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Vector analysis of fault bends and intersecting faults: Discussion

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MCCAIG (1988a) has presented an interesting analogy between the kinematic constraints of rigid plates at triple junctions to the generally non-rigid behavior of fault bends and fault intersections at smaller scales. Based on the stability criteria for rigid blocks in velocity space, geometric constraints on the non-rigid behavior of fault blocks are proposed in terms of likely wallrock strains. The analysis can be a significant contribution to unraveling the kinematics of structures on many scales, and provides one additional constraint on complex natural systems with many degrees of freedom.

In this discussion, I would like to suggest the following: (a) the kinematic scenarios which increase a junction's stability may vary over a much wider range of geometries than depicted by McCaig; (b) additional kinematic solutions may be contrived which also satisfy the conditions of stability; (c) although the analysis is successful at identifying certain deformation mechanisms in velocity space, it may overlook others that contribute to the wallrock strain such as layer-parallel shear. As a result, the method by itself provides limited constraints on displacement rates and the orientation of structures such as faults, kink zones and cleavage. This analysis would be best coupled with dynamic constraints (e.g. from fabric data as well as theoretical and experimental models) to eliminate the numerous unlikely geometric solutions. An example of this coupling is suggested for a simple fault bend. As a minor but preliminary note, clarification of the term 'stability' seems appropriate.

DEFINITION OF STABILITY

McCaig (1988a) suggests, as did McKenzie & Morgan (1969), that a stable triple junction is one whose configuration remains unchanged after an increment of plate movement. This is an ambiguous usage of the term 'stable' since it has been suggested that triple junctions may change configurations while satisfying 'stability' in velocity space, as well as configurations that remain unchanged regardless of an upset of the stability condition (e.g. Apotria & Gray 1988). Furthermore, McCaig has suggested an example where a stable fault bend evolves to another stable configuration by ramp collapse (McCaig's figs. 3a & b). In a strict sense, triple junction stability is defined in velocity space where two conditions must be met: (a) the relative velocity vectors of the *rigid* blocks must sum to zero; and (b) a reference frame must exist in velocity space which is stationary with respect to a point of uniform velocity on each of the boundaries. The dashed lines in the graphical representation of stability (McCaig's fig. 1) depict the loci of points of uniform velocity for that boundary. If the three dashed lines intersect at a point, then there exists a point of uniform velocity on each boundary which is fixed, this is the velocity of the triple junction. McCaig, in his formulation of kink zones, has cleverly made use of the fact that the boundary between two blocks need not have the same velocity as either constituent block.

FORETHRUST AND BACKTHRUST SYSTEMS

In general, the relative displacement rates between fault blocks are poorly constrained from field evidence, and if known, are only time averages. Because the relative velocity of fault blocks is likely to be non-uniform, employing the stability criteria becomes a much more complicated and ill-constrained task. During the evolution of a three-fault system, displacement rates are likely to change due to perturbations in the geometry of fault surfaces as well as reorientation of local stress fields, both having a profound effect on the resulting wallrock strains. However, for the purposes of this discussion, it is assumed that displacement rates are continuous. This discussion omits the treatment of listric normal faults and strike-slip faults, although the same considerations apply.

With regard to forethrust and backthrust systems, volume loss is suggested by McCaig as a possible mechanism for maintaining stability, where one block is subdivided into two, thereby creating a 'quadruple junction'. The new boundary (*CC*′ in McCaig's fig. 2a) is the locus of volume loss. The growth rate of this locus is equal to the vector from the midpoint of CC′ to *A*. While it is realized that the 'locus' may actually be a distributed zone, there are few constraints provided by the vector analysis alone on its orientation and magnitude. The orientation of the volume loss zone, perhaps developed as a pressure-solution cleavage, is drawn perpendicular

