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Influence of detachment layer thickness on style of thin-skinned shortening

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Abstract—There are several parameters which may determine whether detachment folds or thrust faults develop in thin-skinned compressional systems. A fundamental but little publicised parameter is apparent from consideration of detachment fold growth. As a detachment fold amplifies, its core must be filled by redistribution of ductile material. If the mobile material were insufficient to supply the volume required by the fold core through redistribution, fold growth would be inhibited and eventually faulting would occur. The volume of a detachment fold core is compared here with the volume of available underlying mobile material for various amounts of shortening and sizes of fold. The occurrence of detachment folds versus thrusts in several compressional belts is successfully predicted by this relationship. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Detachment folds as structures which accommodate thin-skinned shortening have long been documented (Willis, 1894), but it is well known that while some thin-skinned shortening belts are indeed characterised by detachment folds, others are characterised by thrust systems and their related fold styles (Boyer & Elliott 1982, Suppe 1983, Suppe & Medwedeff 1990). In spite of abundant literature on various aspects of fold evolution in thin-skinned systems, the question of why thrusting rather than detachment folding should occur in a given thin-skinned compressional system has received relatively little attention, although there is general acceptance of detachment folds as being more likely to form in the presence of thick, ductile décollement layers (Wiltschko & Chapple 1977, Jamison 1987, Erickson 1996). Specific work on this problem has focused on the mechanical properties of real and model multilayers (Woodward & Rutherford 1989, Morley 1994, Erickson 1996). It is undoubtedly true that several parameters (for example strain rate, stress state, amount of shortening, mechanical stratigraphy) may have to be considered to fully address this issue. The purpose of this paper, however, is to explore a very simple geometrical idea, arising from an inherent feature of detachment fold growth, which may constitute a fundamental control on the style of thin-skinned shortening. Recognising that detachment fold growth must be accompanied by redistribution of relatively weak strata into the fold core (Wiltschko & Chapple 1977), it is suggested here that if there were insufficient material available to fill the fold core, then fold growth would be inhibited and shortening would have to be accommodated in some other way, for example thrusting (Fig. 1). This problem has also been considered by Dahlstrom (1990) who offered a solution in the form of an alternative model of detachment fold growth. Dahlstrom's model is discussed later. An attempt is made here to quantify the effect of detachment layer thickness on fold style by comparing the area in the core of an evolving detachment fold with the amount of material available in the mobile layers below to fill the fold core. The calculation is first made for an idealised model of a detachment fold overlying a mobile layer and the predictions are then compared with a number of fold belts and thrust belts.

MODEL AND ASSUMPTIONS

Previous considerations of volumetric aspects of detachment fold growth have employed models of varying complexity, the simplest being a symmetrical chevron fold of fixed limb length (Poblet & Hardy 1995). That model for estimating fold core area is adopted here—Fig. 2 illustrates the relevant geometrical parameters; note that the chevron construction also gives a reasonable approximation (a slight overestimate) of the

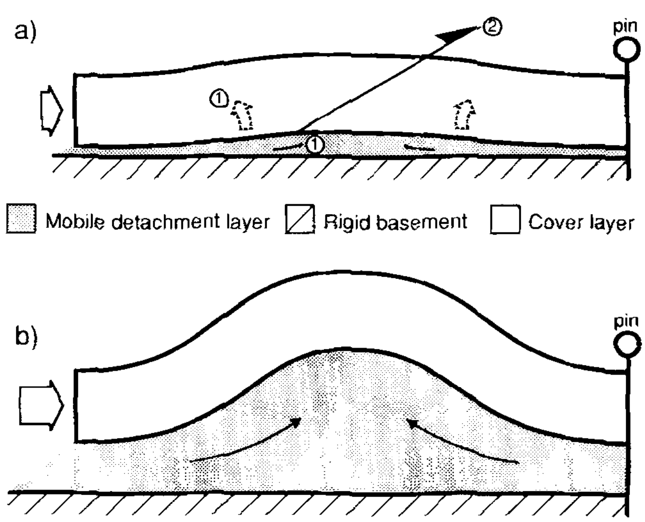

Fig. 1. Control of mobile detachment layer thickness on detachment fold versus thrust development during thin-skinned shortening. (a) If the mobile detachment layer is very thin, significant fold amplification cannot be accommodated by flow from below the synclines into the anticlinal cores (1) and folding at the preferred wavelength is resisted until brittle failure occurs (2). (b) If the mobile detachment layer is relatively thick, ample material is available to redistribute from below the synclines to the anticlinal cores, permitting fold amplification.

