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Extensional fault arrays in strike-slip and transtension

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Abstract

Sedimentary basins developed under conditions of strike-slip or transtension are subject to significant rotational strains, yet faults developed in such regimes are commonly explained using simplified models that ignore rotation. The heaves of extensional faults developed provide a means of quantifying this rotation. For ideal strike-slip (simple shear), the apparent stretch due to fault heaves can be related simply to shear strain. At shear strains (γ) above 1.0, previously formed extensional faults begin to show inversion as reverse faults, becoming fully inverted at $\gamma = 2.0$. In transtensional basins, the apparent stretch is related, in addition, to the initial orientation of the faults, which may itself be related to the incremental strain. In the Stellarton basin of Nova Scotia, Canada, fault heaves and orientations can be measured from subsurface mine plans. Measurements of these quantities indicate that strain was only mildly transtensional, with a small ($<10°$) angle of divergence (α). The measurement of fault heaves potentially provides detailed information on strain wherever strike-slip or transtensional basins have been explored in detail by seismic or other subsurface methods.

Keywords: Kinematics; Strike-slip; Transtension; Fault; Strain; Pull-apart basin

1. Introduction

Sedimentary basins developed in strike-slip settings are subject to deformation from the earliest stages of basin development. However, many analyses of the geometrical features of such basins have been based on, and limited by, hypothetical orientations of stress axes, and infinitesimal strains (e.g. Fig. 1a). Such models neglect the effects of incremental rotations in progressive strain (illustrated schematically for simple shear in Fig. 1b and c). In contrast, kinematic analyses of thrust belts and rifts have focussed on the development and effect of features that involve significant rotations during progressive strain, such as thrust duplexes and listric extensional growth faults. Thus, progressive deformation of sedimentary rocks in these settings is relatively well understood. The effects of rotational strain in strike-slip basins have been relatively neglected, probably because this deformation inevitably involves large departures from plane strain, and is therefore harder to handle geometrically.

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This paper develops a simple kinematic model for the deformation of a sedimentary basin in a strike-slip setting, where extension is manifested in the development of normal faults. The model is based in part on structures mapped in the subsurface of the coal-bearing Stellarton Basin (Fig. 2) in the Carboniferous of Nova Scotia, in the Appalachians of eastern Canada (Waldron, 2004). Published descriptions of other strike-slip basins (Fig. 3) suggest that extensional faults are common, and therefore that the kinematic analysis applied to the Stellarton example is applicable to many other basins developed in comparable settings.

2. Fault arrays in strike-slip and transtensional basins

2.1. Kinematic styles of basin deformation

Fault arrays are common in basins developed in strike-slip and transtensional settings. In some cases the intra-basinal faults are predominantly strike-slip, with rotation of fault blocks about vertical axes in strike-slip duplexes (Woodcock and Fischer, 1986) and similar configurations; Fig. 4a shows one such kinematic style, based on figures by Dibblee (1977),