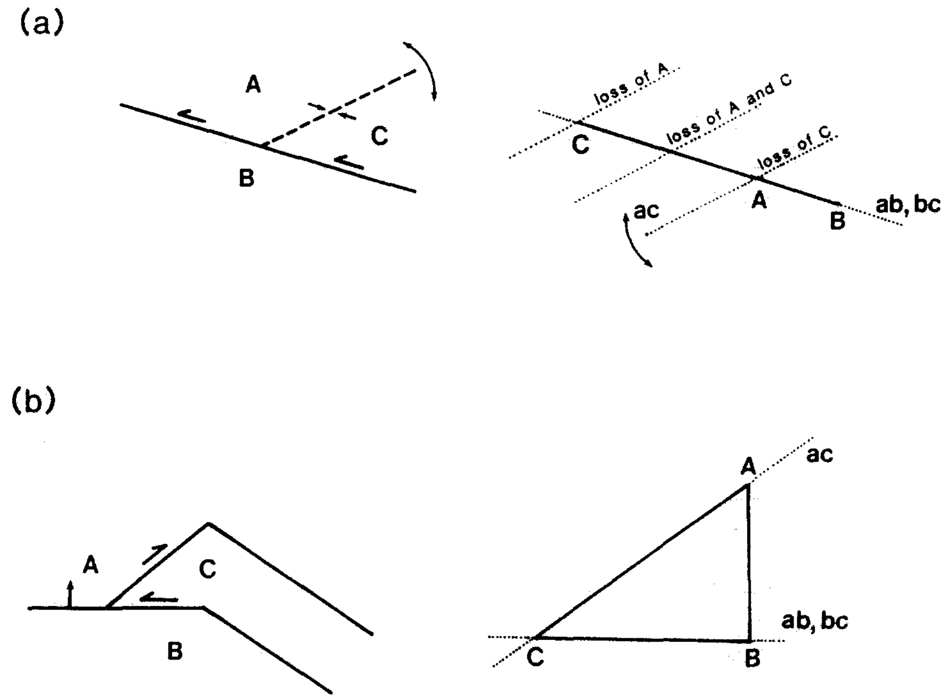

Fig. 1. Alternative kinematic scenarios which satisfy the condition of stability. (a) Preferential volume loss between blocks *A* and *C* in direct space and velocity space. The velocity triangle for this triple junction collapses to a single vector. The orientation of the zone can vary within 180°. Complete volume loss of block *A* or *C* are end-members of a spectrum, where the locus (dotted line) is fixed to block *C* or *A*, respectively, in velocity space. (b) Under the rigid block assumption, a three fault junction is stable if separation occurs between block *A* and *B*.

to the relative velocity **CC**′. Geometrically, this is a special case where the volume loss is symmetrical about the zone, however, it could have any orientation between faults *AC* and *AC*′, with varying degrees of asymmetry, as long as the locus *cc*′ in velocity space passes through point A. The vector analysis further suggests that the magnitude and orientation of the volume loss zone at boundary *CC*′ is a function only of the orientations and relative displacement rates of faults *AC* and *AC*′. This can be misleading because it ignores the primary controls on volume loss processes, namely the rheology of the wallrock material and the differential stress. The orientation of the volume loss zone would be more usefully constrained if the orientation of the principal stresses in block *C* at the time of deformation could be obtained.

The kink zone is an interesting alternative to volume loss, where there is generally no discrete and stationary fault boundary between sub-blocks *A* and *A*′, but a zone of kinking (McCaig's fig. 2b). The kink zone need not be vertical as shown by McCaig, but can be at any angle between fault *AB* and fault *AC*. Varying the orientation of the kink zone results in a trade-off between relative velocities **AA**′, **AC** and **A′C**. The kink zone is not fixed to either *A* or *A*′, but to block *C*. Apparently, the displacement rate across the kink zone (vector **AA**′) is determined solely by the dip of fault *A′C* if the velocity **AB** is fixed. However, the mechanical behavior of block *A* exerts a fundamental control on the displacement rate **AA**′, and whether or not there is a loss of cohesion across the kink zone. More complicated deformation is possible if vector **AA**′ is not parallel to the kink zone (as in the case of layer-parallel shear discussed below).

This junction can also be stabilized by a slightly different process whereby volume is lost preferentially between blocks *A* and *C*. In this case the velocity triangle collapses to a single vector, and no sub-blocks need be formed (Fig. 1a). The locus of uniform velocities along boundary *AC* (the dashed line *ac*) is fixed to block *C* if the entire volume is lost from block *A*, fixed to *A* if volume is lost from block *C*, fixed at any point in between AC if volume is lost from both blocks, or lastly, the boundary *AC* may move with time. The orientation of a volume loss boundary can span 180° between boundary *AB* and *BC*.

There is still yet another kinematic alternative to volume loss and kinking processes which maintains the rigid block assumption, and involves the separation of blocks *A* and *B* (analogous to plate spreading). An example of where this might occur is at the toe of a blind thrust, which is a special case of the forethrust–backthrust system (Fig. 1b). Within a incipient detachment horizon, before the arrival of the thrust toe (block *C*), there may be no motion between *A* and *B*, or kinematically stable sliding involving only the two blocks. As the toe (triple junction) passes, there is no fault-parallel motion between blocks *A* and *B* (which is unstable for rigid blocks), but separation as block *C* is inserted between *A* and *B*, effectively peeling back the cover rocks of block *A*. The observation of wallrock strains near fault bends suggests that, although this solution is geometrically possible, it is mechanically unlikely.

