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A footwall system of faults associated with a foreland thrust in Montana

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Abstract—Some recent structural geology models of faulting have promoted the idea of a rigid footwall behaviour or response under the main thrust fault, especially for fault ramps or fault-bend folds. However, a very well-exposed thrust fault in the Montana fold and thrust belt shows an intricate but well-ordered system of subsidiary minor faults in the footwall position with respect to the main thrust fault plane. Considerable shortening has occurred off the main fault in this footwall collapse zone and the distribution and style of the minor faults accord well with published patterns of aftershock foci associated with thrust faults.

In detail, there appear to be geometrically self-similar fault systems from metre length down to a few centimetres. The smallest sets show both slip and dilation. The slickensides show essentially two-dimensional displacements, and three slip systems were operative—one parallel to the bedding, and two conjugate and symmetric about the bedding (acute angle of 45–50°). A reconstruction using physical analogue models suggests one possible model for the evolution and sequencing of slip of the thrust fault system.

INTRODUCTION

THERE are several approaches that have been used to elucidate the structure and kinematic evolution of a thrust fault system. They include geometric modelling, kinematic modelling, detailed field studies, section balancing (forward and backward modelling) and seismicity distribution studies.

Several recent papers point out a very important field observation that a considerable amount of deformation occurs off the main thrust fault in a contractional deformation (e.g. Holm *et al.* 1988, Protzman & Mitra 1990). This is in contrast to the first-generation geometric and kinematic models of thrusting which set up models with a rigid footwall (e.g. Suppe 1983). Second-generation models now admit to both hangingwall and footwall deformation at ramps on thrust faults (Kilsdonk & Fletcher 1989).

This paper compares a very well-exposed field example of a thrust fault system with a recent study of the distribution of aftershocks associated with movement on a thrust fault. Then, using the field data as a basic geometric constraint, a simple physical model analogue is set up to show a possible kinematic evolution of such a system.

Field example

The thrust fault system is exposed in the riverbank of the Sun River in the Sawtooth mountains of NW Montana (Fig. 1), an area where the regional geology is well known and has been mapped by Mudge (1972). A section of Cretaceous Taft Hill shales, siltstones and sandstones is particularly well exposed on the north bank of the river in the foothills below the Diversion dam (Mudge 1972, Johnson 1988, Watkinson & Weberg 1991). Detailed mapping by Johnson (1988) shows a series of horse structures and westward-dipping, climbing thrusts in the alternating shale and sandstone beds. Figure 2(a) shows one such thrust, the lower portion of which is particularly well-exposed. The thrust climbs through a well-bedded sandstone unit into the overlying shales. Associated with the main fault is a series of smaller faults that occur predominantly, but not exclusively, in the footwall of the thrust. The visible faults in the sandstone unit were field mapped, and the trend and plunge of the slip vector and sense of movement on all the exposed fault planes were recorded. Oriented samples were collected of the fault blocks between the visible faults in order to make oriented, large (7.5 × 5 cm) thin sections to check for microscopic and other possible faults not directly observed in outcrop. Because the faulted section of the unit could be compared with an adjacent, apparently unfaulted portion, an accurate restoration of the unit is possible. The structures were mapped onto previously taken profile photographs. Two former graduate students, Erik Weberg and Sarah Koerber, and myself made independent maps of the outcrop, then synthesized a final copy from the three independent versions. In this way, we feel we produced a representation of the actual geology present that was as accurate as possible.

The overall network of faults in the footwall region of the main fault has a trellis-like appearance (Fig. 2b). The fault blocks between the trellis network of faults are generally rhomb-shaped. The dimensions of the rhombs are typically a half a metre to a metre, with some smaller subsidiary ones mappable. Most of the faults are planar, although some of the lower ones curve into the lower bounding fault of the collapse zone. Three orientations with respect to the bedding planes are prevalent—one is bedding-parallel, the other two are conjugate in geometry about the bedding plane, with an angle of 45–50° between them. The slip surfaces of the faults show polish, stepping and grooving, but no obvious shear or extensional fibres. The sense of movement on the fault surfaces, where it could be determined, was that expected for a thrust system, i.e. the flat-lying and W-

