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Where is the footwall flat? A cautionary note on template constraints

Hemin A. Koyi[a,]*, Antonio Teixell[b]

[a]Hans Ramberg Tectonic Laboratory, Department of Earth Sciences, University of Uppsala, Villavagen 16, S-753 26 Uppsala, Sweden
[b]Departament de Geologia (Geotectonica), Universitat Autonoma de Barcelona, 08193 Bellaterra, Spain

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Abstract

Sand-box models and field observations are used to illustrate limitations associated with template constraints in the analysis and interpretation of thrust systems. Model results show that, at shallow levels, shortening is taken up by displacement along thrust surfaces, whereas ductile deformation accommodates shortening at deeper levels. This variation in deformation style, which also is observed in nature, may contradict the necessity of correspondence between footwall and hanging wall ramp and flat structures. Hanging wall flats that form the base of an imbricate sheet for a relatively long distance may not have the corresponding footwall flats. Unlike the template constraint model, the model footwall flat is represented by a broad zone of ductile deformation with significantly less fault slip than along the shallower parts of the imbricate.

1. Introduction

The ramp–flat kinematic model imposes a series of restrictions in interpreting and constructing cross-sections of deep, unexposed parts of thrust imbricate stacks. One of the principal geometric assumptions of the model is the necessity of a correspondence between hanging wall and footwall ramp and flat structure, the 'template constraints' (e.g. Boyer and Elliot, 1982; Marshak and Woodward, 1988). Undoubtedly, the model allows for slight alterations of the cut-off lengths of lithologic marker units due to flexural shear during fault-related folding and due to thrust-parallel simple shear (e.g. Elliot, 1976; Suppe, 1983), but these are relatively minor. Numerous profiles from different fold and thrust belts are constructed on the basis of these constraints, where deeper structures are directly extrapolated from observations of the shallower geometries. Since the ramp–flat model is essentially geometric, and the natural strain states and the kinematic effects of lithologic and physical variations of boundary conditions are not taken into account, a straightforward application of the model may result in serious errors. Some authors (e.g. Ramsay, 1992; Casey and Dietrich, 1997) have in fact expressed concern on the indiscriminate application of the model to many orogenic belts disregarding material properties and physical conditions.

2. Sand models

A sand-box model is used here to document strain variation with depth in contractional areas. The model, consisting of layered loose sand, was shortened by 47% from one end on a horizontal planar and rigid substrate. The model contained thin layers of coloured homogeneous sand making a constant thickness of 5 mm (Koyi, 1995). Sequential sections were prepared by means of a vacuum cleaner throughout the deformation at every 1.5% shortening for photographing. These sections were used to quantify strain within the model and measure displacement along different thrust

* *E-mail address*: hemin.koyi@geo.uu.se (H. Koyi).

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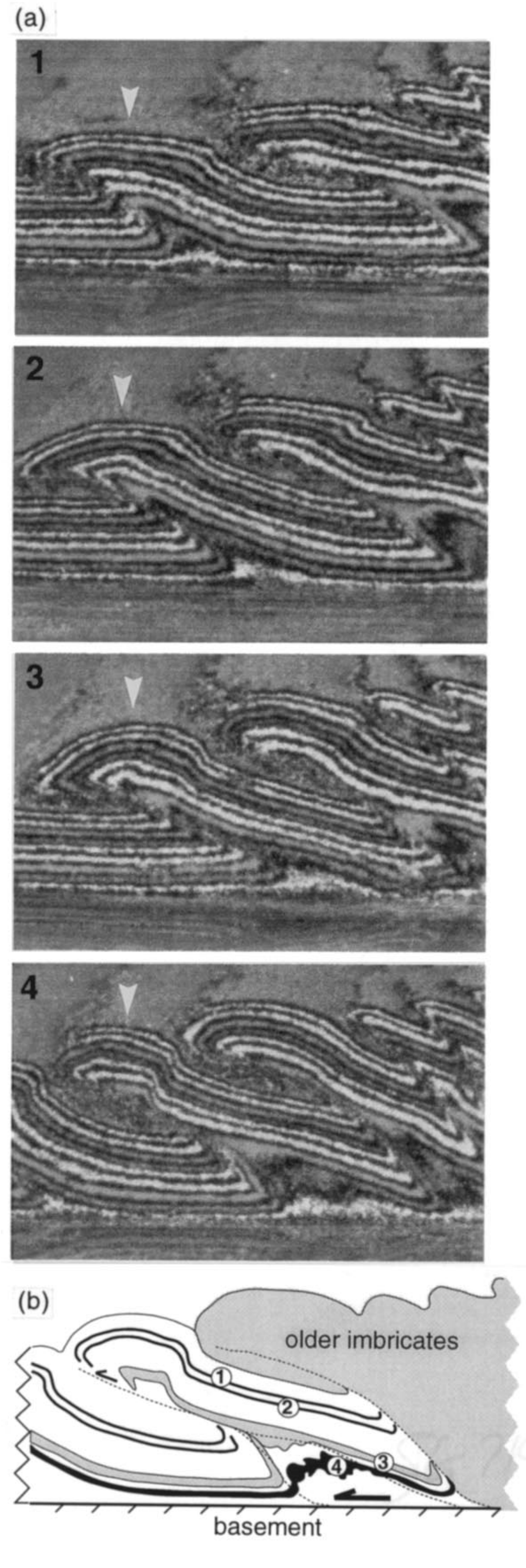