FAULT BENDS AND RAMP COLLAPSE

Hangingwall strain models such as those of Sanderson (1982) suggests that the strain be accommodated by either (a) vertical shear, or (b) a layer-parallel shear mechanism at a fault bend. The latter, a more probable mechanism in upper, 'colder' levels of layered thrust belts, has been further developed by Suppe (1983). McCaig has demonstrated that the vertical shear mechanism (or shear at a high angle to bedding) provides a stable configuration in velocity space, where the relative velocity between A and A' is parallel to the kink zone (McCaig's fig. 3a). However, layer-parallel shear is apparently not reconcilable in velocity space. If the fault bend is drawn as a triple junction, the relative velocity between blocks A and A', which would be parallel to the fault surface for layer parallel shear, is not compatible with the orientation of the kink zone, and is therefore unstable. In this case, the vector analysis alone provides no indication of the actual deformation mechanism.

DYNAMIC CONSIDERATIONS

In the previous examples, I have tried to demonstrate that vector analysis at fault intersections and bends, in and of itself, provides very few constraints on the displacement rates and orientations of wallrock strain features. Therefore, the method would be best coupled with some appreciation of the mechanical behavior of the wallrock, as well as the state of stress in the region undergoing the deformation. This information could be deduced from fabric data in the wallrock, as well as insights from theoretical and experimental models.

A large body of literature exists concerning the mechanics and kinematics of thrust ramp deformation, a special case of the forethrust–backthrust system. Here, I will present a simple example of the hangingwall strains incurred during the development of a forethrust and backthrust, similar to McCaig's figs. 2(a) and 3(a), where reasonable estimates of the orientations of the principal stresses are known from experimental and theoretical models. The example illustrates the importance of considering the end-members of mechanical behavior (i.e. vertical vs layer-parallel shear) on the strains imposed at a fault bend.

Hangingwall accommodation structures at a fault bend are developed in non-scaled rock model experiments of thrust ramps at confining pressure (e.g. Serra 1977, Chester 1985). Discrete backthrusts with small displacements are nucleated as the hangingwall moves through the lower ramp hinge. The orientation of microcracks near the hinge in the experiments suggests that the principal stresses are inclined downward toward the foreland. During subsequent increments of motion, the backthrust becomes inactive as it passes up the ramp, while another active backthrust forms at the hinge. These experiments demonstrate that this type of triple junction is unstable for rigid blocks, and are stabilized by a kink zone fixed to the lower ramp hinge, through which hangingwall material passes (McCaig's fig. 3a). In rock models in which the hangingwall is layered with alternating strong and weak material, layer-parallel slip is a viable mechanism, and only minor development of backthrusts is observed (Chester 1985). In this case, layer-parallel slip reduces the bending stresses at the lower hinge, and reduces the need for a backthrust to accommodate bending.

The perturbation of the principal stresses near the lower ramp hinge has been substantiated by theoretical models (e.g. Wiltschko 1981). In this case, bending stresses with a homogeneous linear viscous hangingwall in the outer arc of the lower hinge may be extensional, with the maximum principal stresses inclined downward toward the foreland, the angle of inclination being an increasing function of ramp dip as well as hangingwall viscosity. Furthermore, as the competency of the hangingwall decreased (the equivalent of an increase in the layer-parallel shear mechanism), the bending resistance, the amount of extension, and therefore the inclination of the principal stresses near the lower hinge, all decreased. As in the rock model experiments, this suggests that layering anisotropy in the hangingwall reduces the need for backthrusting due to decreased bending stresses.

Thus, for this simple case, mechanical arguments have helped to constrain the orientations of the principal stresses, and by inference, the orientation of backthrusts at the apparent lower ramp hinge triple junction. The orientation of a kink zone will depend upon the amount of extension due to bending at the lower ramp hinge, if sliding resistance is small. The amount of extension depends on the ramp dip as well as the relative contribution of layer-parallel shear to the overall deformation. Because back thrusting is not likely to be the sole deformation mechanism at a fault bend, knowledge of the principal stresses provided additional constraints on the other mechanisms such as volume loss, that the vector analysis alone cannot.

In conclusion, McCaig's (1988a) application of vector diagrams in velocity space to fault bends and intersections is a significant contribution to deducing the kinematics of structures on many scales. McCaig clearly states that the vector analysis is not intended to supplant existing techniques for dealing with such fault systems. It has been the purpose of this discussion to suggest that the method should be coupled, if possible, with a dynamic appreciation of the problem. Appropriate caution should be used insofar as many stabilizing mechanisms are possible, and for any particular one, there is generally a wide range of possible configurations in velocity space that will satisfy the stability criteria. The method does eliminate certain configurations that are geometrically impossible, yet ignores the additional constraints provided by mechanics (i.e. vertical vs layer-parallel shear) which is ultimately responsible for wallrock strain. These obstacles emphasize the beauty of the rigid block assumption.