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# Scale dependence, strain compatibility and heterogeneity of three-dimensional deformation during mountain building: a discussion

Richard R. Jones[a,b,*], Robert E. Holdsworth[c], Kenneth J.W. McCaffrey[c], Phillip Clegg[c], Enrico Tavarnelli[d]

[a]*Geospatial Research Ltd, Department of Geological Sciences, University of Durham, Durham DHI 3LE, UK*
[b]*e-Science Research Institute, University of Durham, Durham DHI 3LE, UK*
[c]*Reactivation Research Group, Department of Geological Sciences, University of Durham, Durham DHI 3LE, UK*
[d]*Dipartimento di Scienze della Terra, Università di Siena, Via Laterina 8, I-53100 Siena, Italy*

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**Abstract**

Plate motion at convergent margins causes crustal shortening and orogenic thickening. Relative motion that is oblique to the plate margins is an inevitable consequence of plate kinematics on a sphere and results in non-coaxial three-dimensional deformation that cannot be approximated to simple shear. Models of mountain building that include a smoothly varying component of pure shear shortening allow strain compatibility to be maintained by deforming the upper free surface of the Earth without disrupting the material continuum. However such models do not reflect accurately the nature of deformation in many areas of high strain in the upper crust, which are characterized by interconnected arrays of kinematically linked faults that can be active on several scales of magnitude simultaneously. As brittle deformation increases, the coherence of the material continuum is highly reduced. In such situations, strain compatibility is maintained by partitioning the deformation amongst structures of varying kinematic significance over a wide range of scales and not by smooth variations in strain magnitude acting on a single scale across a material continuum. There is a marked tendency for such partitioned domains to be oriented parallel or sub-parallel to the orogenic grain. Alignment of domains in this way represents a strong structural anisotropy, which acts as a highly significant boundary condition that controls deformation at subordinate scales. Finite strain observed within an individual domain at a given scale need not therefore display the same magnitude or orientation as bulk finite strain at the plate scale and consequently data must be collected from as large an area as possible to relate outcrop-scale structures to global-scale tectonics.


*Keywords:* Heterogeneous strain; Scaling of deformation; Strain partitioning; Discontinuum mechanics

## 1. Introduction

"We have been somewhat alarmed at the separation we see between the conclusions of those investigating global tectonics with those looking at the smaller-scale structural features observed at outcrop or map scale. We hope to see in the future a better integration of the actual geometrical features observed in the rocks themselves with the larger-scale predictions of plate tectonics. These geometrical appreciations should be scale independent and we have to make more position linkages across the scale divide" (Ramsay and Lisle, 2000, preface).

From deformation mechanisms at the scale of the crystal lattice to plate motion on a lithospheric scale, the processes studied by structural geologists and tectonicists span at least 14 orders of magnitude ($10^{-6}$–$10^{+7}$ m). Even restricting our analysis to macroscopic structures by taking the outcrop-scale as a lower limit, the scale divide highlighted by Ramsay and Lisle spans magnitudes from millimetres to tens of thousands of kilometres.

In this paper we discuss the three-dimensional geometric and kinematic predictions inherent in plate tectonic theory of orogenic processes and compare these with outcrop- and map-scale structures using examples from the Southern Uplands of Scotland that developed along a destructive plate

* Corresponding author. Tel.: +44 191 334 4294; fax: +44 191 334 2300.

*E-mail addresses:* r.r.jones@durham.ac.uk (R.R. Jones), r.e.holdsworth@durham.ac.uk (R.E. Holdsworth).

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margin of Iapetus during Palaeozoic times. By relating detailed field data at outcrop and map scales with larger scale information about regional deformation, our aim is to investigate the way in which upper-crustal strain compatibility is achieved across the scale divide.

## 2. Plate kinematics at convergent margins

Since the advent of plate tectonic theory, it has been well understood that there is an intimate relationship between mountain building and convergent plate margins. Dewey (1975) and Woodcock (1986) have demonstrated that the progressive movement of plates on the surface of a sphere will usually give rise to relative motions that are oblique (i.e. neither parallel nor orthogonal) to the margins of the plates. Oblique relative motion at convergent plate margins typically causes triaxial deformation (Dewey et al., 1998). Such deformation is non-coaxial and non-plane strain and cannot be approximated as a plane strain pure shear or simple shear (Fig. 1a–d). Irrespective of how this deformation is accommodated at lower orders of scale magnitude (e.g. in map- and outcrop-scale structures), there is a kinematic requirement at the uppermost scale (i.e. the scale of the plate margin) that the overall bulk strain is non-coaxial and non-plane strain. This gives rise to the typical characteristics of convergent plate boundaries, with shortening across the margin, orogenic thickening, oceanward overthrusting and orogen parallel strike-slip. In terms of bulk strain symmetry (see Paterson and Weiss, 1961), deformation is most likely to be triclinic (Fig. 1d).