Fig. 1. (a) 1–4, sequence profiles of a sand-box model showing the evolution of an imbricate (arrow) at 22.5%, 25%, 26.5 and 35.2% shortening, respectively. (b) A line drawing of profile number 4 in (a) shows variation in deformation with depth within the imbricate. The shallow layer (3) shows an insignificant amount of layer-parallel shortening, whereas the thickened deeper layer (4) has suffered 40% layer-parallel shortening.

surfaces. In this model, the additional complicating factors of erosion, deposition, material anisotropy due to facies changes, time variations in pore fluid pressure ratios across the wedge and changes in friction coupling along the décollement surface were deliberately left out. For more details of model deformation and sectioning, see Mulugeta and Koyi (1992).

Since their final deformation stage can easily be compared to the earlier stages, sand-box models provide a good tool for testing the applicability of the template constraints model. This short note adds evidence from sand-box models, classic analogues for thrust imbrication, emphasising the need for a re-evaluation of the template constraints. During the analysis of sand-box models in terms of ramp–flat kinematics we were faced with hanging wall–footwall mismatches and departures from the ideal situation. Therefore, the ramp–flat geometric rules needed not be obeyed to maintain compatibility in deformation between the hanging wall and footwall flats.

3. Implications for template constraints

In contrast to the template rules, sand-box models show that flats in hanging wall and footwall do not necessarily match, nor do they display the same length or amount of displacement. In many model imbricates, at a certain stratigraphic level, hanging wall flats that form the base of the imbricate sheet for a relatively long distance do not have the correspondent footwall flat (Fig. 1). Instead, the footwall flat is represented by a wide zone of distributed deformation at the deeper level of the model. There, the layers thicken by penetrative strain and folding, which take up the shortening that is accommodated mainly by thrust slip at shallower levels. This is due to enhanced ductility of the deeper layers by the overlying load, which is significant even in centimetre-scale models of homogeneous material (e.g. loose sand) (Mulugeta and Koyi, 1992; Koyi, 1995).

Fig. 1(b) shows that the deep layers (3 and 4) in the rear of the imbricate are intensely thickened close to the ramp, whereas the shallower layers (1 and 2) are expulsed forward along the thrust surface, floored by a hanging wall flat. Even if a thrust may still be traced to the basal décollement of the system, it has a subplanar rather than a staircase geometry, and shows