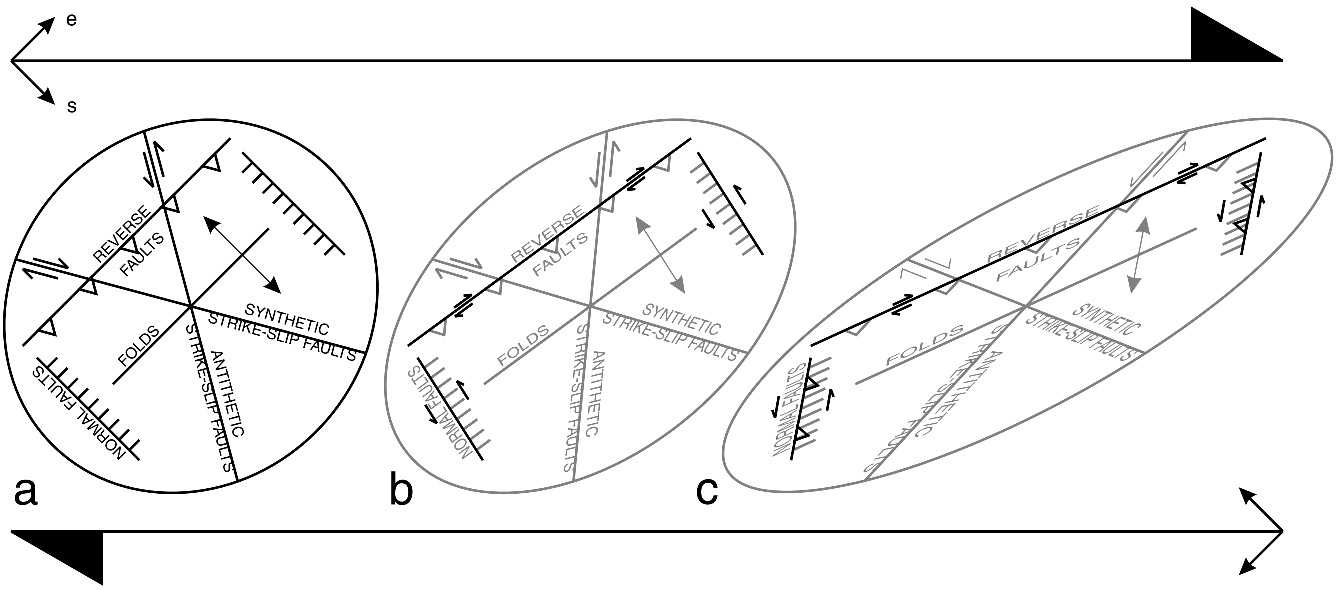

Fig. 1. (a) Diagram illustrating incremental strain associated with simple-shear deformation in a strike-slip zone, after Harding (1974). (b) Modification of (a) by continued simple shear, showing that previous (grey) normal and thrust faults acquire oblique slip (black). (c) Continued shear leads to inversion (black) of previous (grey) normal faults.

and Christie-Blick and Biddle (1985). For example, kinematic models proposed for the Mojave Desert and other basins related to the San Andreas fault (e.g. Garfunkel, 1974; Garfunkel and Ron, 1985; Dokka et al., 1998) are dominated by vertical rotations, in some cases documented with extensive paleomagnetic evidence. However, in many examples, faults with extensional, normal-sense slip are dominant within a basin, typically in an en échelon arrangement (Fig. 4b). This type of behaviour is here termed extension-dominated. Allen et al. (1998) have noted that significant rotations must occur under these circumstances also, on both horizontal and vertical axes, as shown in Fig. 4b. However, the relationship between rotation and the overall deformation environment has not been quantified.

A simple comparison of the bulk strain involved in the two styles suggests that extension-dominated basins should prevail in transtensional settings, because they produce a significant increase in basin-area, whereas wrench-dominated basins probably represent bulk strains that more closely approximate ideal strike-slip. A third, thrust-dominated style, would be anticipated in transpressional settings (e.g. positive flower-structures) where a significant amount of vertical extension occurs.

2.2. Characteristics of extension dominated basins

Arrays of normal faults in natural sedimentary basins deformed in strike-slip settings have been described by many authors (Harding, 1974; Dibblee, 1977; Aydin and Nur, 1985; Cemen et al., 1985; Harding et al., 1985; Wood et al., 1994; Allen et al., 1998). There is significant variation in the fault orientation both within and between basins; in many cases, fault orientations depart significantly from the orientations predicted by Fig. 1a. For example, Rodgers (1980) identified a small basin on the San Jacinto fault where normal faults are almost perpendicular to bounding strike-slip faults (Fig. 3). There are of course several possible explanations for this variation. Pre-existing basement features, or earlier strike-slip faults, may control the orientation of normal faults. Normal faults may develop during fault propagation, at fault tips, which are areas of inhomogeneous stress and strain. Also, basins may depart from the ideal of simple shear illustrated by Fig. 1; transtensional and transpressional strains will produce different initial fault orientations. Finally, progressive strain is likely to change the initial orientations of faults, either by rotation as shown in Fig. 1b and c, or by folding. Many of these effects can be seen in analogue models (Dooley and McClay, 1997; Rahe et al., 1998; Sims et al., 1999), in which normal faults are initiated in variable orientations and undergo rotation in the sense shown in Fig. 1.

The Pennsylvanian Stellarton basin of Nova Scotia (Yeo and Gao, 1987; Waldron, 2004) is interpreted as a pull-apart basin developed at the dextral Cobequid–Hollow fault

Fig. 2. Extensional faults in the Stellarton basin, Nova Scotia. (a) Simplified map of Stellarton basin showing location of underground coal mine data and subsurface fault traces (after Waldron, 2004). Insets show location in Nova Scotia of Stellarton basin and major Carboniferous fault zones: CCFZ = Cobequid–Chedabucto Fault Zone; HFZ = Hollow Fault Zone. (b) Enlarged structure contour map of subsurface Foord coal seam and faults that cut it. Contours are derived from original mine plans (hence depths in feet below sea level) as described by Waldron (2004). Cross-sections A–A′ to E–E′ show deformation of Foord seam by folds and faults. Location ticks show UTM (Universal Transverse Mercator) grid coordinates.