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A review of deformation pattern templates in foreland basin systems and fold-and-thrust belts: Implications for the state of stress in the frontal regions of thrust wedges

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ABSTRACT

Aesthetically appealing thrust systems and related large-scale anticlines, in both active and fossil foreland fold-and-thrust belts, and the economic potential associated with them, have captured the interest of structural geologists for many decades. As a consequence, a large amount of data on sub-seismic deformation patterns from thrust-related anticlines is available in the literature. We provide a review of deformation pattern templates from field data in foreland fold-and-thrust-belts and show that the most frequent trends of sub-seismic syn-orogenic deformation structures hosted in km-scale thrust-related folds frequently and paradoxically indicate a syn-thrusting strike-slip stress field configuration, with a near-vertical σ_2 and a sub-horizontal σ_3, rather than a contractional one where the latter is expected to be the vertical principal axis of the stress ellipsoid. This apparent inconsistency between sub-seismic syn-orogenic deformation structures and stress field orientation is here named "the σ_2 paradox". Field data support a possible explanation of the paradox, provided by the major role played by inherited early-orogenic extensional deformation structures on thrust fault nucleation. Nucleation of major thrusts and their propagation is facilitated and driven by the positive inversion and linkage of the early-orogenic sub-seismic extensional inheritance developed in the foreland basin. This process eventually leads to the development of large reverse fault zones and can occur both in contractional and strike-slip stress field configurations.

Contents

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1. Introduction

Many of the most prolific hydrocarbon systems in the world are hosted in foreland fold-and-thrust belts, where oil migration and accumulation are controlled by deformation structure networks. The use of deformation pattern templates for supporting predictions in reservoirs has significantly contributed to an impressive number of structural studies in foreland fold-and-thrust belts and in the adjacent foreland basin systems (DeCelles and Giles, 1996) since the late 60s (Stearns, 1968; Stearns and Friedman, 1972; McQuillan, 1974; Engelder and Geiser, 1980; Geiser and Sansone, 1981; Hancock, 1985; Marshak and Engelder, 1985; Price and Cosgrove, 1990; Srivastava and Engelder, 1990; Gray and Mitra, 1993; Mitra et al., 1984; Protzman and Mitra, 1990; Ferrill and Groshong, 1993; Lemiszki et al., 1994; Holl and Anastasio, 1995; Railsback and Andrews, 1995; Thorbjornsen and Dunne, 1997; Fischer and Jackson, 1999; Lacombe et al., 1999; Storti and Salvini, 2001; Silliphant et al., 2002; Graham et al., 2003; Sans et al., 2003; Bellahsen et al., 2006a; Wennberg et al., 2006; Lacombe et al., 2006, 2011; Tavani et al., 2006a; Lash and Engelder, 2007; Stephenson et al., 2007; Ahmadhadi et al., 2007, 2008; Amrouch et al., 2010a; Evans, 2010; Savage et al., 2010; Casini et al., 2011; Shackleton et al., 2011; Tavani et al., 2011a, 2011b; Beaudoin et al., 2012; Keating et al., 2012; Tavani et al., 2012a; Awdal et al., 2013; Carminati et al., 2013, among others). A common observation in the great majority of this kind of study is the occurrence, in cylindrical folds, of a deformation pattern characterised by (i) contractional and extensional deformation structures trending parallel to the fold axis (longitudinal structures), (ii) extensional deformation structures trending perpendicular to the fold axis direction, and (iii) conjugate strike-slip faults trending at high angle to the fold axis direction (e.g. Hancock, 1985; Cooper, 1992). The latter two are defined as transversal structures (e.g. Storti and Salvini, 1996) (Fig. 1).

