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The role of bed-parallel slip in the development of complex normal fault zones

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ABSTRACT

Normal faults exposed in Kardia lignite mine, Ptolemais Basin, NW Greece formed at the same time as bed-parallel slip-surfaces, so that while the normal faults grew they were intermittently offset by bed-parallel slip. Following offset by a bed-parallel slip-surface, further fault growth is accommodated by reactivation on one or both of the offset fault segments. Where one fault is reactivated the site of bed-parallel slip is a bypassed asperity. Where both faults are reactivated, they propagate past each other to form a volume between overlapping fault segments that displays many of the characteristics of relay zones, including elevated strains and transfer of displacement between segments. Unlike conventional relay zones, however, these structures contain either a repeated or a missing section of stratigraphy which has a thickness equal to the throw of the fault at the time of the bed-parallel slip event, and the displacement profiles along the relay-bounding fault segments have discrete steps at their intersections with bed-parallel slip-surfaces. With further increase in displacement, the overlapping fault segments connect to form a fault-bound lens. Conventional relay zones form during initial fault propagation, but with coeval bed-parallel slip, relay-like structures can form later in the growth of a fault. Geometrical restoration of cross-sections through selected faults shows that repeated bed-parallel slip events during fault growth can lead to complex internal fault zone structure that masks its origin. Bed-parallel slip, in this case, is attributed to flexural-slip arising from hanging-wall rollover associated with a basin-bounding fault outside the study area.

1. Introduction

Fault zones often display complex internal structure comprising two or more anastomosing, synthetic slip-surfaces. When mapped in three dimensions the degree of complexity is seen to vary, and parts of a fault zone with multiple slip-surfaces can alternate with parts with a single surface. This spatial variation in structure records the evolution of the fault zone with more complex structures arising from several processes including linkage between initially unconnected fault segments, removal of wall rock asperities and sidewall ripout (e.g. Childs et al., 1996b, 2009; Peacock and Sanderson, 1991; Swanson, 2005). This paper demonstrates that bed-parallel slip can make a significant contribution to the development of multiple slip-surfaces within fault zones and therefore to complex internal fault zone structure.

Fig. 1 shows examples of outcrops of normal fault zones in Kardia lignite mine, Ptolemais Basin, Greece, that were affected by bed-parallel slip during their growth. On first inspection both outcrops look like typical cross-sections through normal fault zones, but closer examination reveals geometric characteristics associated with bed-parallel slip. A part of the stratigraphy is repeated in each fault zone and the slip-surfaces in each have discrete steps in vertical displacements (i.e. throw), two features indicative of bed-parallel slip. The most obvious step is at the lower tip of the hanging-wall slip-surface on the right-hand side of Fig. 1a where the throw steps from 2.5 m to 5 cm. Equally significant but less obvious steps occur on the other slip-surfaces in these outcrops. Our interpretations of these and other outcrops, as described