fold core area in more sinusoidal structures. This model does not take into account any layer parallel shortening. The isosceles triangle representing the core of a chevron fold has an apical angle γ, flanked by sides of length $\lambda_D/2$. Employing the formula for area of an isosceles triangle and bearing in mind that $\sin(\gamma/2) = \lambda_F/\lambda_D$, area A_c is

$$A_c = 0.5(\lambda_D/2)^2 \sin\gamma = (\lambda_D^2 \sin\gamma)/8. \quad (1)$$

The transition from competent, folding layers to relatively incompetent, mobile material reflects several controls including lithology and pore pressure. The simple model used here assumes an abrupt transition such as would be the case on passing into a salt layer. The area of mobile layer assumed to be available for redistribution (A_v) is taken to be $\lambda_D t_v$. This embodies the presumption that mobile material moves only from below the evolving synclines into the anticlinal cores rather than flowing in from further afield (Wiltschko & Chapple 1977). In the interests of rendering the results of this analysis dimensionless, the ratio $\lambda' = \lambda_D/t_v$ is introduced. With $t_v = 1$, $\lambda' = \lambda_D$ and the ratio of required material (A_c) to available material (A_v) then is

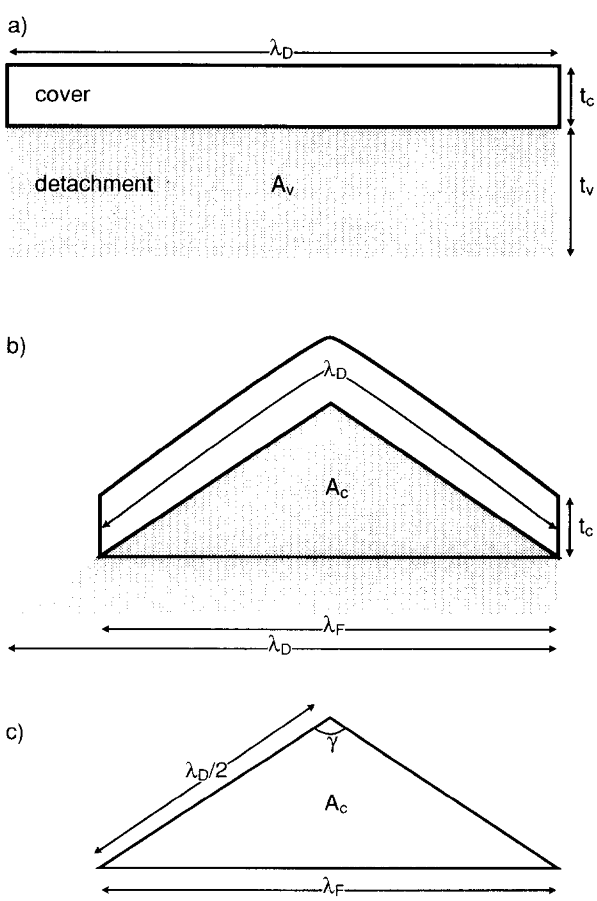

Fig. 2. Geometrical parameters used here to describe a detachment fold. λ_D—Original (dominant) fold wavelength; λ_F—present (finite) fold wavelength; t_c—cover layer thickness; t_v—detachment layer thickness; A_c—area in core of detachment fold; A_v—area of mobile detachment available to supply core of fold. (a) Multilayer, length λ_D, consisting of strong cover layer and weak detachment layer. (b) Symmetrical chevron fold cored by redistributed material from detachment layer. (c) Isosceles triangle representing core of chevron fold. γ—Apical angle.