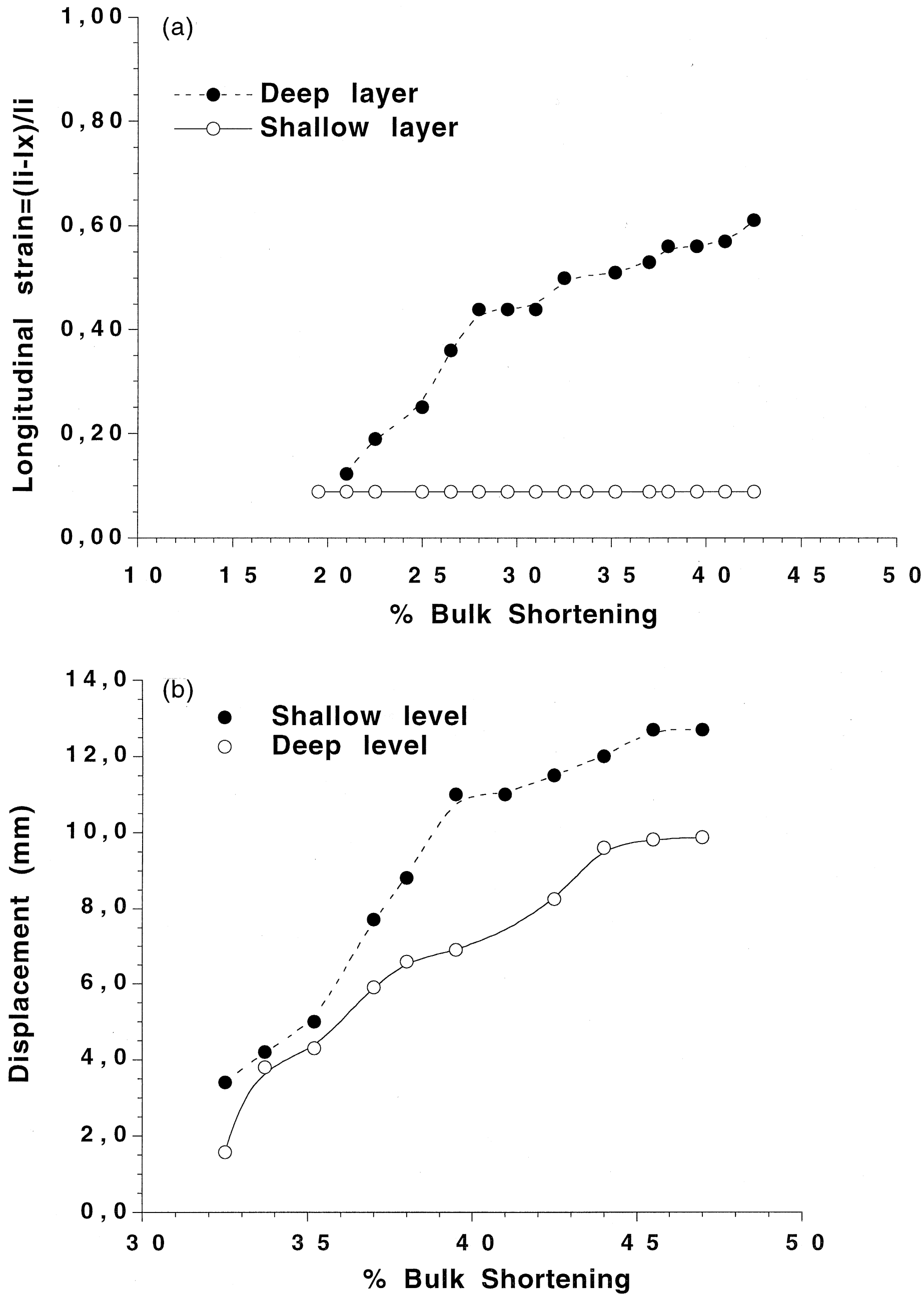

Fig. 2. (a) A plot of longitudinal strain in two layers, located at different stratigraphic levels in a sand-box model imbricate (shown in Fig. 1), with bulk shortening. These measurements were taken from the time the imbricate formed until the end of the model deformation. Shortening in the shallow layer is mainly taken up by displacement along the thrust and partially by folding. Therefore, the layer maintains its initial length after restoration. The deeper layer, on the other hand undergoes significant layer-parallel shortening and does not restore to its initial length. (b) A plot of variation in displacement along the same thrust surface with depth. Note that displacement along the thrust surface is almost constant with depth at the very early stages of deformation. As the deformation proceeds, displacement increases at shallow levels.

much less offset at the deeper levels, implying a decrease of slip with depth. The potential space problems resulting from the ramp–flat mismatch are eliminated by ductile deformation at a deeper level. In a sand-box model, the length of two layers located at two different stratigraphic levels were measured throughout their deformation. The shallow layer showed no layer-parallel shortening (hence no longitudinal strain) with deformation (Fig. 2a). Instead, it was thrusted and folded. During the same time-interval at deeper levels, a layer was shortened by 40% layer-parallel shortening (Fig. 2a). Measurements of displa-

