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SHORT NOTES

Vector analysis of fault bends and intersecting faults

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Abstract—An analogy is drawn between intersecting faults or shear zones and triple junctions of lithospheric plates. Vector analysis shows that fault intersections are always unstable for rigid fault blocks but can be stabilized by the presence of zones of kinking or volume change within the fault blocks.

The method allows rapid assessment of the likely location and orientation of wall-rock strains for any fault geometry and should be used to test kinematic models erected to account for field data.

INTRODUCTION

TRIPLE junctions, where three simultaneously active plate boundaries meet, are familiar elements of plate tectonics. At a triple junction the relative velocities of the three plates must sum to zero and certain rules must also be complied with if the triple junction is to remain *stable* (McKenzie & Morgan 1969). A stable triple junction is one whose configuration remains unchanged after an increment of plate movement. The velocity of a stable junction relative to adjacent plates can be defined by a point in the relative velocity plane.

In this paper an analogy is made between plate boundaries and smaller scale faults and shear zones. Geological maps and cross-sections frequently show intersecting networks of faults some of which must have been active simultaneously. Vector analysis allows stable and unstable intersections to be identified and permits the prediction of wall-rock strains which may stabilize an unstable intersection. The effects of changes in displacement rate and the propagation of new faults can be predicted, as can uplift or subsidence rates for any combination of thrust or extensional faults.

ANALOGY BETWEEN PLATE BOUNDARIES AND DEFORMATION ZONES

The assumption which underpins plate tectonics is that the plates are rigid and may not deform in the plane of section. However, movement in and out of the plane of section is permitted at spreading ridges and subduction zones and it is this which allows stable triple junctions to exist. Similar problems of compatibility have been addressed by structural geologists; for example Ramsay & Graham (1970) showed that in a shear zone with planar undeformed walls the only possible deformations are simple shear parallel to the walls and volume change perpendicular to them. Transform faults are obviously equivalent to shear zones undergoing simple shear parallel to their boundaries. Spreading ridges are geometrically equivalent to zones of symmetric volume increase, while subduction zones are equivalent to zones of asymmetric volume loss.

Figure 1 shows how the stability of a general triple junction is assessed (McKenzie & Morgan 1969). The locus of possible velocities for a triple junction joined to each of the three intersecting boundaries is defined. For example, the position and velocity of a subduction zone is fixed relative to the hangingwall plate. The triple junction can only move along the line of the trench. Therefore the locus of possible velocities for the triple junction must be a line passing through point C and parallel to the line of the trench (Fig. 1b). In Fig. 1 the triple junction is not stable since the lines ab, ac and bc do not meet at a point. A decrease in the velocity AC and

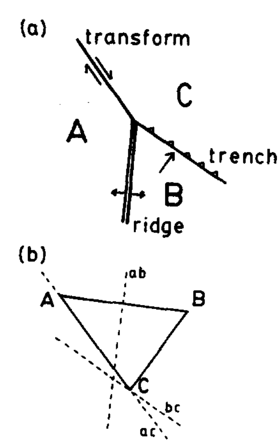

Fig. 1.(a) Triple junction between three tectonic plates. (b) Velocity triangle and stability of junction. *ab*, *ac* and *bc* are the loci of possible triple junction velocities with respect to the ridge, transform and trench (McKenzie & Morgan 1969). Since these do not meet at a point no unique velocity for the junction can be defined and it is therefore *unstable*.

