Journal of Structural Geology, Vol. 14, No. 6, pp. 749 to 751, 1992
Printed in Great Britain

0191-8141/92 $05.00+0.00

Differential transport and continuity of thrust sheets

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(*Received* 15 *October* 1991; *accepted in revised form* 8 *March* 1992)

Abstract—Structural geologists long have strived to establish basic tenets describing the interaction between thrust displacement and lateral extent of thrust sheets. Individual non-metamorphic thrust sheets can be partitioned into segments that exhibit linear variations in displacement along strike. The differential transport between endpoints of each segment define an along-strike bulk shear angle (Ψ), which describes the spatial rate of change in displacement along the length of the fault. Empirical measurements of differential transport angles for continuous thrust sheets from different North American fold–thrust belts yield bulk shear angles that do not exceed 35–40° without formation of tear faults. These values might thus be considered a limit for coherent behavior of continuous non-metamorphic thrust sheets, thereby providing constraints on three-dimensional interpretations of fold–thrust belts.

INTRODUCTION

Geologists working in faulted regions often encounter difficulties in delineating complex three-dimensional geometries of fault-related folds, especially through areas of poor data quality. Understanding how displacement may vary along the strike length of a fault provides one basis for constraining interpretations in these areas. The most commonly described relationship between displacement and fault strike length in fold–thrust belts is referred to as the 'Bow and Arrow rule' (Elliott 1976, see Walsh & Watterson 1989, and references therein for extensional relationships). This rule-of-thumb states that the maximum displacement vector of a thrust is the normal bisector of a straight line joining the thrust's two ends (Elliott 1976). Moreover, the magnitude of this vector is 7–12% of the length of this straight line (Elliott 1976, Tearpock & Bischke 1991).

Several thrust-belt workers (e.g. Dixon 1982, Wilson & Shumaker 1988, Tearpock & Bischke 1991, Wilkerson 1991, Wilkerson & Wellman in press) have recognized that differential transport within a single thrust sheet should vary considerably along strike, and that if displacement does change abruptly over a relatively small distance, then intervening transverse structures (e.g. tear faults or cross-strike discontinuities) must exist to accommodate the deformation. Tearpock & Bischke (1991) observed that the Bow and Arrow rule (Elliott 1976) to some extent describes how differential transport consistently varies along strike for single thrust sheets. The Bow and Arrow rule, although a reasonable generalization for entire thrust sheets, could significantly underestimate possible displacement variations between cross-sections over lesser distances (Wilkerson 1991, Wilkerson & Wellman in press). The purpose of this paper is to use interpretations from non-metamorphic fold–thrust belts in North America to document observed limits in the spatial rate of change of displacement along single thrusts. This work provides a framework within which three-dimensional interpretations of thrust sheets may be evaluated.

APPROACH

Displacement continuity along the length of a thrust fault can be described for individual non-metamorphic thrust sheets by partitioning the thrust fault into segments that exhibit linear variations in displacement along strike using either displacement–distance diagrams (e.g. Mitra 1988, fig. 20) or estimations from serial balanced cross-sections (e.g. Dixon 1982, Wilkerson 1991, Wilkerson & Wellman in press). Differences in transport may be measured in two adjacent cross-sections along any portion of the segment defined by the endpoints (Fig. 1). The differential transport between endpoints of each segment defines an along-strike bulk shear angle (Ψ; Sanderson 1982, Wilkerson 1991, Wilkerson *et al.* 1991, Wilkerson & Wellman in press). The angle Ψ is defined as the arctangent of the difference in displacement between the two cross-sections divided by the distance separating them (Fig. 1). To achieve a reproducible number, the displacement difference is always measured in the transport direction, and the separation distance is always measured perpendicular to the transport direction. This approach can *only* be applied to the same continuous thrust sheet on adjacent sections; that is, this technique is not valid if displacements are measured from different thrust sheets or if transverse structures exist between sections.

