Journal of Structural Geology, Vol. 6, No. 5, pp. 613 to 614, 1984
Printed in Great Britain

0191–8141/84 $03.00 + 0.00
Pergamon Press Ltd.

LETTERS TO THE EDITORS

The calculation of bulk strain in oblique and inclined balanced sections

Dr. P. A. Washington and Dr. R. M. Washington write:

Cooper (1983) proposes that balanced cross-sections which are not parallel to the regional shortening direction can be used to constrain total bulk strain. He further suggests that such sections are preferable to those constructed parallel to the regional shortening direction by projection of data outside the line of the section. We would like to dispute these assertions.

Cooper's thesis is essentially that the strain on any plane through a volume deformed by plane strain can be related to the bulk strain by simple geometric relations. This is true only when the strain is uniformly distributed within the volume, that is, all strain features are continuous throughout the volume and of constant magnitude . Restated, the partitioning of the strain among various structures (fold trains, faults, cleavage zones) must be uniform across the entire width of the area and all of the structures should be continuous. This is where the problem lies.

As Cooper himself points out, structural features are often impersistent, dying out or changing character along strike. This is a critical problem in the balancing of nonstandard cross-sections, since the strain may be partitioned differently at various places along strike, such that the strain measured along the general section may not be simply related to the regional strain field. This can be illustrated by constructing an oblique section across a fold-and-thrust belt which changes character along strike from a fold belt in which the strain is distribution across a large area to a simple thrust belt in which the strain is localized on fault surfaces. Depending on the specific line of the section, the 'balanced' section will show either a great deal more or a great deal less strain than can be accounted for by its non-standard orientation.

Cooper's method of relating oblique sections to the regional structure is no more than an alternate form of projection (projecting an entire oblique section rather than individual datum points). It necessitates the assumption that all structures are perpendicular to the transport direction (consider an oblique thrust ramp where plane strain has been maintained) and that all structures on the oblique section correspond exactly to the structures to be found on a standard section. Although thrust surfaces are commonly continuous over large areas, the stratigraphic throw and/or placement of the ramps varies frequently along strike (Wilson & Stearns 1958, Elliott & Johnson 1980). It is also possible for a fault to die out and the displacement to transfer to another fault with the same stratigraphic throw (Dahlstrom 1970). Folds also transfer displacement along strike. Oblique sections through such areas will probably produce erroneous estimates of bulk shortening, with the relation to the actual shortening varying with the specific line of the section.

Oblique sections can only be balanced with confidence where it is known that no major structural changes occur along strike. Of course, if this is known, then a standard section can be produced by standard projection methods. On the other hand, if all of the data lie along an oblique line, Cooper's method may be preferable to projecting each piece of data individually. We would like to add that a more reasonable approach to balancing nonstandard cross-section data, especially in complex areas, lies in three-dimensional balancing (Washington & Washington 1983).

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Dr. M. A. Cooper replies:

I read with interest the above comments on my recent paper (Cooper 1983) by Washington & Washington. They raise some valid points regarding the problems of using abnormally oriented sections, but I feel that they have misunderstood the applications which I intended for the method.

The partitioning of strain between different structures is an important point. In my own experience (Cooper *et al.* 1983, in press, Hossack & Cooper in press) strain partitioning between different structures is reasonably consistent throughout orogenic belts when viewed on the large scale. At a smaller scale of observation changes may occur but tend to be gradual rather than abrupt. I accept that problems would arise from constructing an oblique section through an orogenic belt from foreland to hinterland. It was not my intention that the technique should be used for such a purpose. I am more concerned that the technique should be applied to smaller-scale problems for which there is good control data not necessarily in an orientation such that a 'best fit' section has a normal orientation (e.g. Cooper *et al.* 1983).

It is true that my technique is merely an alternative form of projection. However, an abnormal section with good control data will yield additional valuable information as it will be closer to geological reality than a normal section into which control data is projected. My technique 'projects' the bulk shortening estimate but does not project structures from their actual location. I consider this additional information to be an important justification for the technique.

A major problem raised by Washington & Washington (in their letter) is the lateral impersistence of structures. Thrust displacement transfer zones and lateral ramps will both produce problems of lateral impersistence. However, rapid changes in bulk shortening along orogenic belts are not common (see the sections of Roeder *et al.* 1978) and where present, as in the Pine Mountain block (Wilson & Stearns 1958), are readily detectable. In general, new structures will develop to replace structures which die out and the overall bulk shortening accomplished will remain relatively constant. The problem of lateral impersistence will become an important source of error in estimating bulk shortening in an oblique section as the angle of obliquity increases. This is because in a section that is strongly oblique to the structural trend, en échelon structures in a transfer zone may be missed altogether or alternatively encountered twice.

The problem raised by Washington & Washington of construction of an oblique section through an orogenic belt which changes character from fold to thrust dominant along strike is misleading. Where such changes occur, for example the Rockies (Thompson 1981) and the Appalachians (Gwinn 1970), the folds are underlain by blind thrusts and the folds which existed above outcropping thrusts have been eroded. A properly balanced section would have to consider subsurface and eroded structures to produce an admissible section and thus the problem does not arise.

I agree with Washington & Washington that the best solution is three-dimensional volume balancing (Washington & Washington 1983) and I hope that they will make their technique widely available as soon as possible.

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