Journal of Structural Geology, Vol. 7, No. 6, pp. 759 to 762, 1985
Printed in Great Britain

0191-8141/85 $03.00 + 0.00

Strains developed in the hangingwalls of thrusts due to their slip/propagation rate: a dislocation model: reply

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(*Received* 29 *March* 1985)

Abstract—Folding related to the propagation of thrusts is common in thrust belts, including the Rocky Mountains. The rare development of such folds in the southern Rockies, due to lithological control, is a special case of the dislocation/ductile bead model, which, it is argued, is of general applicability.

WE THANK Drs Tippett, Jones and Frey for the interest they have shown in our paper (Williams & Chapman 1983) and welcome the opportunity to reply.

We agree that we used an out-dated interpretation of the Turner Valley Structure (Dahlstrom 1970) and we accept that fig. 2 of Tippett *et al.* (1985) incorporating a triangle zone, is a more likely interpretation of the structure (although this section is 13 km to the south of Dahlstrom's structure). We are left, however, with the inescapable conclusion that the revised interpretation (Tippett *et al.* 1985, fig. 2) exhibits a good example of a thrust with diminishing displacement towards its tip. We propose that the overturned fold in the hangingwall is a thrust-tip fold that grew in front of a propagating thrust (as in fig. 2b of Chapman & Williams 1984). The hangingwall of the main thrust in the Turner Valley Structure has accommodated an internal strain which is much greater than that in the footwall, and hence a ductile bead model (Boyer & Elliott 1982, Williams & Chapman 1983, Chapman & Williams 1984) can be used to account for this. In the case of the Turner Valley Structure this has only occurred in the tip region of the thrust.

We accept that in a hindward direction in the Palaeozoic carbonates, there has been little or no internal deformation, and the amount of slip is relatively constant. It is possible that lithology is a major controlling factor on the relationship between slip rate and fault propagation rate and therefore on internal strain.

We have sequentially restored (Fig. 1) the relevant part of the Gordy & Frey (1975) section after Bally *et al.* (1966). The only reasonable way to sequentially restore the section is to incorporate a tip fold growing in front of the propagating thrust. We have assumed a normal sequence of thrusting towards the foreland, but out of sequence thrusting will modify the restoration only slightly. Whilst the main thrust (Fig. 1) was within Palaeozoic carbonates there was little internal strain. When this thrust encountered a change in lithology, mainly to shales, the rate of propagation of the thrust dropped rapidly relative to the rate of slip. This could have been achieved by an actual slowing of thrust propagation whilst slip remained constant, or an increase in slip rate whilst thrust propagation remained constant. In reality, both slip and propagation rates are likely to vary with time. We still believe Dahlstrom (1970) was near the truth when he suggested that the Turner Valley thrust was propagating within a growing fold. We would accept the observations of Tippet *et al.* (1985) that in much of the southern part of the Canadian Rocky Mountain Foothills, thick, internally underformed 'slabs' of rock, notably Palaeozoic carbonates, are carried along thrusts, with relatively constant displacements. Clearly, these rocks have undergone little internal shortening and for slip to have continued, thrusts must have propagated rapidly as a mechanical necessity.

In contrast to the Palaeozoic carbonates, the overlying Mesozoic shales and sandstones show intense internal deformation. More importantly, in the northern Canadian Rocky Mountains hangingwall strains are common as described by Thompson (1981). Tippett *et al.* (1985) attribute this to a change in lithology, in particular the lack of thick Palaeozoic carbonates further north.

We find it difficult to understand the conclusion that our model (Williams & Chapman 1983) 'is not universally applicable' because as Tippett *et al.* (1985) have stated that hangingwall strain occurs in all parts of the Rocky Mountains thrust belt to a greater or lesser degree.

