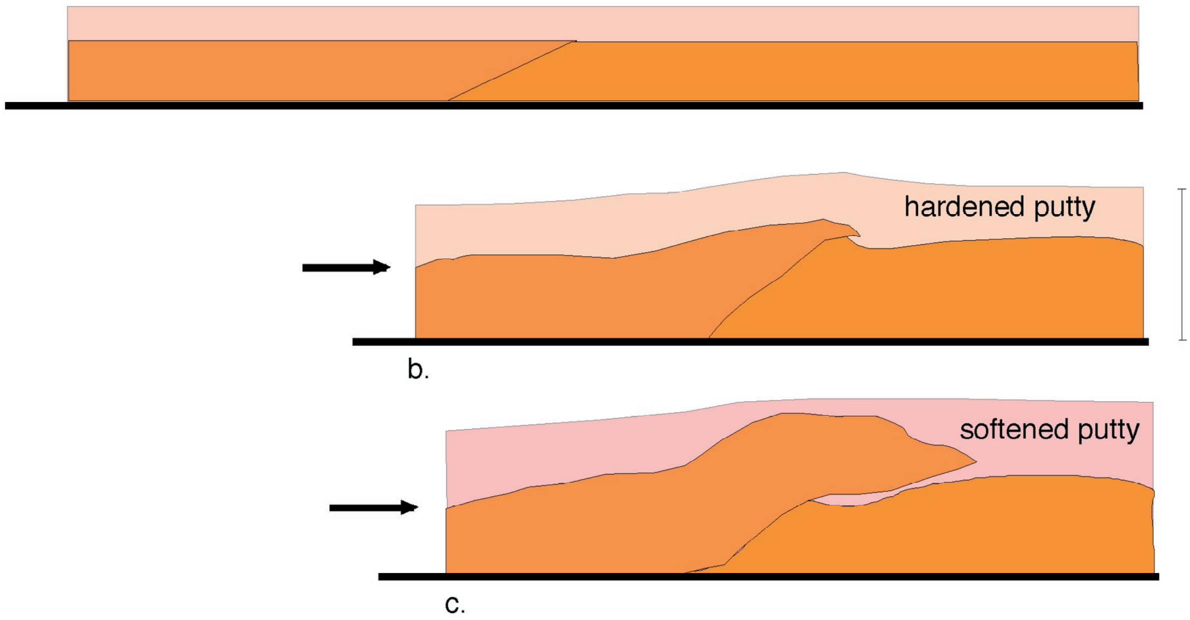


Figure 5. a) Initial set-up of two-layer models detached above a rigid base, while overlain by soft, respectively stiff ductile strata. b) and c) represent the deformed models.

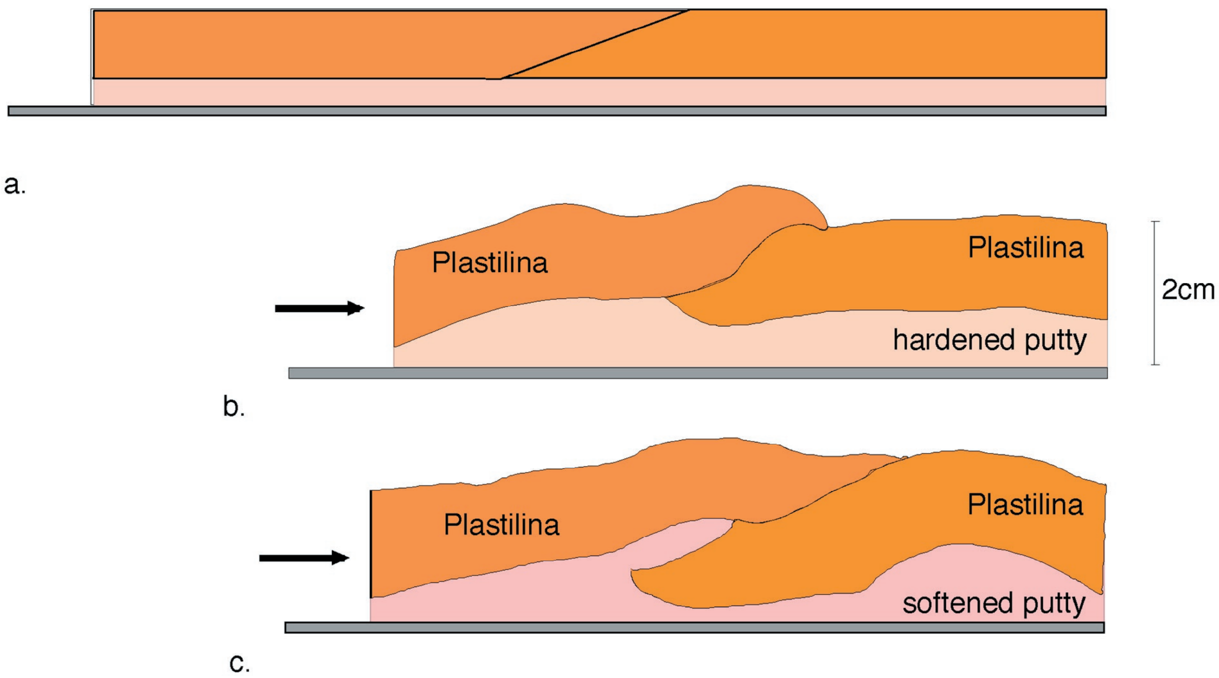


Figure 6. as in 5 except that the deformed models are underlain by ductile strata.