Using empirically measured values from balanced cross-sections through various North American fold–thrust belts (Dixon 1982, Mitra 1988, Evans 1989, Fermor 1990, Wilkerson 1991, Medwedeff in press, Wilkerson & Wellman in press), shortening–strike length diagrams were constructed to illustrate the limits of the spatial rate of change in displacement for single thrust

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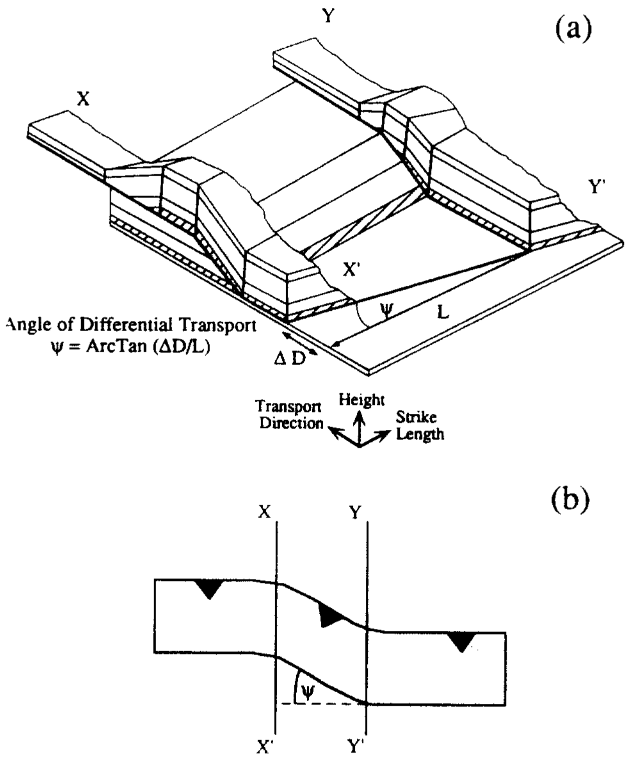

Fig. 1. Differential transport model consisting of (a) a three-dimensional perspective diagram with portions of the hanging wall cut away and (b) a map-view diagram. Ψ is the angle of differential transport, ΔD is differential displacement between adjacent sections measured in the transport direction, and L is the separation between cross-sections measured perpendicular to the transport direction.

sheets (Fig. 2). Lines showing specific angles of differential transport (Ψ) are superposed on Fig. 2 for comparison, including lines representing the range of differential transport (7–12%) predicted by the Bow and Arrow rule for entire thrust sheets. A considerable range in values of Ψ occur for the studied examples. Most data points plot above the predicted range for the Bow and Arrow rule and below $\Psi = 40°$, with the majority of these points less than $\Psi = 32$–$35°$. Data points that fall in the range between $\Psi = 35°$ and $40°$ coincide with sharp changes in fault trends indicative of oblique footwall ramps, suggesting that these structures permit more rapid changes in along-strike differential transport. For comparison, data points above the 40° line represent segments with known intervening tear faults.

DISCUSSION AND CONCLUSIONS

Continuous, non-metamorphic thrust sheets must attain a limiting value of bulk shear strain (represented by the shear angle Ψ), beyond which, the thrust sheet cannot maintain continuity and accommodates excess strain by imbricating the thrust sheet and developing through-going transverse structures (e.g. tear faults or cross-strike discontinuities). This limiting value of differential transport likely depends on lithology, strain rate, overburden, pore pressure, or a combination of these factors. A detailed individual database for specific fold–thrust belts might additionally constrain the range of differential transport or the factors influencing differential transport for thrust sheets in that particular fold–thrust belt. If, however, differential transport angles measured from the studied fold–thrust belts are representative of thin-skinned fold–thrust belts as a whole, then 35–40° may be the empirical maximum Ψ expected to occur in such terranes. Should interpretations of similar regions display abrupt changes in displacement indicative of angles of differential transport significantly larger that these values of bulk shear angle, then the region should be re-examined to determine if there is a reasonable geological explanation or if the sections themselves require modification.