$$A_c/A_v = (\lambda' \sin\gamma)/8. \quad (2)$$

Expression 2 is graphed for various amounts of shortening and a range of λ_D/t_v ratios in Fig. 3. Note that the choice of scale for A_c/A_v on Fig. 3 absorbs much of the latitude in this analysis arising from the assumptions of the model. The discrepancy between A_c calculated in this manner and A_c in a more sinusoidal fold is relatively slight. There is greater discrepancy for other fold styles, for example concentric folding, which produces broad synclines and narrow anticlines at the rheological interface between the folding and the mobile, "detachment" layers (Dahlstrom 1969). Large rheological contrast between cover and detachment layers gives mullion-like structures and the contrast in wavelength of anticlines and synclines is still more pronounced (Talbot *et al.* 1988, Sokoutis 1990). Further departure from the basic relationship shown in Fig. 3 arises from the way that t_v is handled here. A mobile detachment layer is intrinsically unlikely to give rise to plane strain, particularly when it is borne in mind that detachment folds tend to be periclinal (Dubey & Cobbold 1977)—the A_c/A_v ratio given here will be an underestimate towards periclinal fold tips and an overestimate near periclinal fold crests. In the relatively common case where the detachment layer is evaporitic, the principle of volume conservation during deformation (e.g. Dahlstrom 1990) may not even apply, since unroofed periclinal structures may bleed significant quantities of mobile evaporites (Ala 1974, Moretti *et al.* 1990). This leads to uncertainty in estimates of original stratigraphic thickness of a mobile layer; a task difficult enough in areas of limited well control. These various modifications of the basic model each result in some shift of the ordinate scale on Fig. 3, but the underlying idea remains the same. Acknowledging these complications, the transition through $A_c/A_v = 1$ is shown as gradational on Fig. 3. In terms of the basic model used here, the critical λ' which gives $A_c/A_v = 1$ for various amounts of shortening is given by expression 3

$$\lambda'_{crit} = 8/\sin\gamma. \quad (3)$$

This curve is also shown in Fig. 3.

DISCUSSION

Figure 3 illustrates the ranges of λ' ratios which represent multilayers in which detachment folding is free to occur and those in which detachment folding may be inhibited. Reviews of fold wavelength selection have shown that the ratio of λ_D/t_c tends to lie in the range 5–10 (Price & Cosgrove 1990)—this range for λ_D/t_c has been used to estimate λ_D for the purposes of plotting the thrust system examples on Fig. 3. The examples annotated on Fig. 3 have been plotted using λ' and shortening, and show a good match with the predicted structural style, illustrating that, notwithstanding the effect of other parameters, the A_c/A_v ratio seems to constitute a