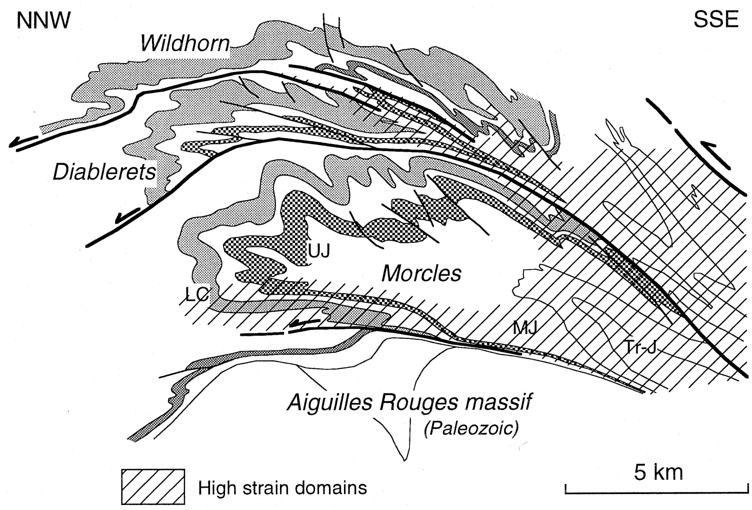

Fig. 3. A profile of the Helvetic nappes of Switzerland, simplified after Pfiffner (1993). The high strain domains traced after strain data reported in Ramsay (1981) and Dietrich and Casey (1989). Note that some thrust faults lose displacement down-section (Wildhorn nappe), and the existence of hanging wall flats that do not have the corresponding footwall flat behind (Diablerets and Wildhorn nappes). Tr–J: Triassic–Lower Jurassic, MJ: Middle Jurassic, UJ: Upper Jurassic limestone, LC: Lower Cretaceous limestone.

cement along the same thrust show variation with depth. Displacement decreases with depth where deformation is mainly taken up by layer-parallel shortening and folding, which results in thickening of the layer (Fig. 2b).

Similarly, variations of deformation style and amount of strain from frontal to deep zones of single, natural thrust sheets have been documented by some workers (Ramsay, 1981; Dietrich and Casey, 1989; Butler, 1984, 1992; Casey and Dietrich, 1997). In the Helvetic nappes of Switzerland, for example, where a sufficient variation of structural level is exposed, thrust offsets that are minor at the intensely strained rear zones of the nappes are seen to grade forward into large hanging wall flats (e.g. Diablerets and Wildhorn nappes; Fig. 3). No corresponding footwall flats are observed, apparently contradicting template constraints. Instead, at deeper ('root') levels, tectonic displacement is taken up by ductile deformation, a combination of heterogeneous simple shear and pure shear, still in low-grade, sub-greenschist facies conditions (Dietrich and Casey, 1989). The geometry described in this region is strikingly similar to that displayed in the sand-box models, where displacement by penetrative deformation in a wide zone at the rear of the sheet is transferred to slip on a narrow fault or shear zone towards the front (Figs. 1 and 3) (see also Ramsay, 1980, fig. 22).

Generally, due to lack of exposure, footwall structures are poorly resolved (Fig. 4a). The existence of a thrust flat segment in the upper plate may correspond to a footwall flat, with a staircase fault geometry (classic interpretation following template constraints), or alternatively, penetrative deformation may accommodate tectonic displacement on a sub-planar fault (Fig. 4b and c). On a large scale, similar relationships to that implied here may apply in the transition from internal to external zones of orogenic belts (e.g. the Scottish Caledonides, the Variscan belt of NW Spain, the French Alps, etc.). It may not be accurate to infer large footwall flats beneath the internal zones to account for the shortening of the off-scraped sedimentary rocks of the foreland fold and thrust belt, since much displacement at shallower levels may be accommodated by penetrative deformation at deeper levels.

In conclusion, based on results of sand-box models and field examples, it is emphasised here that the template constraints in-built in the ramp–flat kinematic model do not always account for the mechanics of internal deformation of thrust imbricates; hence, the geometrical rules that follow cannot be applied indiscriminately in a self-similar way across non-exposed or poorly imaged parts of the crust without a consideration of the particular strain states. Straightforward application of the template constraint may result in inaccuracies in cross-section construction and in calculation of the amount of shortening.