This paper addresses the inherent difficulties regarding strain compatibility with respect to non-coaxial non-plane strains (Ramsay and Huber, 1987; Hudleston, 1999). Before we present field data from a zone of non-coaxial non-plane strain, we discuss theoretical ways in which strain compatibility can be achieved in areas of complex three-dimensional deformation.

### 2.1. Strain compatibility and strain heterogeneity

The cartoon depictions of Fig. 1 represent a simplistic abstraction of bulk (plate-scale) deformation assuming homogeneous strain. Clearly, if one considers the boundaries between the zones of deformation and the undeformed plate interiors depicted in Fig. 1a, c and d, it appears that these representations disregard the standard rules of strain compatibility (Ramsay, 1967, 1976; Ramsay and Graham, 1970; Ramsay and Huber, 1983, 1987; Ramsay and Lisle, 2000). As compatibility cannot be maintained between units of undeformed rock and adjacent units where the strain has a component of *homogeneous* pure shear, it is inevitable that there will appear to be compatibility problems with this kind of depiction.

There are a number of ways, described in the following sections, in which strain compatibility can be re-established. These depictions apply equally well to both orthogonal relative plate motion and the geometrically more complex case of non-orthogonal motion, without compromising the essential kinematic boundary condition that requires bulk deformation to be non-coaxial and non-plane strain when relative motion is oblique. These compatible solutions all involve heterogeneous strain, but differ in the way in which heterogeneity is distributed.

### 2.2. Strain compatibility and smoothly varying heterogeneity

The most straightforward way to satisfy compatibility conditions involves a deformation in which the magnitudes

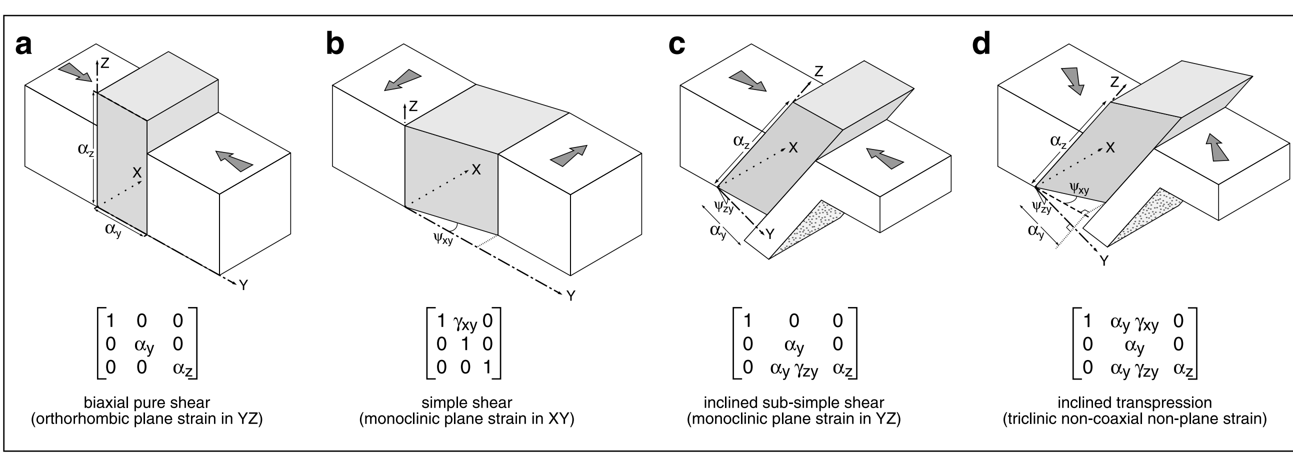


Fig. 1. Symbolic sketches of deformation at plate margins, with strain depicted homogeneously, in order to emphasize the overall symmetry of bulk, plate-scale deformation required by the relative plate motions shown by large arrows. (a) Reference deformation (coaxial plane strain) with orthorhombic strain symmetry. (b) Transcurrent margin (non-coaxial plane strain), monoclinic symmetry. (c) Convergent plate margin with orthogonal relative motion (non-coaxial plane strain), monoclinic symmetry. (d) Convergent plate margin with oblique relative motion (non-coaxial non-plane strain), triclinic symmetry. *X*, *Y* and *Z* are Cartesian reference coordinates with *X* horizontal and *XZ* parallel to the deformation zone boundary. $\alpha_y$ and $\alpha_z$ are ratios of deformed to original width of zone (including any volume change) parallel to *Y* and *Z*-axes, respectively. $\psi_{XY}$, $\psi_{ZY}$ are angular shear strains where $\psi = \tan\gamma$.