Vector analysis of fault bends and intersecting faults: Reply

Andrew McCaig

Department of Earth Sciences, The University, Leeds LS2 9JT, U.K.

(*Received* 27 *October* 1988; *accepted in revised form* 6 *December* 1988)

I welcome the constructive comments on the above article made by Apotria, particularly since they present an opportunity to clarify the manner and circumstances in which the vector analysis technique can usefully be applied. Apotria's discussion centres on two main aspects of vector analysis: (a) the range of kinematic scenarios and solutions which increase a junction's stability is extended; and (b) the application of the methodology in the light of dynamic considerations and experimental work is discussed. In the first case I agree in general with the comments made but hope to clarify the significance of volume change in increasing the stability of a junction. In the second I concur wholeheartedly with Apotria that the method should not be used in isolation, and present a methodology for using it in conjunction with other techniques.

VOLUME CHANGE IN FORETHRUST–BACKTHRUST SYSTEMS

In his fig. 1(a), Apotria shows that a forethrust–backthrust triple junction can be stabilized by a zone of volume loss, which can have any orientation within block A or C, provided the direction of motion across the volume loss zone is parallel to the fault AB. This is very much a special case since slip no longer occurs across fault AC and hence the character of the junction is changed. It is also doubtful whether oblique volume loss across a zone is realistic. Volume loss zones such as stylolites or solution cleavages are expected to form normal to σ_1 and suffer movement perpendicular to their boundaries. In a rotational strain field volume loss may continue when the zone is no longer in this orientation, but it is probably more helpful to partition the resultant 'oblique volume loss' into components of volume loss normal to the zone and fault movement or kinking parallel to it (cf. Ramsay & Graham 1970). Figure 1 shows how a forethrust–backthrust triple junction can be stabilized by an arbitrarily oriented zone of combined volume loss and kinking within the hangingwall block. The motion between blocks A and A' is factorized into components of volume loss and kinking perpendicular and parallel to the boundary. If the triple junction is to be stable, material must move through the boundary in order for the boundary to move with the velocity of block C. However, unlike a pure kink zone (McCaig 1988a), block A moves towards the boundary AA' faster than block A' moves away from it, with the difference in velocity being taken up in volume loss. If the relative velocities of blocks A, B, C and A' and the orientation of the kink zone are all specified in advance, then volume change must in general accompany kinking if stability is to be achieved. In some cases volume gain (e.g. by crack–seal deformation, Ramsay 1980) may be required as shown in Fig. 1(c). However, if the orientation of the kink zone is not specified in advance, an orientation can always be found which does not require any volume change for stability.

DYNAMIC CONSIDERATIONS

Apotria is right to point out that the ultimate controls on the orientation of faults and the deformation of fault blocks must be dynamic—in other words they are controlled by a combination of the material properties of the rock mass and the size and orientation of the principle stresses at the time of deformation. Vector analysis considers only the kinematics of fault bends and intersections and can only be useful if stable configurations are favoured dynamically. In general, there is good reason to suppose this is so; the fact that deformation in many rock masses is concentrated on fault zones

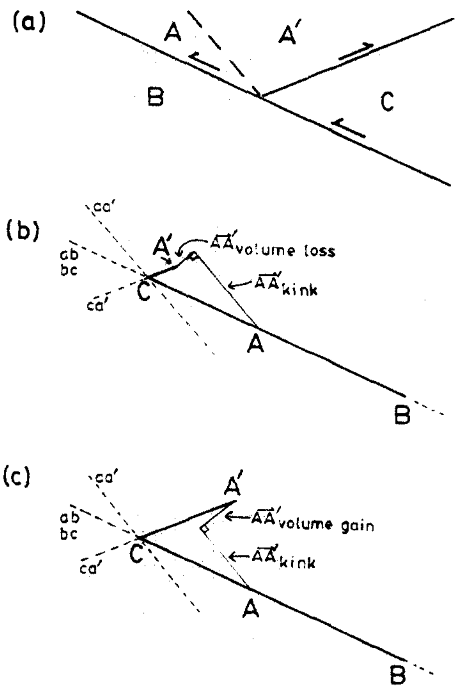

Fig. 1. (a) Forethrust–backthrust triple junction with arbitrarily oriented zone of kinking and volume loss within block A. (b) Velocity diagram showing how a combination of kinking and volume loss across the boundary AA' can result in a velocity vector CA′ parallel to the boundary CA'. The junction is stabilized since the kink–volume loss zone can move with the velocity of block C. (c) If the velocity CA′ is greater, volume gain across AA' may be required to stabilize the junction.