higher layer parallel shortening strain as compared to the previous model, with no or little penetration of the ductile substratum beneath the ramp. The wedge fault geometry seems to require low stiffness contrast between the competent ramping layer and the surroundings.

Ramp-flat accommodation in embedded ductile strata

Figures 7a-c illustrate a three-layer stratigraphic arrangement where the plastilia single layer is sandwiched between ductile units of various competence. The greater the contrast in stiffness, the higher the tendency for the sandwiched competent member to develop buckle folds rather than migrate forward in ramp-flat thrust style (Fig. 7b). In other words, the induced ramp had little or no effect in guiding the subsequent development of the overall structure. Rather, the competent layer buckled and the adjacent soft matrix merely responded to the deflecting stiff layer by offering an overall resistance to its deflection

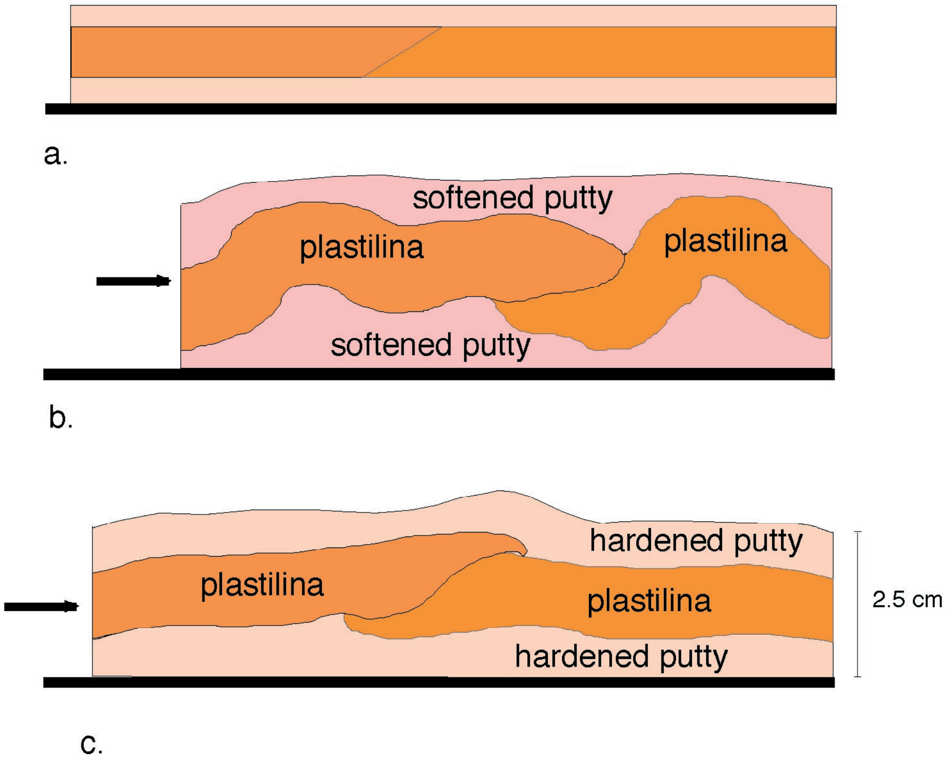


Figure 7. a) Initial set-up of three-layer models where the competent single layer is sandwiched between soft (b) and stiff (c) ductile strata.

(Fig. 7b). Wavelength selection of the stiff member was largely a function of the thickness ratio and viscosity contrast between the stiff member and the softer matrix. The soft matrix thickened beneath growing antiforms and thinned beneath synforms, controlled by the folding instability of the competent plastilina member.

In contrast, the matrix materials was stiff, possessing yield strength. This provided reduced stiffness contrast with the competent embedded member, the initial straight ramp changed shape to a wedge fault, where a footwall synform mirrored the hangingwall antiform (Fig. 7c), in the manner suggested by Ramsay (1992) for the Kimmeridge model. The slip-dependent stretching along the fault surface most likely determined the overall geometry of the wedge fault (Fig. 7c).

Discussion

Since the early days of geology it has been well-known that thrusts may develop from pre-existing folds, by shearing out of middle limbs of antiform-synform pairs (Heim, 1921; Willis, 1890). Such a folding preceeding faulting sequence has been simulated in centrifuge experiments by Dixon and Liu (1992). In contrast, Buxtorf (1915) showed how low-angle reverse faulting could produce drag folds. Chamberlain and Miller (1918) simulated in laboratory experiments initial nucleation of thrust ramps in plaster models of varying competence, followed by failure parallel to bedding.