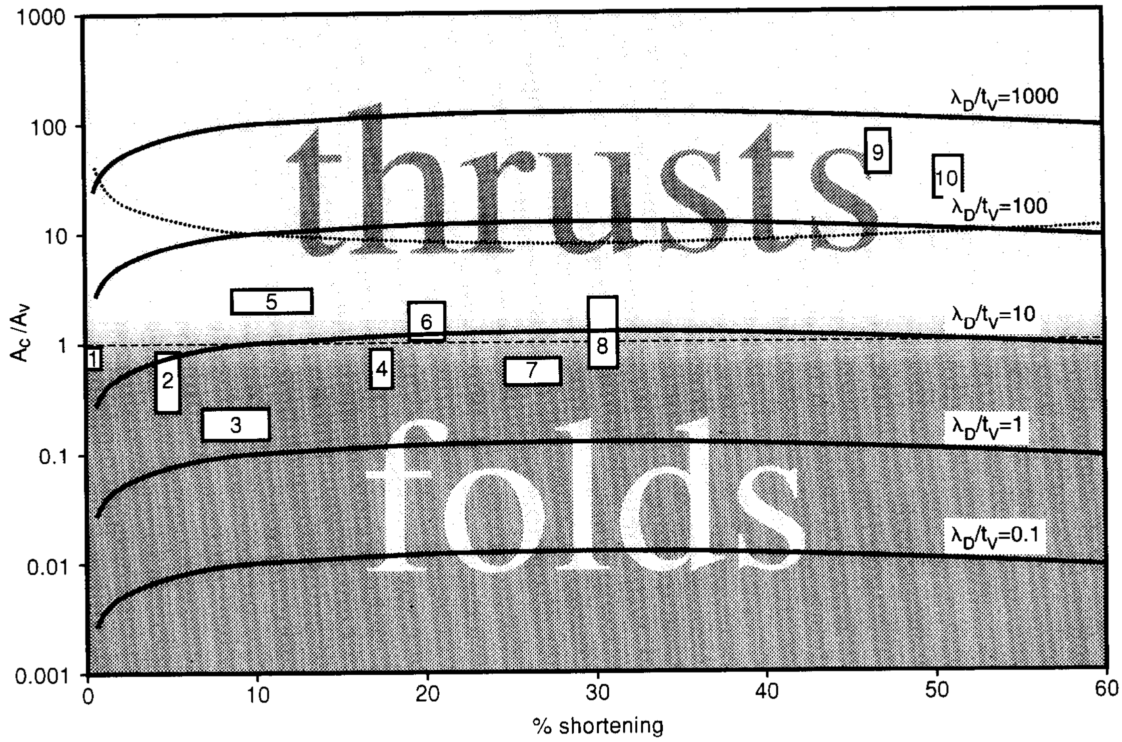

Fig. 3. Ratio of required area (fold core A_c) to available supply from mobile detachment (A_v) plotted against shortening; note ordinate scale. Contoured for a range of dominant fold wavelength (λ_D) to detachment layer thickness (t_v) ratios ($\lambda_D/t_v = \lambda'$). Adjustments to this graph resulting from different fold geometries and out of plane movement are discussed in text. Numbered boxes represent compressional belt examples: 1—Appalachian Plateau detachment folds, Pennsylvania (Wiltschko & Chapple 1977); 2—southern North Sea fold belt (Stewart & Coward 1996); 3—Perdido fold belt, Gulf of Mexico (Trudgill *et al.* 1995); 4—Cordona Basin fold belt, Pyrenees (Vergés *et al.* 1992); 5—Thrust system at Siluro—Ordovician level, Parry Islands, Canada (Harrison & Bally 1988); 6—Zagros, Iran (Koyi 1988); 7—Salt River Range, Wyoming (Jamison 1992); 8—Jura mountains, section from Vellerat to Grenchen (Mitra & Namson 1989); 9—Western Chartreuse thrust system, French Alps (Butler 1992); 10—Ponga Unit, Cantabrian thrust system, Spain (Alvarez-Marrón & Pérez-Estaún 1988). Dotted line shows magnitude of λ_D/t_v at $A_c/A_v = 1$ (same ordinate scale).

significant control on the style of thin-skinned shortening belts. For shortening in the range 5–60 %, multilayers in which the relatively competent, folding layer deforms with a dominant wavelength (λ_D) approximately 10 times greater than the detachment layer thickness (t_v), lie near the geometrically defined boundary $A_c/A_v = 1$. The examples which lie near this boundary are interesting in several respects. Multilayers of this geometry may undergo a transition from folding to thrusting much earlier than at the critical amount of shortening at which the folds lock up (c. 36% for concentric folds)—a mixture of detachment folds and thrusts is indeed seen, for example, in the Jura Mountains (Fig. 3) at around 30% shortening (Mitra & Namson 1989). A number of individual fold structures in the Jura have been interpreted by Jordan & Noack (1992) as hybrid detachment-fault propagation folds, a style postulated by Jamison (1987). Fold structures in the Zagros belt (Fig. 3), show anomalously low λ_D/t_c ratios (Koyi 1988), possibly reflecting suppression of λ_D during the first increments of fold growth due to a dearth of mobile material. It may also be reasonable to suggest that when $A_c/A_v \sim 1$, the λ' ratio is less significant relative to other parameters than it is when A_c/A_v is very small or very large.