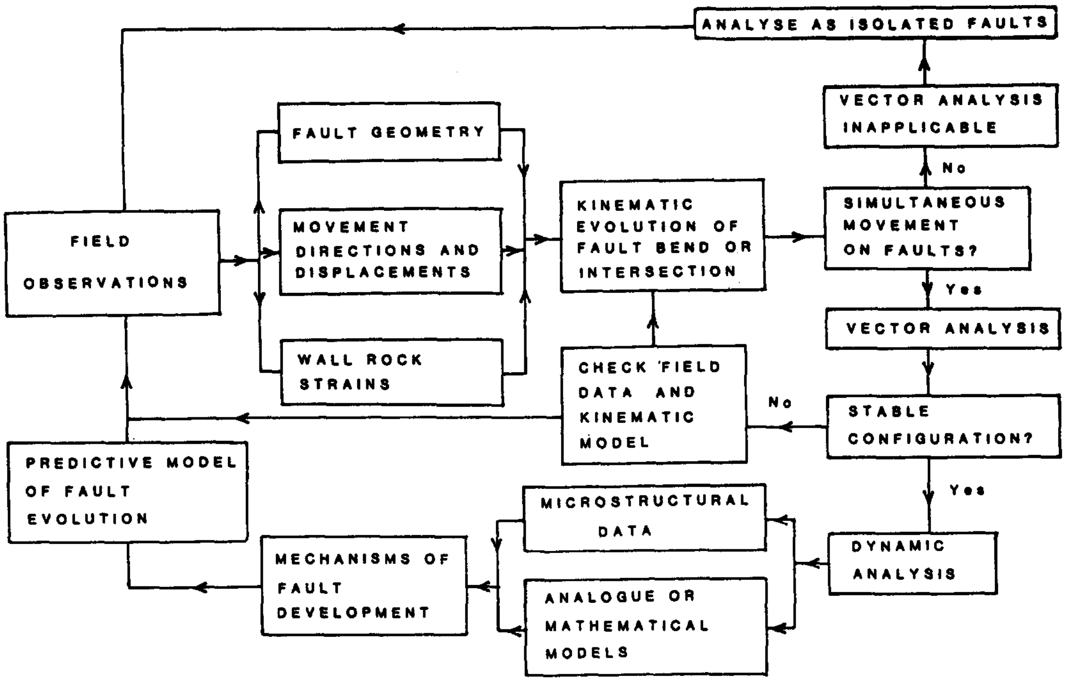

Fig. 2. Flow diagram illustrating how vector analysis could be integrated into a more general study of fault bends or intersections in ancient rocks.

indicates that these are mechanically weaker than unfaulted rock (White *et al.* 1980). We can therefore conclude that rock masses will normally respond to the stress field by movement on existing faults with a minimum of deformation of the intervening rocks, and that new faults will propagate only when existing ones become unfavourably oriented, work-hardening of fault rocks or wallrock occurs, or the stress field alters.

We can usually specify the *geometry* of ancient fault systems reasonably precisely, but the rates of movement on which the vector analysis technique depends are much harder to quantify. If Fig. 1 represents a crustal-scale thrust system it is plausible to suppose that the velocity **BC** is controlled by large-scale plate tectonic movements. The orientations of the various faults and of the kink zone may also be largely determined by the large-scale stress field and mechanical anisotropy of the rock. However, the velocities **A′C** and **AB** together with the rate of volume change across the kink zone may well be locally controlled by a feedback between local stresses due to topography, uplift rates, and strain softening and hardening in the rocks. Careful application of the vector analysis technique can help to determine the relative movement rates on different faults (e.g. by whether volume increase or decrease occurs in wallrocks, Fig. 1) and hence the nature of the dynamic controls on fault evolution.

Clearly, the vector analysis technique is of greatest use in areas of present-day deformation, where the rates of movement across faults can be constrained using seismicity or geodetic data. The extension of the technique from plate boundaries to crustal fault networks (McCaig 1988a) should allow proposed fault geometries such as those shown in Fig. 1 to be tested against patterns of uplift and subsidence, although full allowance should be made for similar strains consequent upon stick–slip motion on major faults (McCaig 1988b). In ancient rocks the technique must be used more cautiously; by predicting strain patterns associated with stable fault intersections vector analysis can help in identifying such intersections and in separating strains due to simultaneous movement on faults from those which may have formed at other times. In some circumstances, the technique could be used to quantify fault slip using wallrock strains. However, as pointed out by Apotria and Gray (1988), vector analysis should form only one component of the study of fault networks and should ideally be combined with field observations, dynamic and experimental modelling, and microstructural studies. Figure 2 is a flow chart, illustrating the methodology which might be applied to a particular field example.

CONSOLIDATED REFERENCES

Apotria, T. G. & Gray, N. H. 1988. The evolution of the Bouvet triple junction: implications of its absolute motion. *Tectonophysics* **148**, 177–193.

Chester, J. S. 1985. Deformation of layered rocks in the ramp regions of thrust faults: a study with rock models. Unpublished M.S. thesis, Texas A&M University.

McCaig, A. M. 1988a. Vector analysis of fault bends and intersecting faults. *J. Struct. Geol.* **10**, 121–124.

McCaig, A. M. 1988b. Deep fluid circulation in fault zones. *Geology* **16**, 867–870.

McKenzie, D. P. & Morgan, W. J. 1969. Evolution of triple junctions. *Nature* **224**, 125–133.

Ramsay, J. G. 1980. The crack–seal mechanism of rock deformation. *Nature* **284**, 135–139.

Ramsay, J. G. & Graham, R. H. 1970. Strain variation in shear belts. *Can. J. Earth Sci.* **7**, 786–813.

Sanderson, D. J. 1982. Models of strain variation in nappes and thrust sheets: a review. *Tectonophysics* **88**, 201–233.

Serra, S. 1977. Styles of deformation in the ramp regions of overthrust faults. *Wyoming Geological Society Guidebook, 29th Annual Field Conference*, 487–498.

Suppe, J. 1983. Geometry and kinematics of fault bend folding. *Am. J. Sci.* **283**, 684–721.

White, S. H., Burrows, S. E., Carreras, J., Shaw, N. D. & Humphreys, F. J. 1980. On mylonites in ductile shear zones. *J. Struct. Geol.* **2**, 175–187.

Wiltschko, D. V. 1981. Thrust sheet deformation at a ramp: summary and extensions of an earlier model. In: *Thrust and Nappe Tectonics* (edited by McClay, K. R. & Price, N. J.). *Spec. Publs geol. Soc. Lond.* **9**, 55–63.