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Double-edge fault-propagation folding: geometry and kinematics

S. Tavani *, F. Storti, F. Salvini

Dipartimento di Scienze Geologiche, Università degli Studi "Roma Tre" Largo S. L. Murialdo 1, 00146 Rome, Italy

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Abstract

Fault-propagation folding is a common folding mechanism in thrust-and-fold belts and accretionary prisms. Several geometrical models relating the fold shape to the ramp shape have been proposed. In all these models, ramps always emanate from a basal fault and propagate upwards. We have developed a new kinematic and geometric model of fault-propagation folding, named double-edge fault-propagation folding. The model simulates folding at thrust ramps as a function of their nucleation site and propagation history within the folded multilayer. The fold shape depends on the initial length and location of the ramp, its dip, and the *S*/*P* ratio (i.e. incremental ramp slip versus propagation) of both the upper and lower ramp tips. This solution increases the geometrical flexibility of fault-propagation folding reducing, for example, the direct dependence between the backlimb dip and the ramp dip, as double-edge fault-propagation folding is characterised by a backlimb panel not necessary parallel to the ramp. Non-parallelism between the ramp and the backlimb is commonly observed in thrust-related anticlines, within fold-and-thrust belts and accretionary prisms. The excess layer-parallel shear imposed by the development of double-edge fault-propagation folding can be easily accommodated by discrete faulting and/or penetrative deformation. The dependence of the fold shape on the fault behaviour provides a tool for including the role of mechanical stratigraphy and environmental conditions of deformation into kinematic models. Natural examples of anticlines that could be modelled by double-edge fault-propagation are presented.

Keywords: Fault-propagation folding; Kinematic model; Excess shear; Fault displacement; Fault *S*/*P* ratio

1. Introduction

Faults and folds in thrust-and-fold belts developing at shallow structural levels exhibit interdependences that have been largely investigated in the last decades (e.g. Rich, 1934; Bally et al., 1966; Dahlstrom, 1969; Elliott, 1976; Hossack, 1979; Suppe, 1983, 1985; Williams and Chapman, 1983; Price, 1988; Woodward et al., 1989, among others). In particular, folding ahead of upward propagating thrust ramps (tip-line folding; e.g. Dahlstrom, 1969; Elliott, 1976; Suppe and Medwedeff, 1984) has long been recognised as an efficient mechanism to accommodate fault displacement (e.g. Dahlstrom, 1969; Faill, 1973; Elliott, 1976; Williams and Chapman, 1983). Several geometric and kinematic models have been proposed for fault-propagation folding. In the simpler model configurations folds grow by flexural slip and no excess layer-parallel shear is predicted (Suppe, 1985; Chester and Chester, 1990; Suppe and Medwedeff, 1990; Mercier et al., 1997). These solutions imply a univocal fold interlimb angle for a given fault step-up angle. The range of possible fold shapes is significantly expanded in the case of either non-zero shear (e.g. Mosar and Suppe, 1992) or bed thickness variations (Jamison, 1987; Chester and Chester, 1990; Mitra, 1990; Suppe and Medwedeff, 1990; Wickham, 1995). In particular, only the cross-sectional area of the structure is preserved in trishear fault-propagation folding (Erslev, 1991; Hardy and Ford, 1997; Allmendinger, 1998; Cristallini and Allmendinger, 2002).

Despite the variety of kinematic and geometric solutions, available models of fault-propagation folding do not yet account for some key features that likely characterise the early evolutionary stages of many natural fault-related folds. Modern accretionary prisms provide the opportunity to place some basic constraints on fault–fold growth as imaged in reflection seismic profiles (e.g. Morgan and Karig, 1995). The first important feature occurring in embryonic structures and then preserved in the mature ones is the presence in the anticlinal backlimbs, of sectors not parallel to the thrust ramps. In particular, these backlimb panels

* Corresponding author. Tel.: +39 0654888049; fax: +39 0654888201.
E-mail address: tavani@uniroma3.it (S. Tavani).

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have a gentler dip than the underlying faults, as shown in the seismic section at the toe of the Cascadia accretionary prism (Fig. 1a). Generally, backlimb panels not parallel to thrust ramps and not produced by faulted detachment folding (e.g. Willis, 1893; Fischer et al., 1992) have been associated with fault-bend folding and related to either the accumulation of viscous material at the lower ramp inflection point (e.g. Jordan and Noack, 1992), or to an excess forelandward layer-parallel shear (Suppe et al., 2004). Backlimb panels not paralleling the ramp can also develop above lower inflection sectors in listric faults. Natural examples indicate, however, that backlimb panels not paralleling the ramp can also occur when none of the above mentioned conditions are satisfied. In the Cascadian accretionary prism, for example, the eastward convergence direction of the Juan de Fuca plate would likely induce a top-to-the-west excess layer parallel shear rather than an eastward shear, as required by the sheared fault-bend folding model of Suppe et al. (2004). Furthermore, in the more evolved anticline imaged in the seismic profile of Fig. 1a (right side), faulted layers located in the backlimb panel not paralleling the ramp are characterised by a rather constant footwall cutoff angle. This does not support the occurrence of a listric flat–ramp transition.