Figure 3 gives a perspective on the debate surrounding the models for detachment fold growth. Dahlstrom (1990) pointed out that with fixed limb length ($\lambda_D/2$) the fold core area A_c increases very rapidly to a maximum at around 30% shortening, then falls. Although Dahlstrom recognised that there is ample mobile material to redistribute at low λ' ratios (satisfying the law of volume conservation for fixed limb length detachment folds as originally envisaged by De Sitter (1956) and Wiltschko & Chapple (1977)), he noted that this was not the case where the λ' ratio was large. This led Dahlstrom (1990) to propose an alternative model for detachment fold growth at high λ' ratios involving limb lengthening commensurate with the amplification of isoclinal-style detachment folds during shortening, maintaining low A_c. Unfortunately, no field examples were described to reinforce this suggestion. The discussion presented here offers an alternative view, suggesting that at large λ' ratios ($\lambda_D/t_v > 10$), the law of conservation of volume may force the evolution of thrust-related fold structures.

The view presented here might seem to differ from that of Jamison (1992), who studied a range of fold styles including detachment folds and fault-bend folds in the Wyoming–Idaho–Utah thrust belt. Jamison (1992) felt that there was negligible mechanostratigraphic variation between these different fold structures and concluded that evolution of stress state was the most important control upon fold style. Whilst that conclusion may be valid in that particular thrust system, Fig. 3 shows Jamison's field example lying reasonably close to the $A_c/$

$A_v = 1$ boundary, the zone where λ' may be inherently less significant than other parameters. It is therefore suggested here that stress evolution as discussed by Jamison (1992) is generally less fundamental a controlling parameter on shortening style than λ'.

APPLICATION

(1) Prior to drilling for hydrocarbons in anticlinal fold closures, a key issue is whether or not the structure is breached by faults. If the quality of available seismic data is relatively poor, it might be difficult to assign risk to breaching. However such data might still be sufficient for determining fold wavelength, and if the thickness of the detachment were known, then the relationship shown in Fig. 3 might indicate whether the structure was likely to be breached (fault-propagation fold) or not (detachment fold). This approach could supplement direct geometrical analysis of fold shape, which is not necessarily diagnostic (Jamison 1987, Epard & Groshong 1993).

(2) A genetic relationship between multilayer geometry and structural style as discussed here could prove useful during reverse modelling of compressional systems involving evaporites. For example, spatial and temporal variation in evaporite layer thickness could be considered in tandem with the transition from folding to thrusting.

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REFERENCES

Ala, M. A. 1974. Salt diapirism in southern Iran. *Bull. Am. Ass. Petrol. Geol.* **58**, 1758–1770.

Alvarez-Marrón, J. & Pérez-Estaún, A. 1988. Thin-skinned tectonics in the Ponga region (Cantabrian Zone NW Spain). *Geol. Rdsch.* **77**, 539–550.

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

Butler, R. W. H. (1992). Structural evolution of the western Chartreuse fold and thrust system, NW French Subalpine Chains. In: *Thrust Tectonics* (edited by McClay, K. R.). Chapman and Hall, London.

Dahlstrom, C. D. A. 1969. The upper detachment in concentric folding. *Bull. Can. Petrol. Geol.* **17**, 326–346.

Dahlstrom, C. D. A. 1990. Geometric constraints derived from the law of conservation of volume and applied to evolutionary models for detachment folding. *Bull. Am. Ass. Petrol. Geol.* **74**, 336–344.

De Sitter, L. U. (1956). *Structural Geology*. McGraw-Hill, New York.

Dubey, A. K. & Cobbold, P. R. 1977. Non-cylindrical, flexural slip folds in nature and experiment. *Tectonophysics* **38**, 223–239.

Epard, J.-L. & Groshong, R. H. 1993. Excess area and depth to detachment. *Bull. Am. Ass. Petrol. Geol.* **77**, 1291–1302.

Erickson, S. G. 1996. Influence of mechanical stratigraphy on folding vs faulting. *J. Struct. Geol.* **18**, 443–450.