A maximum Ψ of 35–40° not only is consistent with examples described in this paper, but also is corroborated by observations of upper limits of differential transport defined by measurements of strike-parallel extension of thrust sheets in external zones of the Alps (30°; Platt *et al.* 1989) and by measurements of the shear angle incurred prior to development of through-going faults in shear-box physical experiments (between 28° and 36°; Wilcox *et al.* 1973). The combined observations suggest that rocks at different scales can sustain a signifi-

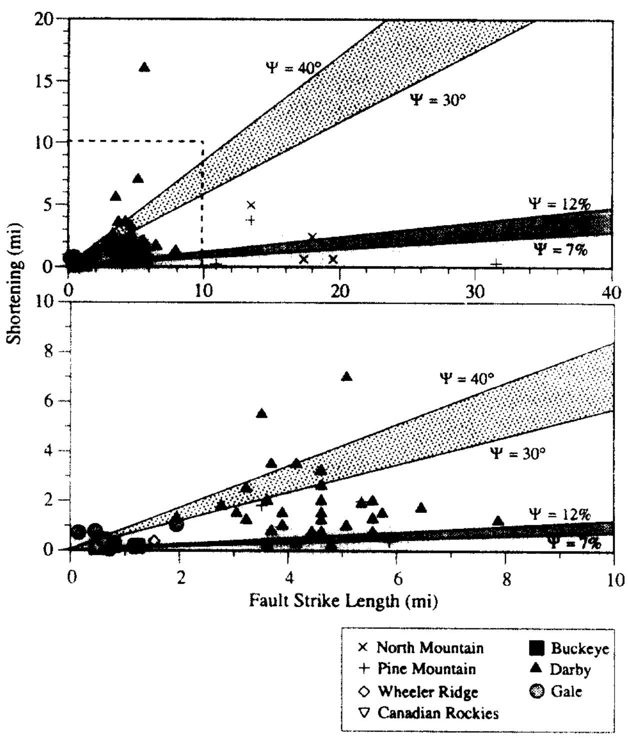

Fig. 2. Shortening–strike length diagram depicting limits of the spatial rate of change in displacement for single thrust sheets in North American fold–thrust belts (dashed box detailed in lower figure). Measurements are from the Ouachita fold–thrust belt, Oklahoma (sub-Choctaw thrusts; Wilkerson 1991, Wilkerson & Wellman in press); the Canadian fold–thrust belt (Fermor 1990); the Wyoming fold–thrust belt (Darby–Hogsback thrusts; Dixon 1982); the Transverse Ranges (Wheeler Ridge thrust; Medwedeff in press); the Southern Appalachian fold–thrust belt (Pine Mountain thrust; Mitra 1988); and the Central Appalachian fold–thrust belt (North Mountain thrust; Evans 1989). Lines showing specific angles of differential transport (Ψ) are superposed on the diagram. Observations suggest that Ψ=35–40° is an upper threshold for differential transport in non-metamorphic fold–thrust belts. Data points representative of segments across known tear faults are above the 40° line.

cant bulk shear strain (0.70–0.84 for $\Psi = 35$–$40°$) in the horizontal plane before rupture. This strain is significantly greater than both experimental elastic strain measured for intact rock prior to failure (10^{-3}) and strain released by earthquakes (10^{-4}–10^{-5}), suggesting that the bulk shear strain is anelastic and accommodated by large-scale cataclastic deformation within the thrust sheet (Medwedeff in press, and references therein).

In conclusion, the utility of these empirical observations on differential transport of continuous thrust sheets is that: (1) they render insight into the degree thrust sheets maintain lateral continuity at a regional scale; and (2) they place reasonable constraints on differential displacements within thrust sheets, thus providing a useful tool in projecting interpretations of seismic sections or cross sections in thrusted areas with little data.

Acknowledgements—This material was supported by a National Science Foundation Fellowship and an Exxon Production Research summer internship and was submitted as part of my Ph.D. dissertation at the University of Illinois. I thank S. Marshak for his encouragement and assistance on this manuscript, and G. Mitra, S. Treagus, D. Phelps and an anonymous reviewer for their constructive comments.

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