Several examples of thrust-tip folds (including two from the North American Cordillera) are represented on a displacement–distance graph in Fig. 2 (see Chapman & Williams 1984). We submit that a thrust-tip strain (or ductile bead) model is the norm and is universally applicable. Occasionally, possibly due to lithological control, little strain is imparted on the hangingwall rocks

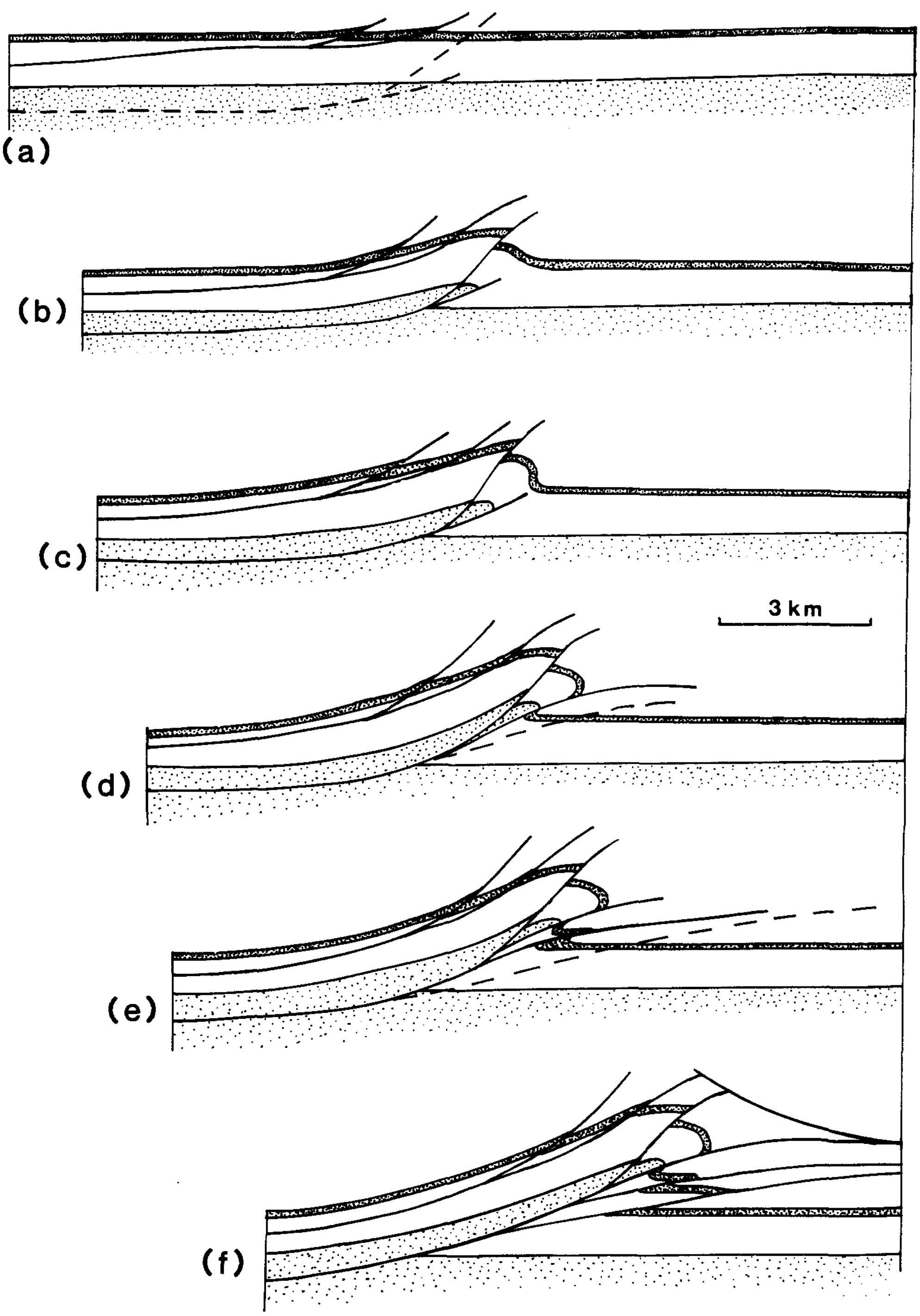

Fig. 1. Progressive development of the Turner Valley structure. The original section of Gordy & Frey (1975) after Bally *et al.* (1966) has been sequentially restored and a thrust-tip fold results. The model assumes a normal sequence of thrusting but if out-of-sequence thrusting is assumed it modifies the restoration only slightly.