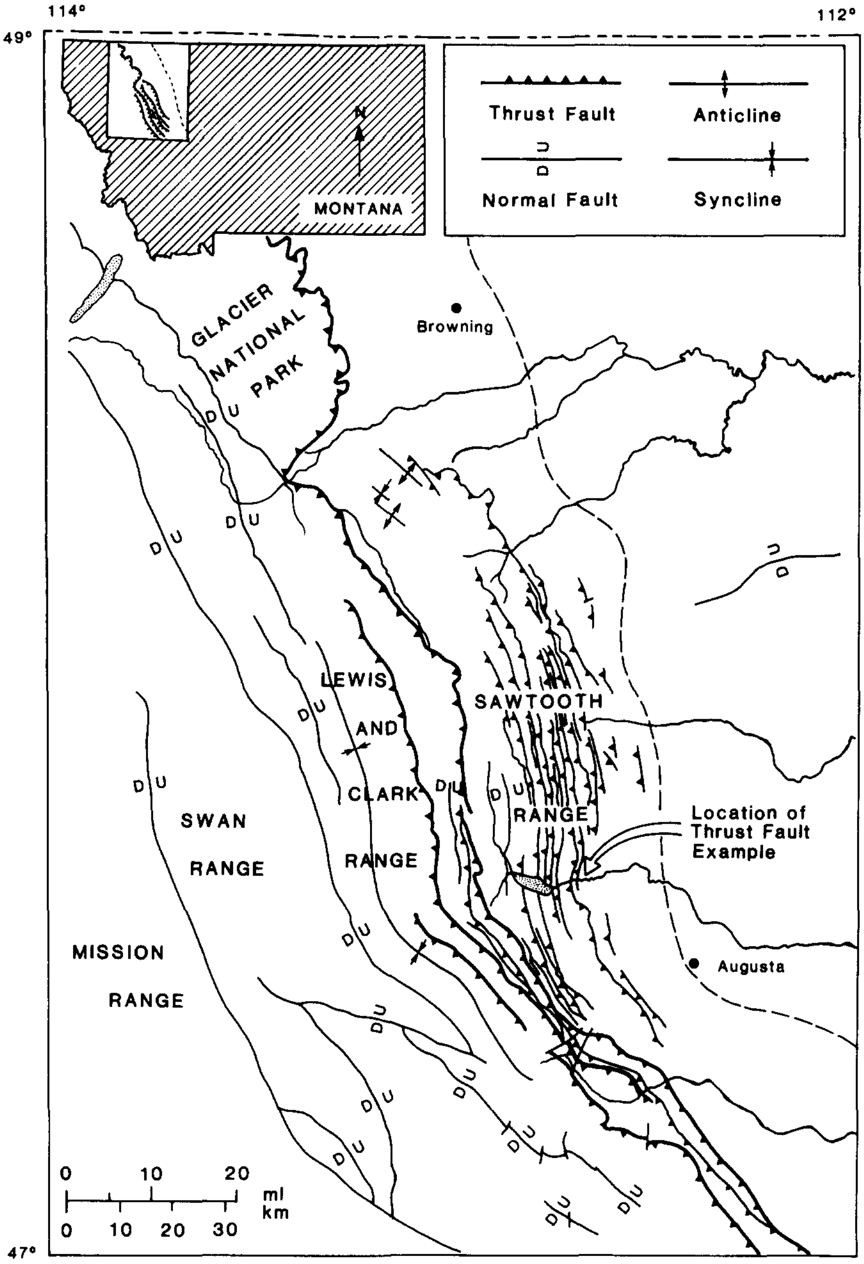

Fig. 1. Regional map of northcentral Montana, modified from Mudge (1972), with major structural features shown. The location of the field example of the thrust fault system is shown.

dipping faults gave a top-to-the-east, reverse motion, while the E-dipping surfaces gave a top-to-the-west sense of motion. The slickensides are essentially in the profile plane and therefore the movement is essentially in two-dimensional plane strain (see also Johnson 1988).

Fault sets can be seen in thin section with the same orientations as those mapped in the field (Fig. 2c). The displacements are <1 mm, and some of the microfaults show dilation and are filled with calcite fibres. No subset is observed within these, the smallest sets, and no microfracturing of grains was observed. It appears that these are the small end of geometrically self-similar sets of faults, with the smallest sets showing clear evidence of slip and dilation. There is no obvious visible control on the size of the faults, such as bedding unit thickness, or rock type. Whether larger sets occur in the region is not obvious, although individual examples of large faults are observed with the same relative orientation to bedding, that is bedding-plane 'flat' faults, E-dipping 'back'-faults and W-dipping 'forward' faults, but it is not clear that they occur in a trellis-like network.

While it was not possible to everywhere see the bedding plane trace within the fault blocks, the general impression was that there was little obvious rotation of bedding directly connected to rotation of fault 'blocks'.

