Journal of Structural Geology, Vol. 15, No. 6, pp. 805 to 808, 1993
Printed in Great Britain

0191-8141/93 $06.00+0.00

Brevia

SHORT NOTE

A kinematic model for the origin of footwall synclines

MARK A. MCNAUGHT* and GAUTAM MITRA

Department of Geological Sciences, University of Rochester, Rochester, NY 14627, U.S.A.

(*Received* 16 *April* 1992; *accepted in revised form* 4 *November* 1992)

Abstract—The origin of footwall synclines at the base of thrust ramps can be related to the kinematic evolution of fault-propagation folds. The conventional fault-propagation fold model does not predict the development of footwall synclines because it assumes a high propagation to slip ratio for development of the lower flat which does not allow for folding before the thrust cuts up section. An alternative model, where the propagation to slip ratio remains finite throughout the development of the fault-propagation fold, produces a detachment fold at the thrust tip during propagation of the thrust along the lower flat. If the thrust cuts up through the ductile core of the detachment fold during ramp formation, it will leave behind the forelimb of the detachment fold as part of a footwall syncline.

INTRODUCTION

EVEN though footwall synclines are a commonly observed structure below thrust ramps, their origin is problematic in terms of existing models of folding related to thrusting. These models restrict folding to the hanging wall of thrust faults, leaving the footwall undeformed, with no syncline developed below the fault. The failure of these models to account for the development of footwall synclines reflects an incomplete understanding of the evolution of thrust belt structures. A better understanding of thrust belt structures may be obtained by considering a simple kinematic evolution, such as the approach of Mitra (1990).

Traditionally footwall synclines are thought to originate as drag folds. The force a moving thrust sheet exerts on strata underlying a ramp causes the strata to rotate toward the transport direction. As a mechanically driven process drag cannot be accounted for in geometric models, but drag folds do present geometric problems during section restoration. During drag the oldest bed cut by the thrust ramp is pulled away from the youngest bed below the ramp, causing a space problem (Fig. 1a); accommodating structures are required to fill the void at the base of the ramp. Such accommodating structures are difficult to explain in the simple kinematic evolution assumed for most models.

More recently footwall synclines have been related to fault-propagation folds (FPF). In classic FPF models (Suppe & Medwedeff 1984, Jamison 1987) the thrust propagates through the undeformed foreland so no footwall syncline is developed (Fig. 1b); without modification these models cannot explain the development of footwall synclines. Suppe (1985) suggested one possible modification: a footwall syncline can develop when a FPF locks and the thrust cuts up through the forelimb of the fold leaving the lower part of the forelimb behind as a footwall syncline. However, the axial plane of this type of syncline does not extend down to the base of the ramp. The syncline is restricted to the part of the section above the fault tip line at the time of fold lockup. While this mode of formation may be important for some footwall synclines, it does not explain those synclines that involve the lowest layers cut by the thrust ramp.

ALTERNATIVE EXPLANATION

An alternate mechanism can be suggested for the origin of footwall synclines by considering a simple kinematic development of folds at the tip of a thrust fault. Deformation that occurs at the tip of a fault accommodates the transition from the slipped region above the fault to the unslipped region in front of the fault (Williams & Chapman 1983). When the ratio of fault propagation to fault slip is high, little deformation is needed at the tip of the fault because the small amount of slip can easily be accommodated on the relatively long fault. When the ratio of propagation to slip is low, more deformation is needed to accommodate the larger displacement gradient.

The type of fault-related fold that develops is determined by the ratio of fault propagation rate to fault slip rate (PR/SR). Ideal fault bend folds form on faults where the PR/SR ratio is high as seen in fault bend fold models where the fault is completely developed before the first increment of slip. The long length of the fault before slip occurs requires that the propagation rate must have been much greater than the slip rate. The only folds that develop are related to bends in the fault

*Present address: Department of Earth Resources, Colorado State University, Fort Collins, CO 80523, U.S.A.