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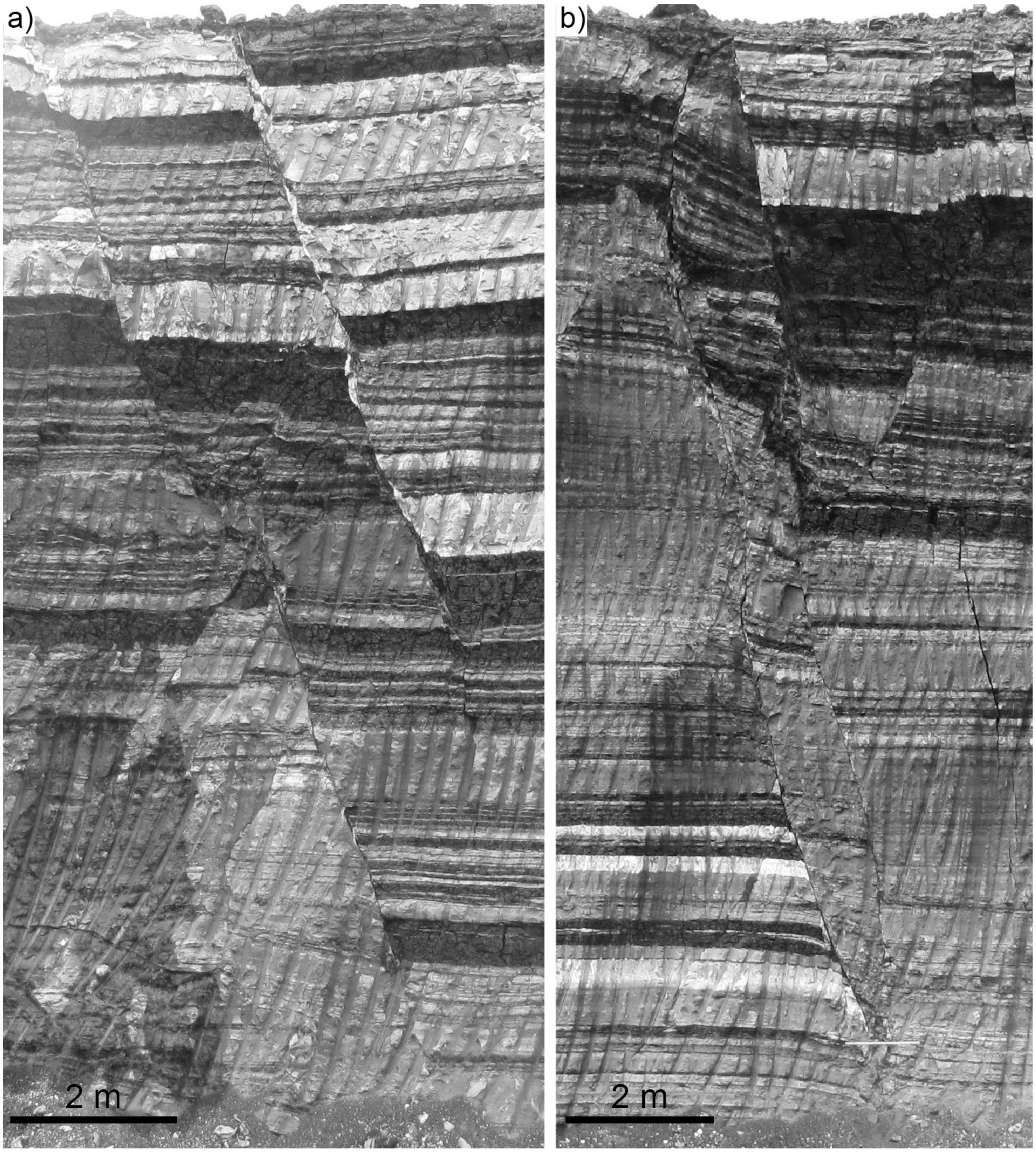

Fig. 1. Outcrop photographs of ca. 4 m (a) and ca. 5.5 m (b) throw normal fault zones offsetting the Pliocene lignite-marl sequence in Kardia open pit mine, Ptolemais Basin, NW Greece.

later, demonstrate that bed-parallel slip during the growth of these fault zones gave rise to the observed complex fault zone structure.

Bed-parallel slip is quite common in multilayer sequences, and can be related to flexural-slip folding (e.g. Tanner, 1989; Watterson et al., 1998), flexural-slip within fault propagation folds (e.g. Withjack et al., 1990; Gross et al., 1997; Sharp et al., 2000; Ferrill et al., 2007) and tilting of multilayer sequences (e.g. Ferrill et al., 1998; Watterson et al., 1998; Wibberley et al., 2007; Van der Zee et al., 2008). The influence of bed-parallel slip on faulting has been discussed in the published literature (Salehy et al., 1977; Ferrill et al., 1998; Watterson et al., 1998; Wibberley et al., 2007; Van der Zee et al., 2008; Roche et al., 2012a), but without a detailed investigation of its impact on fault zone structure. Watterson et al. (1998) described how fault zone and fault rock thickness can be increased by the removal of fault surface asperities formed by offset of the margins of fault zones by bed-parallel slip during faulting. Here we examine the impact of bed-parallel slip on fault zone internal structure and how it can give rise to the formation of multiple slip-surfaces within fault zones.

Kardia mine provides the ideal setting for this study because: (i) there is abundant and clear evidence of coeval bed-parallel slip and fault displacement within the multilayer sequence, (ii) the alternating sequence of lignite and marl allows for detailed inspection of fault displacements, and (iii) details of fault zone structure are preserved at high strains with individual fault slip-surfaces defined by discrete features unaffected by brecciation, tensile fractures or significant development of fault rock. In this paper, we present several examples of fault zone structure that on first inspection resemble typical cross-sections through fault zones but that actually initiated as single fault surfaces that became progressively more complex due to the influence of bed-parallel slip. The objectives of this paper are to illustrate the potential significance of