Comparison with the aftershock distribution data

There are several recently published examples of the analysis of minor shocks associated with a main seismic event (e.g. King & Yielding 1984). One of the most detailed analyses of aftershocks associated with a major

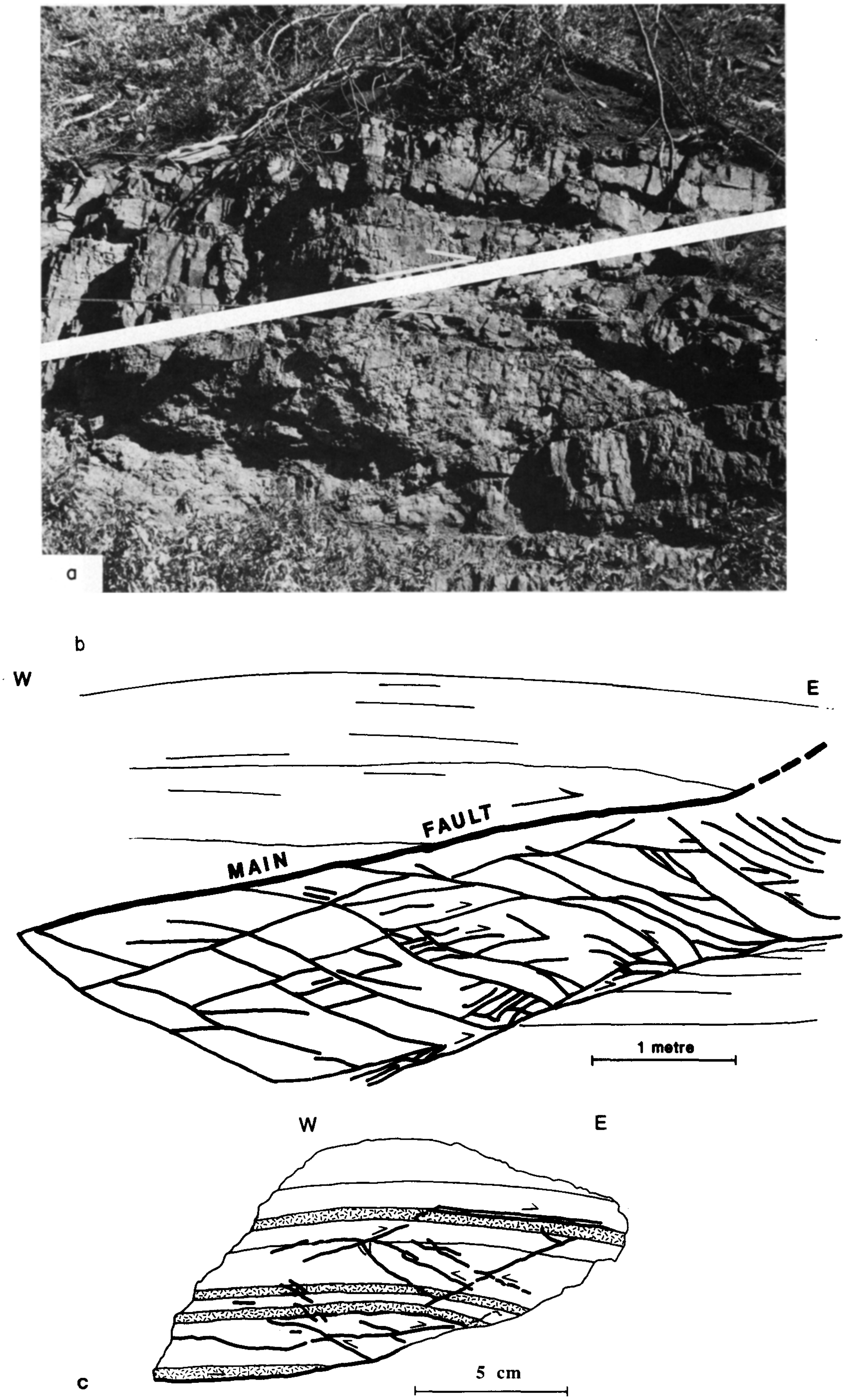

Fig. 2. (a) Profile photograph of the field example. The main fault is outlined. (b) Mappable faults in the field. The major fault is emphasized. (c) Oriented hand sample with the smallest set of faults, along with the bedding trace (stippled), verified by thin section.

