General Discussion

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General discussion

J. G. Ramsay, F.R.S. (*ETH-Zentrum, Zürich, Switzerland*). Several of the cross sections and profiles through various parts of the Himalayas that have been presented at the Meeting were based on geometric techniques appropriate to the frontal thrust belt of the Rocky Mountains of Canada and the U.S.A., or to the soft sediment deformation in and around Taiwan. In these reconstructions, faults, especially thrusts, are considered to exert the dominant control on the forms of structures. Fold forms appear only as fault bend folds developed as a consequence of movement of thrust sheets over irregular step-like thrust plane topography. In these models the effect of rock competence only seems to be considered as a characteristic rock property controlling the ramp-flat geometry of the fault planes, and the rock properties seem to exert little or no influence on the fold style. I would suggest that this current fashion of making constructions to depth is not only mechanically unsound, but it does not accord with the observations of structural geometry. First, the folds we see often show rounded hinges, tight interlimb angles, and changes of layer thickness that are not those of the constant thickness open kink-like folds arising from nappe transport over ramps and flats. The observed geometric variations of bed thicknesses in folds also often imply quite marked difference of ductility of the rock layers: the beds do not behave in a passive way to retain a constant layer length. In all folded rocks found in the crystalline units and in many in the non-metamorphic terranes, cleavage and schistosity are characteristically present. When deformation markers are seen it is very clear that rock deformation has been ductile and that the strains can be very high ($X:Z = 50:1$), quite outside the values predicted from the development of fold bend folds, and that cleavage also implies moderate to high rock strains. I fail to understand why some workers persist in using a model that is so much at odds with the undisputed observations and accept geometric constraints on their constructions that are inappropriate to the behaviour of deformation styles in a ductile crust.

R. W. H. Butler (*Department of Earth Sciences, Open University, U.K.*). Professor Ramsay criticizes the use of thrust tectonic models to explore the geological structure of mountain belts. He allies these models to a rather narrow and out-moded idea of balanced section construction, namely that for sections to balance they must conform to a simple 'Rocky Mountain' style (see Ramsay & Huber 1987) where line lengths are preserved and all deformation is contained on very narrow faults. If the aim of such section construction in the metamorphic parts of mountain belts was to completely predict structure to depth as in some oil and gas fields (Suppe 1983), his criticisms would be valid. However, that has never been the aim nor indeed the method adopted. So what have been the aims of regional section construction and structural restorations across broad tracts of mountain belts?

(i) Section balancing can be used to test gross crustal structure. For example, in northern Pakistan we predict that where cover rocks alone are stacked up, the crystalline basement from which these sheets have detached must continue further north, ultimately under the Kohistan arc terrane (Coward *et al.* this symposium, and references therein). In contrast, the Everest transect can accommodate crustal shortening beneath the surface expression of thrust structures with only limited detachment (Burg & Chen 1984; Butler & Coward 1988). Models such as these are important in planning the location of vastly more expensive seismic experiments and in the interpretation of resulting reflection profiles.

(ii) Structural restorations can indicate where plate convergence is being accommodated within the continental lithosphere. The crude restorations in the western Himalayas suggest that approximately one third of the bulk convergence between India and stable Asia has been accommodated south of the suture since collision. It may well be more but India certainly can be shown not to behave as a rigid indenter as once believed (Butler & Coward 1988).

(iii) Structural restorations can provide time-slice views of mountain belts from which it is possible to predict the evolution of the main orogenic loads that drive subsidence and sedimentation on the Indian foreland (Lyon-Caen & Molnar 1985). Coupled with gravity, stratigraphic and sedimentological data it is possible then to model the bulk thermo-mechanical behaviour of the lithosphere.

(iv) Combining structural restorations with pressure–temperature estimates within mountain belts, it is possible to reconstruct the interplay between horizontal and vertical movements that, coupled with erosion, control the morphology of the Himalayan ranges.

So what of the method? Clearly to gain truly representative estimates of orogenic shortening or to predict subsurface structure on a fold-by-fold, thrust-by-thrust basis we require the complete incremental restoration of all ductile strains, rotations and displacements in three dimensions together with estimates of volume changes associated with fluid flow and metamorphism. This has yet to be achieved even in the most well-studied and structurally simple parts of mountain belts. But in areas approximating to plane strain it is relatively straightforward to restore the complex catalogue of non-fault-bend straining folds outlined by Ramsay (see Butler 1988 for discussion) by using formational area balancing with local bed-thickness restoration. It is possible to simplify the structure for restoration purposes so that extending bed-length segments are not included in the final shortening value, an approximation which considers displacements to be localized onto infinitesimally narrow faults. The simplifications have been outlined at length elsewhere; they produce minimum estimates of orogenic shortening. They are not dependent on the narrow range of structural styles as advocated by Professor Ramsay.