and the thrust propagates rapidly (e.g. southern Rocky Mountain Foothills). Our model still applies, and the southern Rocky Mountains represent one end of the spectrum, where fault propagation is very fast relative to slip (Williams & Chapman 1983). The lithology of both the thrust sheet and detachment horizon may be one of the controlling factors on fault propagation rate. In Alpine terrains it has been known for many years that competent slabs of rock, such as Mesozoic carbonates, overlying easy-slip horizons such as evaporites or shales usually become detached as continuous, relatively undeformed sheets. We would also point out that buckle folding is not the only way to accommodate internal strain in the hangingwalls of thrusts, layer parallel-shortening may occur separately (e.g. Cooper *et al.* 1982) or may be superimposed on the folding.

In the Variscan foreland thrust belt of SW England, South Wales and Southern Ireland, folds related to the propagation of thrust tips abound, although ramp anticlines or fault bend folds also occur. Variation in the

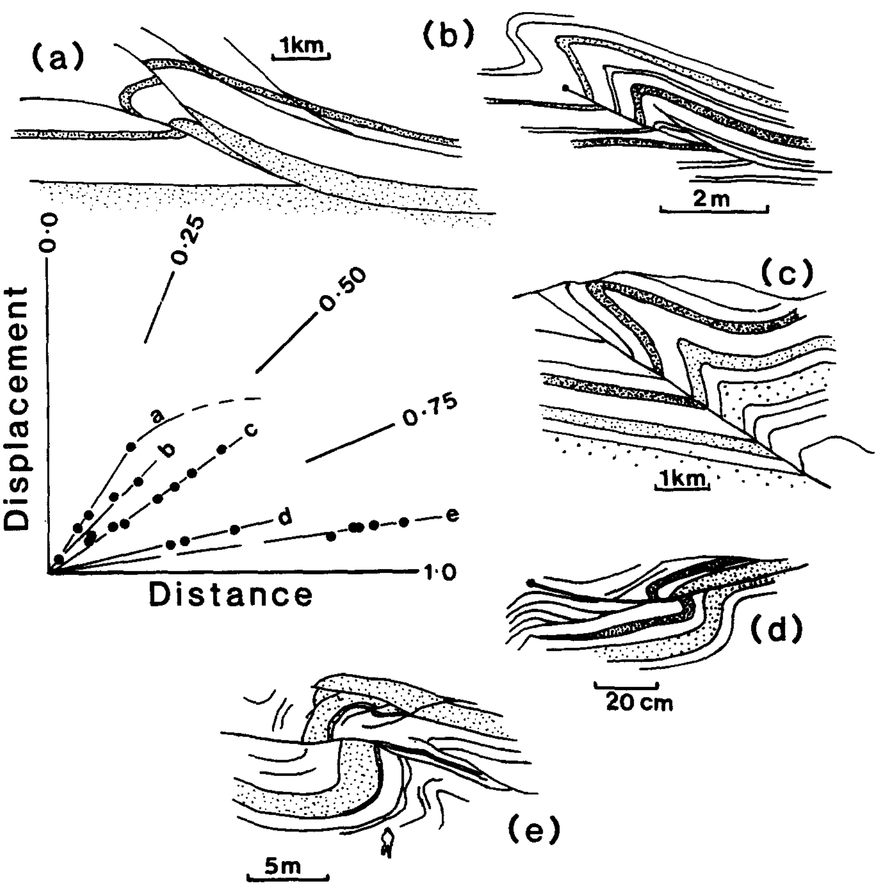

Fig. 2. Examples of thrust-tip related folds from the Variscan orogen of Britain and the Rocky Mountain thrust belt. (a) Turner Valley structure (after Gordy & Frey 1975) with the lower thrusts restored. (b) and (e) Carboniferous rocks at Broadhaven, Pembrokeshire, Wales (after Williams & Chapman 1983). (c) Structure of part of the Stewart Peak culmination in the Idaho–Wyoming thrust belt of the western U.S.A. (after Lageson 1984). (d) Small-scale fold-thrust structure in Devonian rocks from the east side of Plymouth Sound, England (after Chapman 1983). The variation in slip on each structure is plotted on a displacement–distance graph which shows values of relative stretch between hangingwall and footwall (after Chapman & Williams 1984).