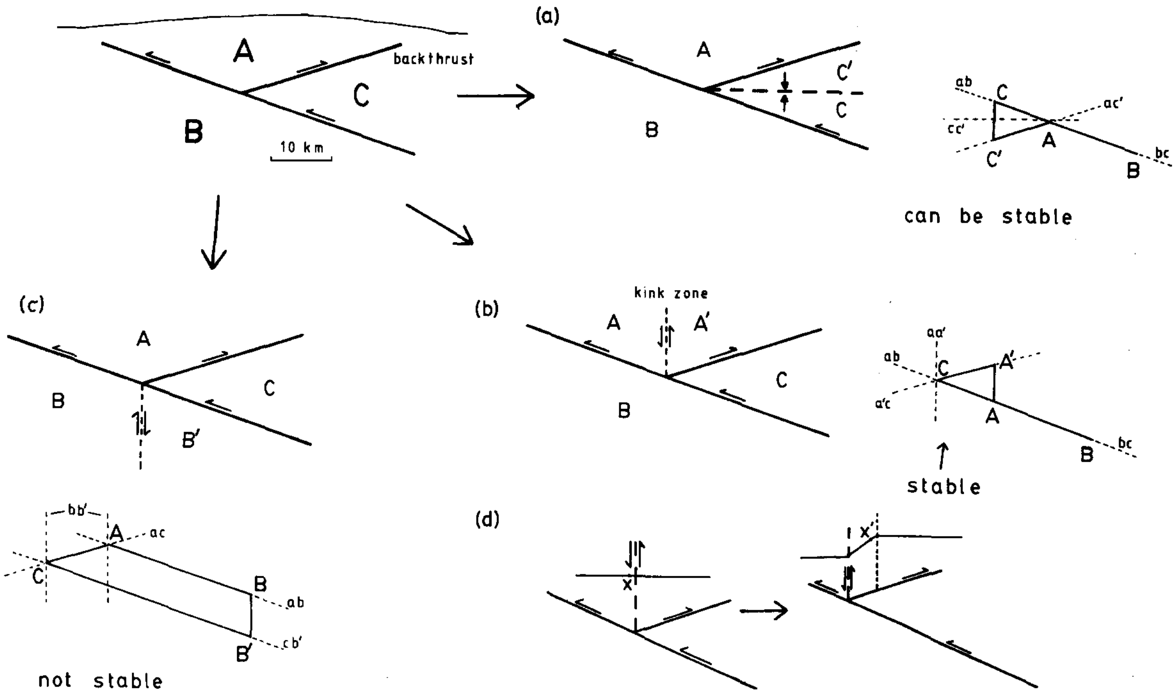

Fig. 2. Analysis of a pop-up structure. (a) Triple junction can be stabilized by a volume loss zone in block C if cc' passes through point A in velocity space. (b) A kink zone cutting block A results in a stable triple junction moving with the same velocity as block C. (c) A kink zone in block B cannot produce a stable junction. (d) Deformation of a passive marker line after 2.5 Ma of movement on the system shown in (b) with $BC = 5$ mm yr^{-1}. Note the sudden change in uplift rate of point X as it passes through the kink zone.

a change in subduction direction ***BC*** could stabilize the junction giving it the same velocity as plate C.

APPLICATION TO FORETHRUST–BACKTHRUST SYSTEMS

Figure 2 shows a schematic forethrust–backthrust system separating an orogenic belt into three blocks, A, B and C. An arrangement of this type has been proposed for the Pyrenees by Williams & Fischer (1984). This configuration is analogous to a transform–transform–transform triple junction and can never be stable (McKenzie & Morgan 1969). The 'rigid plate' assumption must therefore be relaxed permitting the stabilization of the triple junction by specific internal strains in the fault blocks.

Figure 2(a) shows one possible solution; if a zone of volume loss cuts block C into two parts it is possible to have relative movement parallel to each fault. If the velocities ***BC*** and ***BA*** are in the correct proportion to each other it is also possible to generate a *stable* triple junction moving with the velocity of block A.

Large-scale volume loss is probably unrealistic on the scale of an orogenic belt, however it may be applicable to similar geometries on a small scale. A zone of pure-shear deformation in the same position as the volume-loss zone in Fig. 2(a) would have a similar effect but would not lead to stability since the boundary C–C' must increase in length. In the velocity plane this restricts the locus of potentially stable junctions to that part of cc' lying to the left of ***C–C'***. Although pure-shear deformation within block C allows movement to be parallel to the three fault boundaries, the *instability* of the junction must inevitably lead to displacement gradients along the faults and changes in the angles between them.

A more likely solution is a *kink zone* cutting block A, as shown in Fig. 2(b). This results in uplift of A' relative to A and movement of A' parallel to the boundary between it and C. The stability criterion for a kink zone is an interesting one not considered by McKenzie & Morgan (1969). Material moves *through* the kink zone, with internal deformation being restricted to the line of kinking. The line of the kink, and any triple junction at the end of it, will therefore move relative to both A and A', and can be stable if it has the same velocity as block C, as shown. Figure 2(c) shows that a kink zone cutting block B is not a viable solution.

Once the geometry of the system and the velocities ***AB*** and ***BC*** have been specified the remaining velocities and the movement of any part of the system relative to block B can be immediately calculated. For example, if ***AB*** is 5 mm yr^{-1} and ***BC*** is 10 mm yr^{-1} and the ramp angle is 30°, the uplift rate of point X (Fig. 2d) will be 0.25 mm yr^{-1} initially and 0.75 mm yr^{-1} once the kink zone has been passed. Figure 2(d) shows that the nucleation of a backthrust will lead to a hangingwall anticline which could be misinterpreted as the result of movement over a simple fault bend at depth. This structure can be rapidly restored simply by moving the triple junction back down the main fault by the width of the kink.