Fig. 4. (a) The field example of the fault system, with a displacement of 2 m on the main fault. (b) The block model retrodeformed. Note the few gaps (dark areas) or overhangs. About 26% shortening is restored. The middle section (maroon) undergoes predominantly a normal, dip-slip sense of movement during the extension. Note the predominant lack of block rotation.

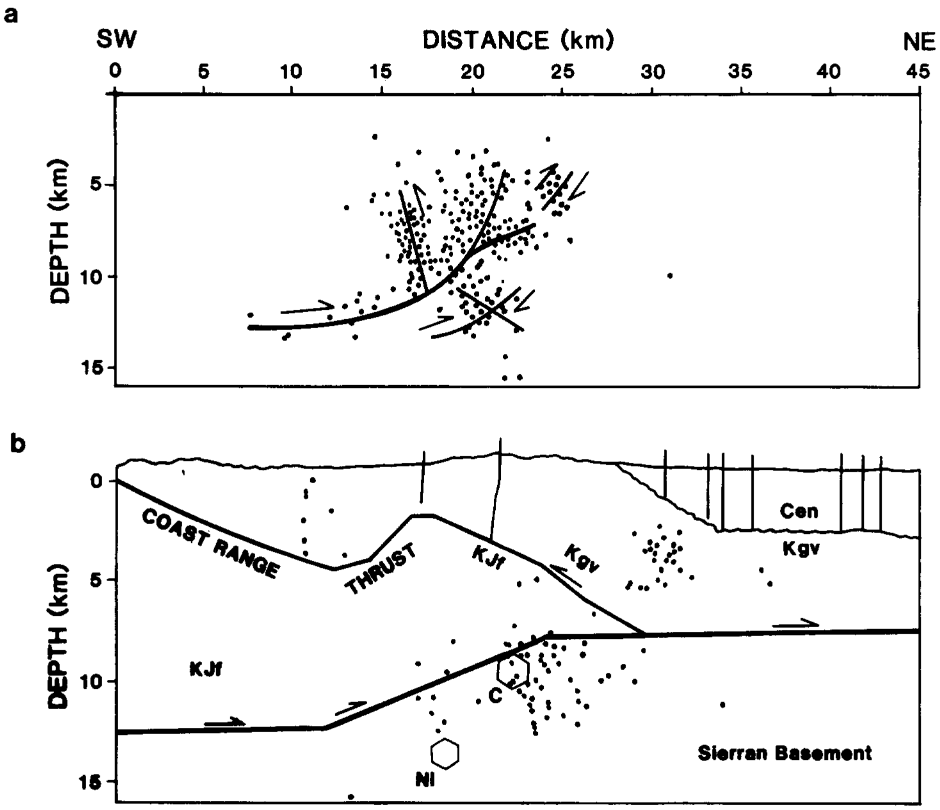

Fig. 3. Eberhart-Phillip's (1989) analysis of the Coalinga thrust in California. The figures are simplified versions of her original figures, (a) is abstracted from her fig. 15(b), and (b) is from her fig. 17 (reprinted with permission), where she superposes Namson & Davis's (1988) balanced cross-section on the seismicity distribution model, interpolated along the same cross-section. Aftershocks within 10 km are projected onto the section, as well as the Coalinga main shock (large hexagon), located 16 km southeast, and the 1982 M5.4 New Idria main shock (smaller hexagon), located 4 km northwest. Heavy vertical lines show well control used for the balanced cross-section. The cross-section from Namson & Davis (1988) shows the Cainozoic (Cen), Great Valley (Kgv) and Franciscan (Kjf) rocks; the heavy line is a primary ramp thrust.

shock on a thrust fault is that by Eberhart-Phillips (1989). Allowing the possibility of some problem of accuracy of location of all the foci, there appears to be a pattern to the aftershock locations, which presumably represent motion on minor faults as a response to the main fault motion. The total pattern appears to reflect the bulk strain adjustment of the system. The striking feature is the amount of adjustment off the main fault, both in the footwall and hanging wall, and that there does appear to be some conjugate nature to the slip system present (Fig. 3).

While obviously the distribution of slip will be in part determined by the detailed local geology, the main pattern of distribution appears to be very comparable to the fault system at the Sun River Canyon example, particularly in the footwall. However, one very interesting question presents itself, and that is, for any one main movement event, how many of all of the faults present adjust? This raises a more general point. Given a distribution of 'fossil' slip systems, what can we tell about the slip sequencing on such a system? Is it simultaneous or not? Are the geometric criteria observed in the fault system adequate to determine relative age and sequencing? What will be the difference between the historical slip and the active slip associated with a main earthquake event?