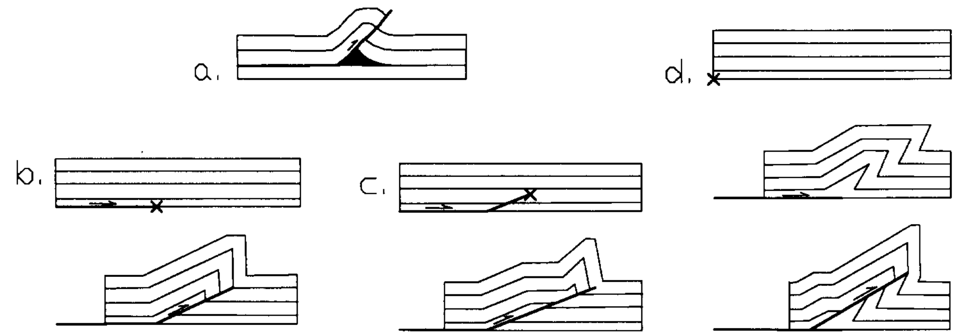

Fig. 1. (a) Folding of footwall due to drag of overriding thrust sheet. Hatched area is void that develops at base of ramp. (b) Evolution of a conventional fault-propagation fold (after Jamison 1987). (c) Evolution of a fault-propagation fold above a 'pre-existing' ramp (after Chester & Chester 1990). (d) Evolution of a fault-propagation fold producing a footwall syncline. X marks point where the fault begins to propagate with a finite propagation to slip ratio and the fold begins to grow.

trajectory; there is no folding to accommodate slip at the fault tip.

Fault-propagation folds develop on faults where the PR/SR ratio is lower. The fold develops to accommodate the decrease in slip at the fault tip. Conventional FPF models (Jamison 1987) assume that growth of the fold begins when the thrust starts to propagate up the ramp (Fig. 1b). For the tip of the fault to reach the base of the ramp, however, it must have previously propagated along the lower flat. Since beds remain undeformed before the fault begins to propagate up the ramp, the thrust must have had a high PR/SR ratio when propagating along the lower flat. The PR/SR ratio then decreased when the thrust cut up section forming the FPF.

An alternative suggestion for FPF geometry has been made by Chester & Chester (1990). They explain the geometry of some FPFs by having the fold start to grow when the fault propagates past a point that is above the lower flat (Fig. 1c). In this case also, in order to reach this point without any deformation in the sedimentary section, the thrust must have propagated across the lower flat and part way up the ramp with a high PR/SR ratio. Once this point is reached the fault continues to propagate up section with a lower PR/SR ratio, allowing folding to occur at the fault tip.

Like the conventional FPF model, the model of Chester & Chester (1990)does not produce a syncline in the foot wall. It does however illustrate that the geometry of a FPF is altered depending on where changes in the PR/SR ratio occur. As an alternative to these two FPF models, we can consider a model where the PR/SR ratio remains low throughout the structural evolution (Fig. 1d). As the fault 'starts' to propagate along the flat at the hinterland edge of the section a detachment fold will develop in the hanging wall to accommodate the slip at the fault tip. The presence of detachment folds at the core of fault propagation folds (Mitra 1990) and the truncation of detachment folds in a duplex (Homza & Wallace 1991) have been described from other areas. Once the detachment fold has developed the thrust can take advantage of the thickened weak basal layer as a place to cut up section. This leaves behind the forelimb of the detachment fold as a footwall syncline (Fig. 1d).

The translated detachment fold model of Mitra (1990) is similar to the model presented above. The major difference is that in Mitra's model translation does not alter the hanging wall geometry, suggesting that the fault on which translation occurs has a higher PR/SR ratio than the fault on which the detachment fold grew. This is in fact the reverse of the traditional FPF model where the propagation to slip ratio is high along the lower flat and is low along the ramp. In our model the geometry of the early detachment fold is altered as the fault propagates up section because the propagation to slip ratio remains low throughout the evolution of the structure.