An analogous structure is a triangle zone such as the Alberta Syncline (Jones 1982). Here no fault zone is present between blocks A and B so that points A and B in Fig. 2(b) will be coincident. To be stable the junction between the backthrust and the forethrust must move

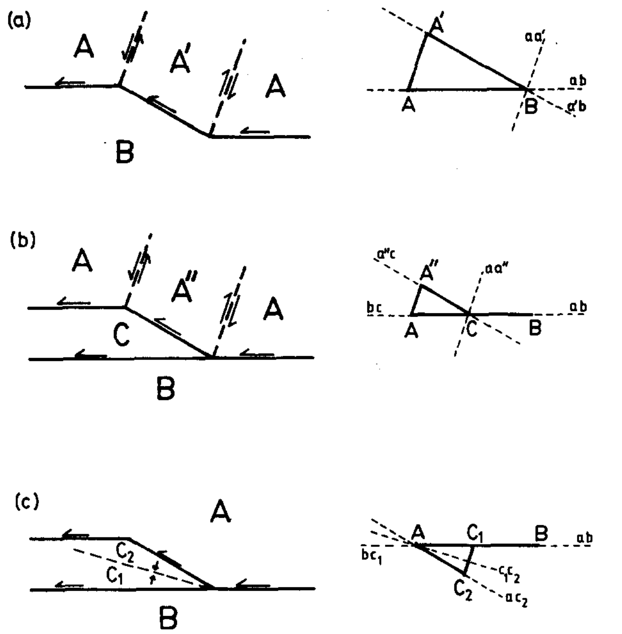

Fig. 3.(a) Movement over thrust ramp accommodated by kink zones in hangingwall block. (b) Propagation of a new flat from the base of the ramp with reduction in displacement rate over ramp. (c) Volume loss within block C can remove the necessity for kinking in block A.

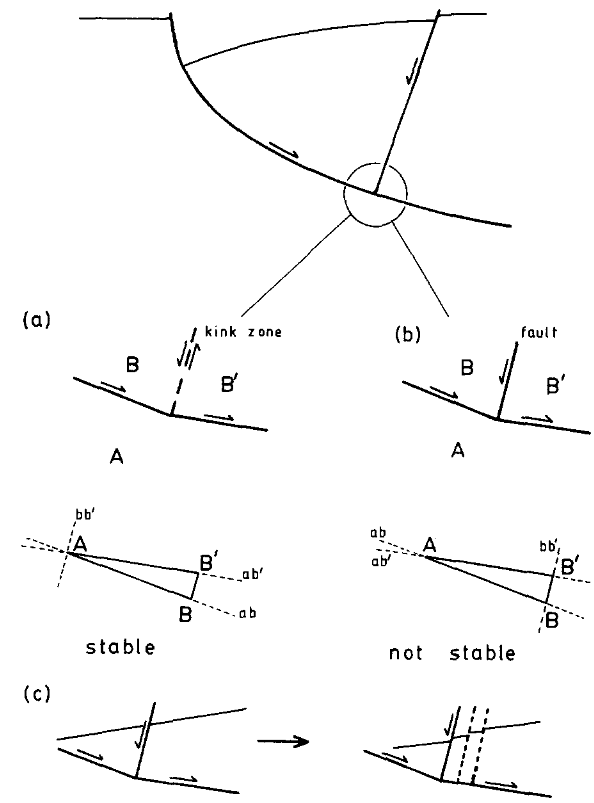

Fig. 4. Listric normal fault modelled as a series of planar segments. Movement over these can be accommodated stably by kink zones (a) or unstably by antithetic faults (b). The latter will continually move away from the triple junction and become unstable, resulting in a family of successively active antithetic normal faults.

with the velocity of block C and the kink zone A–A' is still necessary.

FAULT BENDS AND RAMP COLLAPSE

Folding as a hangingwall block moves over a ramp–flat fault trajectory has been analysed by many authors in terms of the final geometry which results (e.g. Rich 1934, Sanderson 1982) but not by the method described here. Vector analysis is difficult to apply to models involving complex hangingwall strains, such as those of Suppe (1983), but economically describes kink zone models such as those described by Sanderson (1982) and used by Knipe (1985). The triple junction formed by the two fault segments and the kink zone is stable and has the velocity of the footwall block.

If a new flat propagates from the foot of the ramp there must be a period during which both faults are active, even if all the movement will eventually transfer to the lower one. Figure 3(b) shows how the displacement can transfer smoothly onto the lower fault, with a consequent reduction in the rate of kinking in the hangingwall block. Alternatively, a zone of volume loss in block C (Fig. 3c) can remove the need for kinking in block A while maintaining slip across the ramp. Removal of material allows the boundary C_1–C_2 to shorten such that the triple junction is stable and moves with the velocity of block A. Such a zone might be seen as a low angle pressure-solution cleavage. Pure-shear shortening across C_1–C_2 reduces the need for kinking in block A but leads to instability for the same reason as in the previous example.