The Andersonian theory of faulting (Anderson, 1951) predicts for orogenic systems a contractional stress ellipsoid with a vertical minimum principal axis σ_3. This assumption has enjoyed widespread adoption in analytical (e.g. Elliott, 1976; Chapple, 1978; Davis et al., 1983; Dahlen et al., 1984; Fletcher, 1989) and numerical models (e.g. Koons, 1995; Beaumont et al., 1996; Simpson, 2011; Ruh et al., 2012) of thrust wedge dynamics and kinematics. Field-based structural geology and deformation microstructure analysis (e.g. calcite twins, Lacombe, 2010), document that the principal axis σ_3 has been mostly sub-horizontal over large areas, both before and during thrusting (e.g. Lacombe et al., 2012). This observation that σ_3 rather than σ_2 is horizontal in fold and thrust belts, implies stresses associated with strike-slip rather than compression, and is referred to here as the σ_2 paradox. In the following sections, we provide a review of the typical structural assemblages that occur in the different sectors of foreland fold-and-thrust belts and foreland basin systems, with the twofold purpose of: (1) discussing how inherited extensional structures developed during foreland flexure/foredeep formation can provide properly oriented discontinuities facilitating the nucleation of large thrusts, even when σ_3 instead of σ_2 lies on fault surfaces; (2) placing constraints on the stress field evolution before and during thrusting, showing and discussing a robust explanation of the σ_2 paradox. Available data, in fact, suggest for two early-orogenic extensional stress field configurations characterised by mutually perpendicular layer-parallel stretching directions, respectively (Fig. 2). This deformation predates layer parallel shortening (LPS), which very frequently occurs in a strike-slip stress field configuration. Subsequent thrusting and fold amplification may imply a severe time-space dependent reorganisation of the stress field that, in the majority of the structural positions within folds, can continue to be characterised by a sub-horizontal σ_3.

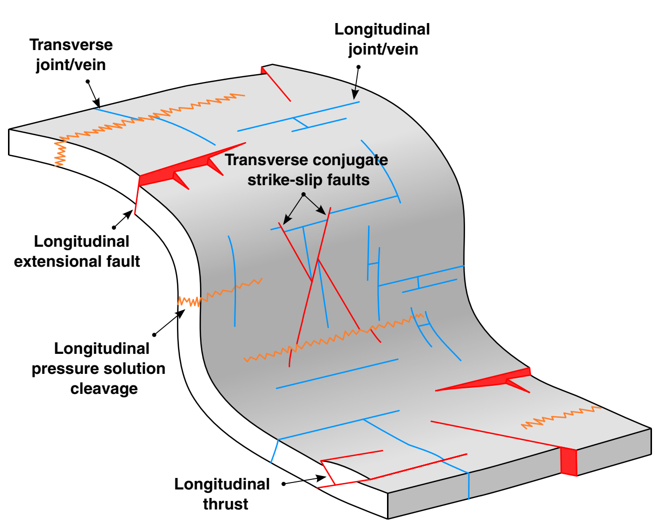

Fig. 1. Geometry of deformation structures commonly observed in thrust-related anticlines.

2. Deformation structure patterns in foreland fold-and-thrust belts

Despite its apparent simplicity (Fig. 1), the deformation pattern recorded in fold-and-thrust-belts typically results from a long-lasting pathway that can be schematically simplified in six major stages (Fig. 2): (i) foreland flexuring, taking place in the peripheral bulge and in the outermost region of the foredeep; (ii) along-strike stretching, occurring in the foredeep; (iii) layer-parallel shortening, which may occur both in the innermost region of the foredeep and at the toe of thrust wedges; (iv) syn-folding deformation sensu-stricto, occurring during the growth of thrust-related anticlines; (v) late stage fold tightening; and (vi) gravity-driven extensional deformation.

2.1. Foreland-flexuring

Convergent plate margins are characterised by the development of extensional deformation structures such as joints, veins and dilation bands, oriented parallel to the belt-foreland basin system (Fig. 3A). These structures, which form the older syn-orogenic assemblage, are associated with the flexure of the downgoing lithosphere. Flexuring causes outer-arc extension in the peripheral bulge and in the outermost sector of the foredeep (Turcotte and Schubert, 1982; Bradley and Kidd, 1991; Doglioni, 1995; Langhi et al., 2011). The minimum principal axis of the stress ellipsoid σ_3 lies on the bedding surfaces and strikes perpendicular to the foredeep trend. The effective minimum principal axis of the stress ellipsoid can attain negative values in the shallow subsurface, whilst the effective minimum stress can attain negative values also at depth. Development of longitudinal extensional faults with rather constant, high cutoff angles during this stage, indicates that the overburden favours a stress field with a positive and sub-vertical σ_1. Perpendicularity between bedding and σ_1 in the entire peripheral bulge area ensures that slip along bedding-parallel anisotropies is inhibited. The σ_2 principal axis of the stress ellipsoid strikes orthogonal to the σ_1–σ_3 plane, that is sub-horizontal and parallel to the peripheral bulge trend. Foreland flexure-related deformation structures are increasingly documented in both exposed foreland areas and within the adjacent fold-and-thrust belt frontal regions (Calamita and Deiana,