Harrison, J. C. & Bally, A. W. 1988. Cross-sections of the Parry Islands fold belt on Melville Island, Canadian Arctic Islands: implications for the timing and kinematic history of some thin-skinned décollement systems. *Bull. Can. Petrol. Geol.* **36**, 311–332.

Jamison, W. R. 1987. Geometric analysis of fold development in overthrust terranes. *J. Struct. Geol.* **9**, 207–220.

Jamison, W. R. 1992. Stress controls on fold thrust style. In *Thrust Tectonics* (edited by McClay, K. R.). Chapman and Hall, London.

Jordan, P. & Noack, T. (1992). Hangingwall geometry of thrusts emanating from ductile decollements. In *Thrust Tectonics* (edited by McClay, K. R.). Chapman and Hall, London.

Koyi, H. 1988. Experimental modeling of role of gravity and lateral shortening in Zagros Mountain Belt. *Bull. Am. Ass. Petrol. Geol.* **72**, 1381–1394.

Mitra, S. & Namson, J. 1989. Equal-area balancing. *Am. J. Sci.* **289**, 563–599.

Moretti, I., Wu, S. & Bally, A. W. 1990. Computerized balanced cross-section LOCACE to reconstruct an allochthonous salt sheet, offshore Louisiana. *Mar. Petrol. Geol.* **7**, 371–377.

Morley, C. K. 1994. Fold-generated imbricates: examples from the Caledonides of Southern Norway. *J. Struct. Geol.* **16**, 619–631.

Poblet, J. & Hardy, S. 1995. Reverse modelling of detachment folds; application to the Pico del Aguila anticline in the South Central Pyrenees (Spain). *J. Struct. Geol.* **17**, 1707–1724.

Price, N. J. & Cosgrove, J. W. (1990). *Analysis of Geological Structures*. Cambridge University Press, Cambridge.

Sokoutis, D. 1990. Experimental mullions at single and double interfaces. *J. Struct. Geol.* **12**, 365–373.

Stewart, S. A. & Coward, M. P. 1996. Genetic interpretation and mapping of salt structures. *First Break* **14**, 135–141.

Suppe, J. 1983. Geometry and kinematics of fault-bend folding. *Am. J. Sci.* **283**, 684–721.

Suppe, J. & Medwedeff, D. A. 1990. Geometry and kinematics of fault-propagation folding. *Eclog. geol. Helv.* **83**, 409–454.

Talbot, C. J., Koyi, H., Sokoutis, D. & Mulugeta, G. 1988. Identification of evaporite diapirs formed under the influence of horizontal compression: a discussion. *Bull. Can. Petrol. Geol.* **36**, 91–95.

Trudgill, B. D., Rowan, M. G., Weimer, P., Fiduk, J. C., Gale, P. D., Korn, B. E., Phair, R. L., Gafford, W. T., Dischinger, J. B., Roberts, G. R. & Henage, L. F. (1995). The structural geometry and evolution of the salt-related Perdido fold belt, Alaminos Canyon, northwestern deep Gulf of Mexico. In *GCSSEPM Foundation 16th Annual Research Conference, Salt, Sediment and Hydrocarbons*, (edited by Travis, C. J., Vendeville, B. C., Harrison, H., Peel, F. J., Hudec, M. R. & Perkins, B. F.), pp. 275–284.

Vergés, J., Muñoz, J. A. & Martinez, A. (1992). South Pyrenean fold and thrust belt: role of foreland evaporitic levels in thrust geometry. In *Thrust Tectonics* (edited by McClay, K. R.). Chapman and Hall, London.

Willis, B. (1894). Mechanics of Appalachian structure. *United States Geological Survey 13th Annual Report, part II*, pp. 213–281.

Wiltschko, D. V. & Chapple, W. M. 1977. Flow of weak rocks in Appalachian Plateau folds. *Bull. Am. Ass. Petrol. Geol.* **61**, 653–670.

Woodward, N. B. & Rutherford, E. 1989. Structural lithic units in external orogenic zones. *Tectonophysics* **158**, 247–267.