LISTRIC NORMAL FAULTS

A listric normal fault can be approximated by a series of planar segments. Deformation at the fault bends can be accommodated by a series of kink zones as illustrated in Fig. 4. The kink zones can have a wide range of orientation but the orientation of the kink zone will determine whether the displacement rate on the fault increases or decreases with depth. In the well-known CHEVRON construction (Verrall 1981) the kink zones are all vertical and displacement rate on the fault necessarily decreases downwards. Only a kink zone which bisects the obtuse angle between the fault segments will maintain the same displacement rate on each segment. For a listric fault these kink zones will converge and it is apparent that a listric fault with constant displacement rate *must* lead to a complex distortion in the hangingwall block.

In Fig. 4(b) the kink zone is replaced by an antithetic fault; swarms of such faults are seen on some seismic sections (e.g. Wernicke & Burchfiel 1982) and are frequently depicted in idealized normal fault systems (e.g. Gibbs 1984). This configuration is not stable and the antithetic fault intersection will move off down the main fault. However, a new antithetic fault may be generated leading to a family of faults with small displacements only one of which is active at any one time. This is geometrically analogous to the kink zone already

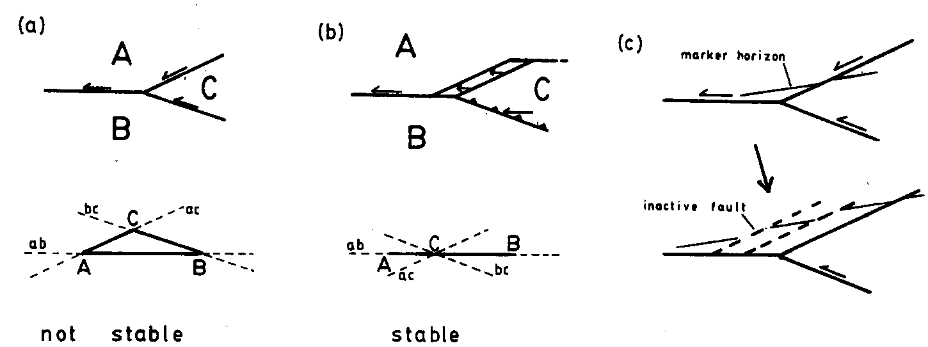

Fig. 5.(a) At a bend in a strike–slip fault bounding block B a third intersecting fault is necessary to balance the velocity triangle. However this configuration is not stable. (b) A stable junction can be produced by allowing dip–slip motion ("volume loss and gain") across AC and BC, although the appearance will change as a pull-apart opens adjacent to AC. (c) In a complex strike–slip zone unstable junctions may result in the generation of successively active accommodating faults (see also Fig. 4b).

described. During movement over a succession of fault bends a complex array of cross-cutting and sequentially active antithetic faults could be generated.

STRIKE-SLIP FAULTS

In strike-slip fault systems, analysed in map-view, movement out of section is the rule rather than the exception (Harding 1985). The movement on oblique-slip reverse and normal faults can be resolved into horizontal components which must be included in map-view vector diagrams and down-dip components which can be approximated by map-view volume loss or gain. Figure 5 illustrates how oblique-slip is generally *required* to stabilize intersections of strike-slip faults since kink zones in a horizontally constrained system are difficult to generate.

DISCUSSION AND CONCLUSIONS

Vector diagrams are rigorous means of evaluating the stability and evolution of arrays of faults, kink zones and zones of volume change. For a given array it is simple to assess whether given intersections and fault bends are stable in the absence of general wall-rock strains. More general strains such as pure shear deformation in the fault blocks (e.g. cleavage development within thrust sheets) can be assessed in a more qualitative way in terms of their consequences for displacement rates and directions between fault blocks.

It is frequently possible to observe wall-rock strains and arrays of microfaults in the vicinity of fault bends and intersections (e.g. Knipe 1985, McCaig work in preparation). These observations can then be tested against a vector model for the intersection. Since only a limited range of wall-rock strains will increase the stability of the junction it should be possible to separate strains associated with the intersection from those imposed earlier or later. Since changes in the movement rates on intersecting faults can lead to changes in possible accommodating strains it may also be possible to evaluate relative movement rates on different fault segments. Examples of the application of vector analysis to real shear zone intersections from the Pyrenees will be given elsewhere (McCaig work in preparation).

In this paper all analysis has been conducted in two dimensions. However, there is no reason why the same analysis should not be extended to three dimensions. A given intersection may appear stable in one section plane but unstable in another: obvious examples in plate tectonics are triple junctions involving two non-parallel trenches, where the downgoing slabs may interfere with one another in the subsurface despite an appearance of stability in map view.

Vector analysis is not intended to supplant existing techniques for dealing with fault arrays, but is a rapid technique for visualizing the consequences of movement on any proposed or observed set of intersecting faults.

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