EXAMPLE

An example of this type of structure can be seen in the South Eden Canyon (SEC) area of northern Utah (McNaught 1990). This area is located along the trace of the Meade thrust, one of the major thrusts of the Idaho–Wyoming–Utah segment of the North American Sevier thrust belt. Deformed Mesozoic strata are here exposed where the valley has cut through the Tertiary conglomerate that unconformably overlies the Mesozoic section.

The Laketown (Meade) thrust places overturned Paleozoic and Mesozoic strata on a footwall flat in the Jurassic in the area around South Eden Canyon (Fig. 2a). Jurassic strata above this flat are folded by the emplacement of the thrust. The flat is, in turn, folded above the younger Sheep Creek anticline.

East of the Sheep Creek anticline is an E-verging overturned syncline in the Jurassic Twin Creek Formation (Fig. 2a). Between the W-dipping limb of the overturned syncline and the E-dipping limb of the upright Sheep Creek anticline is an unusually thick section of the lowermost member (Jtgs) of the Twin Creek Formation. This thickened section represents a detachment between the younger Twin Creek Formation (in the hanging wall) and the older Nugget Sandstone (in the footwall).

The interpreted evolution of this area is illustrated in Fig. 2(b). Initially a detachment fold developed above the Meade thrust as it propagated along a footwall flat at the base of the Twin Creek Formation. Later the thrust cut up into the ductile core of the fold and through the forelimb forming a footwall syncline. This syncline was then rotated due to the formation of the Sheep Creek anticline to give rise to the present configuration seen in the SEC area.

DISCUSSION

The kinematic model presented here offers a straightforward explanation for the development of footwall synclines at the base of thrust ramps that is not available in conventional geometric models.

The fault PR/SR ratio is fundamental to all fault related fold models. By changing the point where the thrust 'starts' to propagate or by having later translation of a fold, different PR/SR ratio histories are being assumed. Geometrically the model presented here is more complicated than the conventional FPF model, but it is kinematically simpler since the PR/SR ratio is held constant. Conventional FPF models require a more complicated kinematic history because the PR/SR ratio must change at the flat–ramp transition.

The growth of a footwall syncline under a ramp can be explained by holding the PR/SR ratio constant, but this is just one end-member situation for developing a fault propagation fold. Likewise the conventional FPF model is another end-member situation that allows the PR/SR ratio to change abruptly at the flat–ramp transition. Real fault-propagation folds probably develop under conditions between these two extremes, where the PR/SR ratio at the flat–ramp transition changes, but remains finite.

The models presented here are only the first step in understanding the growth of fault propagation folds. They allow for only one change in the PR/SR ratio, and the change is only between 'fast' and 'slow'. Actual FPF geometries can be further complicated by spatial and temporal changes in the PR/SR ratio. For the simple model presented here it has also been assumed that all slip on the thrust has been accommodated at the tip. If other mechanisms accommodate slip, such as deformation within the thrust sheet itself, a more complicated FPF geometry might develop.