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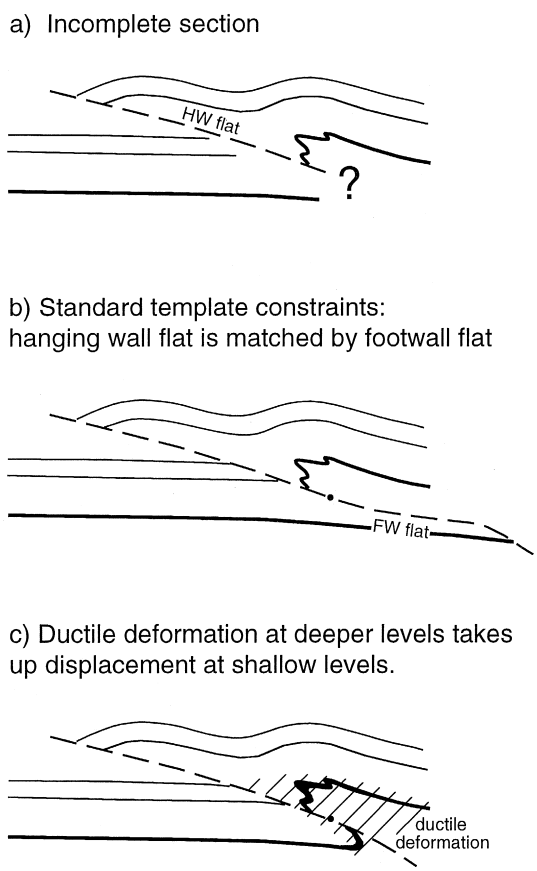

Fig. 4. Schematic diagrams illustrating two alternative interpretations of the deeper structure in an incomplete section (a); (b) a standard template constraint, where the hanging wall flat is matched by a similarly long footwall flat or (c) an alternative interpretation of the section (a) where the hanging wall flat is matched by penetrative deformation at deeper levels. The dot indicates the known extent of the thrust surface.

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References

Boyer, S.E., Elliot, D., 1982. Thrust systems. American Association of Petroleum Geologists Bulletin 66, 1196–1230.

Butler, R.W.H., 1984. Evolution of Alpine fold–thrust complexes: a linked kinematic approach. In Structural Geology of Fold and Thrust Belts, eds. G. Mitra and G. Fisher, 29–44. Johns Hopkins University Press, Baltimore.

Butler, R.W.H., 1992. Evolution of Alpine fold-thrust complexes: a linked kinematic approach. In: Structural geology of fold and thrust belts, eds. S. Mitra and G. Fisher, pp. 29–44. Johns Hopkins University Press, Baltimore.

Casey, M., Dietrich, D., 1997. Overthrust shear in mountain building. In Evolution of Geological Structures in Micro- to Macro-scales, ed. S. Sengupta, 119–142. Chapman & Hall, London.

Dietrich, D., Casey, M., 1989. A tectonic model for the Helvetic nappes. In Alpine Tectonics, eds. M.P. Coward, D. Dietrich and R.G. Park, 47–63. Geological Society Special Publication, 45.

Elliot, D., 1976. The energy balance and deformation mechanisms of thrust sheets. Philosophical Transactions Royal Society London A 283, 289–312.

Koyi, H., 1995. Mode of internal deformation in sand wedges. Journal of Structural Geology 17, 293–300.

Marshak, S., Woodward, N., 1988. Introduction to cross-section balancing. In Basic Methods of Structural Geology, eds. S. Marshak and G. Mitra, 303–332. Prentice Hall, Englewood Cliffs.

Mulugeta, G., Koyi, H., 1992. Episodic accretion and strain partitioning in a model sand wedge. Tectonophysics 202, 319–333.

Pfiffner, O.A., 1993. The structure of the Helvetic nappes and its relation to the mechanical stratigraphy. Journal of Structural Geology 15, 511–521.

Ramsay, J.G., 1980. Shear zone geometry: a review. Journal of Structural Geology 2, 83–99.

Ramsay, J.G., 1981. Tectonics of the Helvetic nappes. In Thrust and Nappe Tectonics, eds. K.R. McClay, N.J. Price, 293–309. Geological Society Special Publication, 9.

Ramsay, J.G., 1992. Some geometric problems of ramp–flat thrust models. In Thrust Tectonics, ed. K.R. McClay, 191–200. Chapman & Hall, London.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding. American Journal of Science 283, 684–721.