Another noticeable feature that is recognised in many anticlines at the toe of accretionary prisms is the evidence that thrust ramps in their early evolutionary stages may not be linked to either the basal or/and the upper décollement (e.g. Davis and Hyndman, 1989; Moore et al., 1990), as in the example from seismic line in the Nankai accretionary prism (Fig. 1b). Such a feature has also been recognised in thrust-related anticlines in fold-and-thrust belts (e.g. Williams and Chapman, 1983; Eisenstadt and De Paor, 1987; Ellis and Dunlap, 1988; Morley, 1994; McConnel et al., 1997) (Fig. 2a and b), as well as obtained in analogue models (e.g. Liu and Dixon, 1995; Storti et al., 1997) (Fig. 2c). Modelling of the stress field acting ahead of thrust sheets also indicates that the most suitable site for ramp nucleation can be located either in the upper part (Goff and Wiltschko, 1992) or in the central sector of the deforming multilayers (Storti et al., 1997).

We propose a new geometric and kinematic model, named double-edge fault-propagation folding, where the two main features illustrated above are implemented (Fig. 3). In this model, deformation occurs by flexural slip and bed thickness is preserved. The nucleation zone of thrust ramps can have a variable length and can be localised anywhere within the folded multilayers, regardless of the lower and upper décollement position. In the presented paper, only the case of ramp nucleated as a single segment/point is considered. In the more general case, fault ramps can also originate by the linkage of multiple fault segments (e.g. Eisenstadt and De Paor, 1987; Ellis and Dunlap, 1988; Cartwright et al., 1995; Childs et al., 1996). The resulting fold geometry is expected to be complex and its description is beyond the scope of this work. Double-edge fault-propagation folding also includes the possibility of varying the ramp slip versus propagation rate ratio (*S*/*P*; e.g. Williams and Chapman, 1983; McNaught and Mitra, 1993; Hardy and McClay, 1999) during fold growth, at both ramp tips. Total displacement is partitioned into slip along the ramp, folding, and layer-parallel shear. We provide the analytical formalisation of the model for both the circular hinge (e.g. Tavani et al., 2005) and the

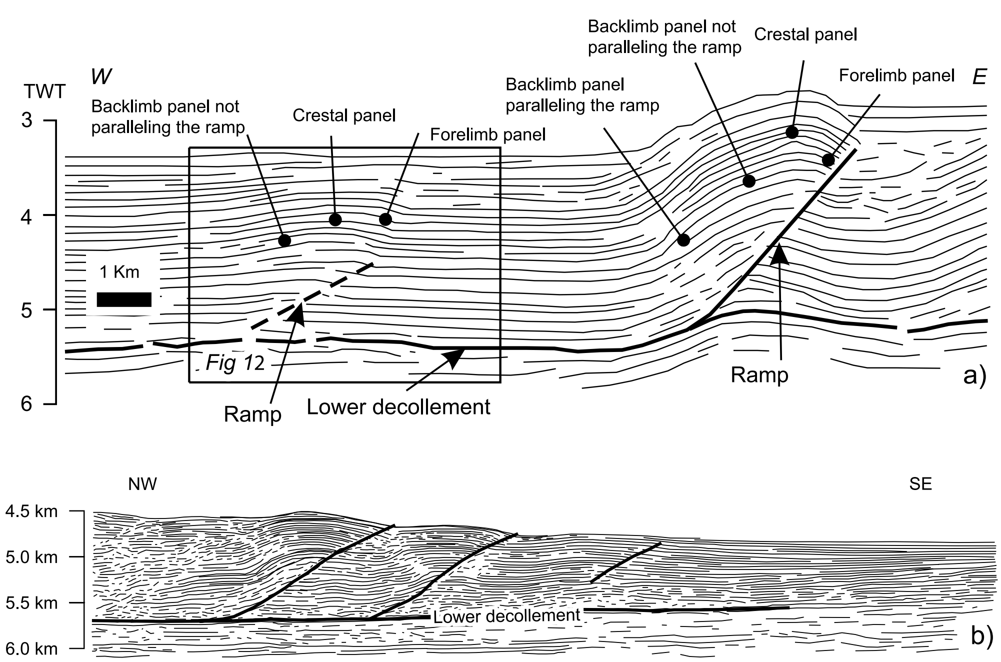

Fig. 1. Line-drawing of geoseismic cross-sections from modern accretionary prisms: (a) Cascadia accretionary prism (after Flueh et al., 1998); (b) Nankai accretionary prism (after Moore et al., 1990).