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The mechanics of first order splay faulting: The strike-slip case

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ABSTRACT

First order splay faults, as defined here, are secondary faults that form at acute angles symmetrically on either side of a primary fault of the same sense of shear. We show that these faults form when the primary fault becomes critically misaligned with the principal stresses such that splay fault formation, on the optimum plane for faulting, is favored. First order splay faults, in distinction from other splay faults, are secondary only in the temporal sense – they are subsequent but not subordinate, in a tectonic sense, to the primary fault. Here we analyze the case of strike-slip faults, and compare it with data for several continental transform fault systems, where we show that the splay faults form in the most favorable direction: parallel to the plate motion vector. We also discuss and speculate on several outstanding problems with regard to first order splay faults: the placement of them in space, means by which primary faults become misoriented in the stress field, and the mechanics of first order splay fault-primary fault junctions, once formed.

1. Introduction

The term ‘splay fault’ is common in the literature, but it is usually used in a casual sense to refer to any secondary fault that diverges from another at an acute angle. While there are a variety of secondary faults that might fit that simple description, here we define first order splay faults in a more restrictive way.

This work is motivated by a systematic study of branching within the San Andreas fault system (Ando et al., 2009). In that study we found a dominance of fault junctions of a generalized “y” shape (Fig. 1, inset). If we call the long branch of the “y” the primary fault and the short branch the splay we found that the angle between them showed a well-defined distribution as shown in Fig. 1. The distribution is mirror symmetric: the same distribution of splay angles is found for left (negative angle) and right (positive angle) splays. Within each type of splay, right or left, the distribution is strongly skewed with the peak value near the lower limit. This suggests that the splay formation mechanism has a well-defined minimum angle but a poorly defined maximum. In both cases the peak value of the splay angle is about 17° (see Ando et al. (2009) for a more detailed analysis). Because the San Andreas fault was continuously active during the formation of the branches shown in Fig. 1, we note that during the formative stage primary and splay faults were concurrently active. For the San Andreas system, the numbers of right and left splays are approximately equal. These splay faults, such as the San Jacinto, Calaveras, and Hayward faults, though secondary, in the sense that they formed after the formation of the San Andreas fault, are of first order; they are of the same order of magnitude as the San Andreas in terms of their length, slip rate, or net slip.

These well-defined properties of what we have called first order splay faults suggest to us that we have isolated a set of secondary faults that must share a common mode of origin. It is the purpose of this paper to explore that mode of origin. To begin, in order to differentiate what we wish to call a first order splay fault from all other species of secondary faults, some of which have also been called splay faults, we need to offer a definition of what we mean by a first order splay fault. We start with a precise definition as shown in Fig. 1 (inset). Later, when we have offered a mechanical model for their origin, this definition becomes more restrictive.

The first order splay faults in Fig. 1 have purposefully been drawn as not meeting the primary fault because it is shown later that they do not, in general, do so. However, if the splay fault is projected to meet the primary fault, it will define a line of intersection. We then can make our definition.

Definition: For any fault to be called a first order splay fault its sense of shear must be the same as the primary fault, the respective slip vectors must lie in the plane perpendicular to the line of intersection of the two faults, its slip vector must lie symmetrically at an acute angle on either side of that of the primary fault, and both faults must be concurrently active at the

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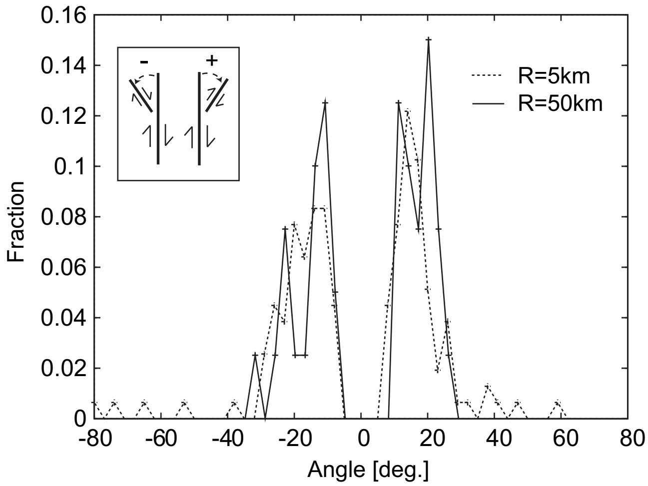

Fig. 1. Histogram of splay faults of the San Andreas fault system, from Ando et al. (2009). The geometry of the splays is shown in the inset, right splays are given positive angles, left splays, negative. The splay angle distribution was found to be independent of *R*, the scale length used in fitting the faults. Two extreme values of *R* are shown in the figure.

time of formation of the splay fault. They must also be of the same order as the primary fault, in terms of length, slip rate, or total slip.