Physical model 'analogue'

As a starting point to investigate those questions, a simple-minded physical 'analogue' experiment was carried out. Using the field map for the geometric information, blocks of modelling clay were cut out to the same shapes and relative dimensions as the mapped fault blocks. This did not include the smaller subsidiary faults, nor any of the sets observed in the thin sections. The blocks were lubricated with Vaseline, then assembled to construct the mapped example. The assembled mosaic was then retrodeformed by placing it in a lightly confined press (see the Appendix) to restore the faulted layering to its original thickness (Fig. 4b). The aim was to observe the sequence of slip between the blocks, to see how effective the fault system was in achieving a bulk change in shape, to see how many gaps would be created and finally to see how much internal deformation of the fault blocks was required to avoid gaps or overlap. One assumption of the procedure is that all those faults simulated were present throughout the total shortening history, i.e. that no major new faults would have formed during the deformation. This assumption will be discussed later, as will another assumption that the sequencing of slip between the fault blocks that occurred during the palinspastic restoration is simply the reverse of the sequence that would have occurred during the contraction of the system. In a contracting model, an arbitrary decision would have had to be made as to when to cut the upper layers, i.e. at what stage would the 'main' fault have 'cut' through the upper layers, rather than achieving the shortening by folding?

Figure 4(b) shows the successive stages of restoration. The slip sequence of the fault blocks observed in the model is only one possible slip sequence on the observed system of faults—it remains unknown how probable it is that it was the same in the natural system. Because of the necessary assumptions and the simple nature of the method of restoration, it was not considered worthwhile to analyse in great detail the slip sequences between the blocks. However, three main features are worthy of comment. Firstly, the distribution of main slip is partitioned in three main domainal areas. During the restoration of the thickened zone, a central zone of predominantly forward normal slip occurred on the E-dipping faults (the maroon-coloured blocks in Fig. 4b). This zone is 'buffered' between two zones of predominantly back slip on W-dipping sets on either side.

Secondly, very little rotation of the fault 'blocks' occurred. Most of the extension occurred by back slip of the blocks down the forward sole fault against the buttress of the undeformed block (orange-coloured, on the east side in Fig. 4b). Lastly, very little internal deformation of the blocks occurred. One notable exception was a block (the first yellow one on the east side, Fig. 4b), which rotated and unfolded against the sole fault.

If one assumes that the shortening sequence is merely the reverse of the extending sequence, with reverse slip instead of normal slip occurring on the faults during contraction, this appears to be an effective way of achieving a bulk shortening of between 20 and 30% with very few gaps (the dark areas in Fig. 4b) or overhangs. Presumably, if this sequence does mimic the natural example, the gaps and overhangs would be accommodated by movement on the subset of small displacement faults, by minor dilation on the minor faults (observed in the natural example), by comminution of the overhangs by the main bounding fault (a zone of fault gauge is observed along this fault) and, finally, by localized folding of fault blocks and/or bedding.

The model also suggests that folding could have been a precursor to the main thrust fault, a suggestion that is born out by an adjacent structure that appears to be a lower amplitude version of the example modelled, without a developed main fault. Hayes (1891), Willis (1894) and Chamberlin & Miller (1918), have all made this suggestion previously—that a fold is often a precursor of a fault. Model analogue work by Willis (1894) and Blay *et al.* (1977), for example, demonstrated the process. In current terminology, structural geologists would refer to this sequence as an 'out-of-fold fault', or 'fault propagation fold' (Suppe 1985).

Discussion and comparison with other model analogue work

Most of the modelling of thrust systems assumes an initial starting geometry to the faults and generates a sequence that involves foreland propagation of horses to create a duplex style (e.g. Mitra & Boyer 1986). They do not in general allow for, or address the generation of, associated minor faults. Wojtal (1986) has given a detailed field description and strain analysis of minor faulting associated with the hanging walls of some Appalachian thrusts, but did not address footwall faults.

An advantage of the clay or sand-box method of fault modelling is that it is possible to start with an unfaulted medium with the faults initiating in the progressive deformation (e.g. Oertel 1965, McClay & Ellis 1987, Reches 1988, Gapais *et al.* 1991). Reches modelled the initiation and propagation of faults in a clay medium in pure shear. The Gapais *et al.* (1991) paper illustrates the initiation of faults in an isotropic sand medium in bulk strain conditions ranging from coaxial strain to simple shear. These authors' models were also in bulk plane strain and, since my field example appears to be very close to two-dimensional slip, they form a good basis for comparison.