Here, centrifuge experiments are used to simulate various ramp-flat accommodation styles which occur in deeper levels of the crust, where flow may progress simultaneously as slip accumulates along fault surfaces. In this environment flow and faulting are independent and interactive and not sequential processes, where the one results from the other. The conception is that of discrete faults in flowing environments which change length while slip accumulates in the slip direction, in the manner discussed by Means (1989). It is this aspect of ramp-flat accommodation which the models simulate.

It is well known from previous experiments that a rock subjected to compressive loading in the laboratory, at low temperature and pressure fails by shear failure when the strength limit is exceeded. Invariably, these faults are oriented at angles of ≈ 30º with respect to the maxium compression direction (e.g. Paterson, 1978). However, as pressure and/or temperature are increased or pore pressure or strain rate are lowered strain localisation by shear failure may give way to stretching faults (Means 1989), and ultimately to ductile flow (Heard, 1976). This means ramp-flat accommodation in changing environments, spanning from the brittle to the ductile field. However, most existing geometric models assume parallel behaviour where faults do not change shape and where folds in the hangingwall are inferred to form by layer parallel slip and angular kinking (e.g. Suppe, 1983). These assumptions may not be valid in particular situations where flow is involved with faulting. Evidence from structures formed in experiments and nature invariably suggest that aspects of the interactive development of ramps-flat geometries may involve ductile material response when and if enviromental conditions change.

In the tests under discussion, ramp-flat accommodation exhibited different styles, ranging from ductile fault bend folding in single competent layers (Fig. 4c) to wedge faults in rheologically stratified strata (Figs. 6c and 7c). In these models ductile deformation progressed simultaneously as slip accumulated along the thrust surfaces.

Ductile fault bend folding

In the models fault bend folds with smooth fold shapes developed only in cases where decoupling and overthrusting of the plastilina hangingwall block progressed above surfaces of reduced frictional resistance. However, this geometry developed when there was a near balance between the yield stress and gravity stress ($\sigma/\rho gh \approx 1$, cf. Fig. 4a & b). Under particular boundary conditions, the geometry of ductile fault bend folding (Figs. 4c and 5c) is very similar to the classic fault bend fold model (e.g. Suppe, 1983) except for the accumulation of ductile strain and change of fault shape during forward transport. In the classic fault bend fold model the range of fold geometries which can be produced is a simple function of fault shape and finite displacement. By comparison, in the material models both the hangingwall and footwall pairs, as well as the surroundings accumulated ductile strain (by layer thickening or thinning) in the range 10-25 %, simultaneously as slip accumulated along the fault surfaces. Moreover, the shapes of the hangingwall anticlines have rounded forms which confirm better to a contact strain model than a kink model (Ramsay, 1992). In the models footwall synclines also developed in case the load imposed by the overthrusting hangingwall blocks exceeded the yield limit of materials, even in situations where deflection of the footwall into the substratum was constrained by a rigid base (e.g. Fig. 4). However, the form of footwall synclines differ depending on the strength contrast between the layers. In the classic fault bend fold model, folds are only developed in the hangingwall of the structure, with the footwall remaining inert.

Wedge faults

The experimental results discussed above suggest that the observed sigmoidal shape of wedge faults not only require brittle failure and subsequent movement on that ramp (Cloos, 1961) but also a ductile accommodation response. The geometry of wedge faults observed in experiments is in very good accord with that observed at kimmeridge (Ramsay, 1983).

The experiments addressed the geometry of ductile ramp-flat accomodation in flowing environments. However, it remains a challenge to identify and distinguish the whole sequence of ramp-flat accommodation, spanning from the brittle to the ductile field, in changing environments, controlled by the rheological stratification.

Conclusions

This paper attempted to discuss some of the geometric features of ductile ramp-flat accommodation in terms of mechanical behviour of model materials. The models show that the geometry of ramp-flat thrust accommodation in ductile environments clearly differ from the classical fault bend fold model (Suppe, 1983). Some of these differences include involvement of layer shortening, formation of wedge faults and footwall synforms. Based on the results of the model experiments, the following conclusions seem warranted.

1) Ramp-flat accommodation in a single competent plastilina layer detached above a rigid base was by ductile fault bend folding;

2) When the competent plastilina layer was underlain or sandwiched between stiff ductile strata (exhibiting an order of magnitude contrast in strength and viscosity) the initial ramp adjusted to a wedge fault where the footwall synforms mirrored that of the hangingwall antiforms. Such models are analogous to the kimmeridge model of thrust accommodation;

3) Ramp-flat accommodation above soft viscous substrata resulted in the weak material being injected into the ramp during overthrusting.

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