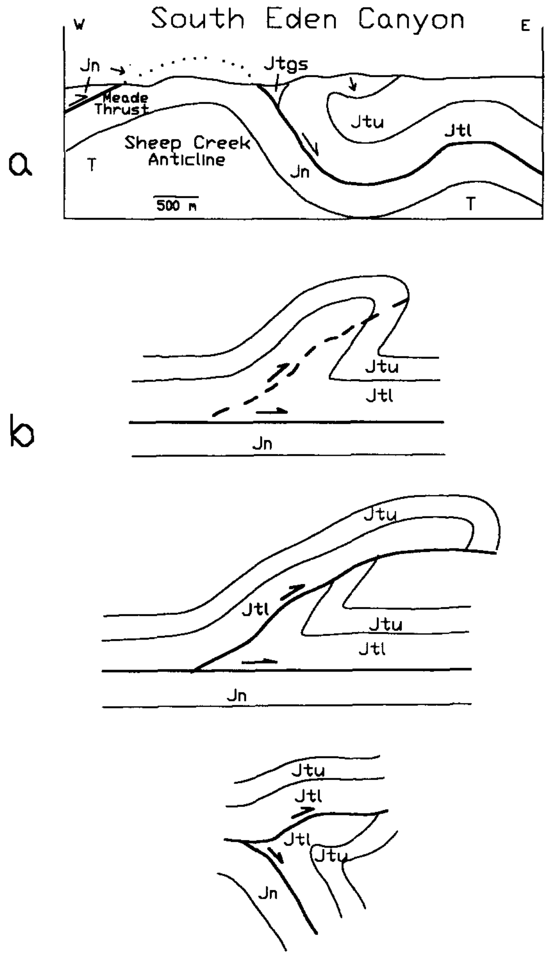

Fig. 2. (a) Cross-section across the South Eden Canyon area, Utah (T, Triassic; Jn, Nugget Sandstone, Jtgs, Gypsum Springs Member of the Twin Creek Formation; Jtl, lower Twin Creek Formation; Jtu, upper Twin Creek Formation). Half arrows indicate motion on detachment surface. Full arrows indicate younging direction on overturned beds. (b) Evolution of the South Eden Canyon area. Development of a detachment fold. Thrust ramps up through core of detachment fold leaving behind footwall syncline. Folding above the Sheep Creek anticline rotates footwall syncline.

CONCLUSIONS

(1) A footwall syncline developed at the base of a thrust ramp is part of detachment fold that accommodated slip at the thrust tip as it propagated along a flat. When the thrust cut up section it made use of the ductile core of the detachment fold leaving behind its forelimb as part of a footwall syncline.

(2) Conventional fault propagation fold models require that the thrust propagate instantaneously across the lower flat before changing to a finite propagation rate as it propagates up the ramp. Alternative FPF geometries, like those suggested in this paper, can be modeled by assuming different propagation rates and slip rates for the thrust during the development of the fold.

Acknowledgements—This research was supported by NSF grants EAR-8507039 and EAR-8916629 to G. Mitra and by a grant from Sigma Xi to M. McNaught. Comments by two anonymous reviewers helped improve this paper.

REFERENCES

Chester, J. S. & Chester, F. M. 1990. Fault-propagation folds above thrusts with constant dip. *J. Struct. Geol.* **12**, 903–910.

Jamison, W. R. 1987. Geometric analysis of fold development in overthrust terranes. *J. Struct. Geol.* **9**, 207–219.

Homza, T. X. & Wallace, W. K. 1991. A duplex formed by the thrust-truncation of detachment folds in the Arctic National Wildlife Refuge (ANWR), northeastern Alaska. *Geol. Soc. Am. Ann. Meeting Abs. w. Prog.* **23**, A423.

McNaught, M. A. 1990. The use of retrodeformable cross sections to constrain the geometry and interpret deformation of the Meade thrust sheet, southeastern Idaho and northern Utah. Unpublished Ph.D. thesis, University of Rochester, New York.

Mitra, S. 1990. Fault-propagation folds: geometry, kinematic evolution, and hydrocarbon traps. *Bull. Am. Ass. Petrol. Geol.* **74**, 921–945.

Suppe, J. 1985. *Principles of Structural Geology*. Prentice-Hall, Englewood Cliffs, New Jersey.

Suppe, J. & Medwedeff, D. A. 1984. Fault-propagation folding. *Geol. Soc. Am. Abs. w. Prog.* **16**, 670.

Williams, G. & Chapman, T. 1983. Strains developed in the hangingwalls of thrust due to their slip/propagation rate: a dislocation model. *J. Struct. Geol.* **5**, 563–571.