The first thing to say about this definition is that it does not specify the direction of the line of junction; thus it can apply to strike-slip, normal, thrust faults, or anything in between. Here, however, we will be concerned only with strike-slip cases. Most studies of secondary faults have been of those that are produced by and restricted to the regions of stress concentration associated with fault tips, jogs, and other geometric irregularities. (e.g. de Joussineau et al., 2007; Du and Aydin, 1995; Kim and Sanderson, 2006; Martel and Boger, 1998). Because such secondary faults are restricted to the region of stress concentration they are of second order with respect to the primary fault. Some of these have been called splay faults, but they do not fit our definition of first order splay faults. De Joussineau et al. (2007), for example, used the term splay to refer to 'wing' cracks, which are opening mode cracks that form 'horsetails' on the extensional sides of mode II fault tips. Although these may be later reactivated in shear and thus be called faults, they are asymmetric with respect to the primary fault, they do not originate as faults, and they are of second order. Reidel shears, a form of secondary fault that is not tip-related (e.g. Freund, 1974), are also eliminated because they are asymmetric with respect to the sense of shear. The statement 'same shear sense' also eliminates conjugate faults and various types of antithetic faults. The statement 'concurrently active' eliminates junctions of faults that may have formed during different tectonic episodes.

There have been various efforts at modeling fault branching. Du and Aydin (1995) considered the effect of the orientation of the remote tectonic stresses on the propagation of a strike-slip fault. They found that if the maximum compressive stress σ_1 makes an angle with the fault greater than 45° with a right-lateral strike-slip fault, the fault would bend into the extensional side of the fault tip (positive angle in terms of Fig. 1) at an angle proportionate to the degree to which the angle of σ_1 exceeds 45°. Conversely, if the σ_1 direction is less than 45° the bend would be into the compressional quadrant (negative). (That the neutral angle at which the fault does not bend is 45° rather than, say, the Coulomb angle results from the particular failure criterion they assumed, that of maximum distortional strain energy, in which the normal stresses are squared so that compression and tension are not discriminated.) Their model does not define a minimum bend angle, as the results of Fig. 1 would require, because they choose to deal with locations near the tips of pre-existing faults where stress perturbations are strong; the effect of this perturbation is dominant only near these tips, at greater distances the remote tectonic stress becomes predominate.

These modeling results suggest that the response of the fault tip to variations of tectonic stress direction will be a fault bending rather than branching. Although we point out some examples of this behavior later, branching at the fault tip does not appear to explain, in general, the formation of first order splay faults.

Poliakov et al. (2002) studied the problem of branching resulting from the dynamic stresses associated with earthquake propagation. Because the end of the earthquake may be well away from the physical end of the fault, this problem considers branching from the stem of the primary fault, which seems more relevant to our problem. They found that such branching is influenced by the remote tectonic stress direction but that this was asymmetric: for a given deviation of σ_1 from the neutral direction, the favored branch on the extensional side had a greater angle than one on the compressional side. This difference from the Du and Aydin (1995) results is because Poliakov et al. (2002) assumed a frictional failure criterion for the fault branches.

These results are instructive, but they assumed cohesionless (i.e. pre-existing) branches. The effect of pre-existing branches, jogs, and other geometrical irregularities on earthquake propagation is an important problem in earthquake mechanics and has therefore attracted considerable interest (e.g. Bhat et al., 2004, 2007; Duan and Oglesby, 2007). It is not, however, our problem, which is the initial formation of first order splay faults in cohesive rock.

All the modeling studies of fault branching reviewed above assume that the branch fault nucleates in the stress concentration associated with the fault or earthquake tip or some other geometrical irregularity of the primary fault. All such cases predict that the secondary fault initiates at the primary fault and propagates away from it. We point out later that there is a considerable spatial gap between the primary fault and the nearest tip of first order splay faults, which are best interpreted as having nucleated at a distance from the primary fault and then propagated towards it. This observation greatly simplifies our problem, because it means that we can ignore stress concentrations associated with the primary fault and pose the problem entirely in terms of the regional tectonic stresses.

2. A criterion for first order splay fault initiation

The term 'branching' was used in the introduction in a geometric, not genetic sense. However, the terms primary and secondary faults were used with care, to indicate that one pre-existed the other. These are essential to what follows.

2.1. Failure criterion for first order splay faulting

We propose that first order splay faults form when the primary fault is sufficiently misoriented with respect to the stress field that it becomes favorable to form a new fault in the optimal orientation; this is the splay. This situation is illustrated in Fig. 2 with a Mohr diagram, in which there are two failure criteria: a frictional one for sliding on a pre-existing fault, and a Coulomb criterion, with cohesion τ_o, for the formation of a new fault. Let us suppose that the primary fault has become misoriented with respect to the principal stresses (there are various ways that this can happen, discussed in a later section). This is represented as a rotation of the fault, either to the right or left, on the Mohr circle, as shown in the inset to Fig. 2. As the fault rotates in the stress field, in order for the primary fault to remain active, the stress difference $(\sigma_1 - \sigma_3)$ must increase, as shown