One of the most striking features of the experiment is the way the systems tend to partition the dominant slip from conjugate systems into regimes or domains, but domains that are ephemeral and spatially transitory in terms of active slip. Another important observation is that "arrays of conjugate faults start to develop after about 10% uniform strain and accommodate most of the subsequent deformation" (Gapais *et al.* 1991). If that observation were to be true in many natural situations, then the assumption made earlier that the array of the major faults mapped represents the main faults that were present throughout the deformation would be reasonable. Both Reches (1988) and Gapais *et al.* (1991) demonstrated that some secondary faults did form throughout the progressive deformation. The geometric relationship between these and the main faults was not always distinctive enough to tell from geometric criteria alone which were the oldest or youngest, i.e. cross-cutting criteria should be used with care.

A final point of comparison with the sand-box models is that the faults in the sand-box experiments typically initiated in conjugate sets in accordance with the Coulomb criterion (acute angle between sets of about 60°). The angle between the sets generally increases with progressive deformation, especially in simple shear, in contrast to the pure shear experiments (Gapais *et al.* 1991, p. 149). In our field example, the angles are typically 45–50°, which have also been observed in clay experiments (Reches 1988), in contrast to the sand-box experiments. It may well be that the existence of the third slip plane parallel to the bedding constituted an element of planar anisotropy and as such affected the original conjugate angles, as well as the cohesion properties.

While it is not possible in the natural example to everywhere see the original bedding trace to observe the exact amount of rotation of the bedding by fault block rotation, it appears to be low. It turns out that the rotation or not of the bedding-plane trace is one of the best pieces of information or constraints on the restoration. It would be interesting to generate analogue models with a bedding plane slip component.

As Gapais *et al.* (1991, p. 154) point out it is difficult to assess the bulk kinematic strain field, i.e. how much simple shear vs pure shear, from the fault geometries alone. Overall, the fault system I have mapped appears to have a fairly high symmetry—generally orthorhombic and a general lack of block rotation. As such, this suggests a predominantly pure shear bulk shortening, with very little effect of 'drag' by the main fault on the geometry of the footwall minor faults.

I believe that it is because of the overall symmetry of the system and general lack of block rotation that the restoration appears to be reasonable and successful. If the faults were less symmetric about the bedding and/or block rotation was more, then a bulk pure shear restoration might not be effective—different boundary conditions would be required and the assumption of reversibility of sequences inappropriate. This would make it far less tractable.

CONCLUSIONS

By combining and synthesizing information gathered from several different sources of data, it is possible to model an evolution of a system of thrust faults accommodating a considerable amount of horizontal shortening. Domainal slip systems appear to be an effective method of achieving bulk shortening off the main fault. In this particular field example most of the off-the-main fault deformation is in the footwall and appears very similar to a recent seismic example.

While there are obviously some limitations and shortcomings to analogue simulation by palinspastically restoring a field-based block model, it does demonstrate in a general way the feasibility of achieving bulk strains by discrete slip between blocks, demonstrate the importance of slip partitioning and sequencing in domains and makes another basis for comparison with clay and sandbox models.

This well-exposed example demonstrates the self-similar nature of the fault system over at least a certain size domain. The lack of obvious physical controls on the size distribution of the faults suggests that the distribution may be predominantly dictated by kinematic constraints (cf. King 1983, Gapais *et al.* 1991). This field example provides a good example for comparison with models that have been proposed to explain earthquake magnitudes, '*b*' values and total fault budgets (King 1983, Scholz & Cowie 1990, Marrett & Allmendinger 1991, Walsh & Watterson 1992).

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APPENDIX

Experimental procedure

Using the field map (Fig. 2b) as a pattern, 3 cm thick blocks were cut out of Plasticine modelling clay of the same shape and relative size as the natural fault blocks. They were lubricated with Vaseline and the whole mosaic assembled. The different colours of clay were selected purely to add contrast to the model, to make it easier to observe the offset between the blocks. The assembled mosaic was then encased in a softer modelling clay to create a rectangular block, with a layer of soft clay below as well as above the fault mosaic. The whole rectangular block was placed in a plane strain press, with the underside of the block lubricated with talcum powder. The model was then shortened in a direction perpendicular to the layering, with concomitant plane-strain extension of the layering. The sides of the block were confined by the rigid sides of the press, maintaining a plane-strain, no area change configuration.