displacements on individual thrusts is the rule, not the exception in this 200 km orogenic segment (e.g. Figs. 2b, d & e). We do not dispute the style of tectonics described by Tippett *et al.* (1985) but classify it as a special case of the ductile bead model, controlled in part by lithology. Using the ductile bead model, the summation of displacements referred to by Tippet *et al.* (1985) is still possible along a major detachment (see Chapman & Williams 1984).

Tippet *et al.* (1985) criticize our crystal dislocation analogy because strain in rocks is not totally elastic. In both crystals and rocks a strain is imparted as a dislocation moves through the body. Crystallographic strain is elastic and recoverable, whereas in a rock body both recoverable and permanent strain may be involved in the movement of a dislocation. In rocks this permanent strain can be recorded, by distance–displacement methods (Chapman & Williams 1984). Finally, we would draw attention to a recent paper by King & Stein (1984) describing surface folding above an active buried reverse fault, where seismic faulting at depth is accommodated at the surface by active folding with no visible fracturing. This is an example of active ductile bead folding.

REFERENCES

Bally, A. W., Gordy, P. L. & Stewart, G. A. 1966. Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains. *Bull. Can. Petrol. Geol.* **14**, 337–381.

Boyer, S. E. & Elliott, D. 1982. Thrust systems. *Bull. Am. Ass. Petrol. Geol.* **66**, 1196–1230.

Chapman, T. J. 1983. A guide to the structure of the Lower to Middle Devonian Staddon Grits and Jennycliff Slates on the east side of Plymouth Sound, Devon. *Proc. Ussher Soc.* **5**, 460–464.

Chapman, T. J. & Williams, G. D. 1984. Displacement–distance methods in the analysis of fold-thrust structures and linked-fault systems. *J. geol. Soc. Lond.* **141**, 121–128.

Cooper, M. N., Garton, M. R. & Hossack, J. R. 1982. Strain variation in the Henaux Basse Normandie Duplex, Northern France. *Tectonophysics* **88**, 321–324.

Dahlstrom, C. D. A. 1970. Structural geology in the eastern margin of the Canadian Rocky Mountains. *Bull. Can. Petrol. Geol.* **18**, 332–406.

Gordy, P. L. & Frey, F. R. 1975. Geological cross-sections and composite seismic reflection sections through the Foothills. In: *Structural Geology of the Foothills between Savanna Creek and Panther River, S.W. Alberta, Canada* (edited by Evers, H. J. & Thorpe, J. E.). Canadian Society of Petroleum Geologists–Canadian Society of Exploration Geophysics, Calgary.

King, G. & Stein, R. 1984. Surface folding, deformation rate, and earthquake repeat time in a reverse faulting environment. The 1983 Coalinga, California Earthquakes. *Spec. Publs Calif. Div. Mines Geol.* **66**, 61–69.

Lageson, D. R. 1984. Structural Geology at Stewart Peak Culmination, Idaho–Wyoming Thrust Belt. *Bull. Am. Ass. Petrol. Geol.* **68**, 401–416.

Thompson, R. I. 1981. The nature and significance of large 'blind' thrusts in the northern Rocky Mountains of Canada. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 449–462.

Tippett, C. R., Jones, P. B. & Frey, F. R. 1985. Strains developed in the hangingwalls of thrusts due to their propagation rate: a dislocation model: discussion. *J. Struct. Geol.* **7**, 755–758.

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