Despite being minimum values, shortening in the western Himalayas determined from balanced sections is so large (over 470 km together with at least 150 km on the MMT) that it is possible to test simple models of India–Asia collision and begin to tackle the aims outlined above. At present the preferred model, as outlined by Coward *et al.* (this symposium; see also Butler 1986), of varying levels of detachment within the Indian crust developed during thrusting is consistent with the mappable surface geology (as interpreted by section balancing), the generation of foredeep basins, available geophysical data (gravity, earthquake epicentres and fault-plane solutions, seismic refraction and shallow reflection profiles) and uplift patterns in the mountain belts. It is interesting that the same broad conclusion was reached by Argand (1924), albeit with a far weaker data base. Professor Ramsay's 'undisputed observations' are entirely consistent with this model. The vast bulk (say 90%) of the net convergence between India and Asia that is located south of the suture appears to be accommodated by movements along relatively discrete thrust sense zones of simple shear rather than by pure shear buckling, upright cleavage or schistosity (say 10%). Although recognizing their limitations, certainly in markedly non-plane-strain settings, cross sections balanced for formational area and displacement provide a test of structural models and a regional framework to incorporate entirely separate geological information. Small-scale structures provide important information on the kinematics of large-scale detachment and ultimately can be used to determine strain rates etc., at least when combined with microstructural work. But the integration with 'non-structural' data is crucial if we are to understand the tectonics of mountain belts. It is unclear how myopic focusing on small-scale structures and strain measurements without the broader view offered by regional section construction will achieve our aims.

References

Argand, E. 1924 In *Proc. 13th. Int. Geol. Congr., Brussels.*

Burg, J. P. & Chen, C. M. 1984 *Nature Lond.* **311**, 219–23.

Butler, R. W. H. 1986 *J. geol. Soc. Lond.* **143**, 857–873.

Butler, R. W. H. 1988 In *Tectonic evolution of the Tethyan Regions* (ed. A. M. C. Sengör). Proc. NATO Advanced Study Inst.

Butler, R. W. H. & Coward, M. P. 1988 In *Tectonic evolution of the Tethyan Regions* (ed. A. M. C. Sengör). Proc. NATO Advanced Study Inst.

Lyon-Caen, H. & Molnar, P. 1985 *Tectonics* **4**, 513–538.

Suppe, J. 1983 *Am. J. Sci.* **283**, 684–721.

Ramsay, J. G. & Huber, M. I. 1987 *The techniques of modern structural geology. Volume 2. Folds and fractures.* London: Academic Press.

M. P. Coward (*Department of Geology, Imperial College, U.K.*). Professor Ramsay's discussion is claimed to be a general comment on several contributions. I shall, therefore, answer it in a general way, not specifically about any one contribution. He claims to fail to understand why some workers persist in using a model based on techniques appropriate to the frontal thrust belt of the Rocky Mountains, etc. I presume that even the most ardent critic of thrust geometry has to admit that thrusts do dominate the frontal structures of the Himalayas. They are clearly imaged on seismic profiles and are exposed in the frontal ranges from Nepal to Pakistan. However, few of these thrusts carry kink-band, fault-bend folds (Suppe 1983); many have folds or fold-trains developed by buckling of beds on fault hanging-walls due to variations in displacement on the fault. As Professor Ramsay claims, the fold inner arcs may show complex structures formed by the accumulation of weak material such as shale or salt. When constructing cross sections it is unwise to opt for one particular fold model or construction technique, e.g. the fault-bend fold model of Suppe (1983), constant or variable heave models (Verrall 1981; Williams & Vann 1987; Wheeler 1987), isogen models of Ramsay & Huber (1986). The construction should be compatible with the field and/or seismic observations. To follow this further: it is often very unwise to produce cross sections from simple map or seismic data alone, even though apparently there may be adequate orientation data, until clear observations have been made in the field on fold shape, fault sequence, strain, etc.

Professor Ramsay claims that the current fashion in interpreting sections to depth does not accord with observations on geometry. Viable cross sections must use all the available data, from the surface and from depth. These could include measurements of dip, bed thickness, strain and cleavage, incremental strains, compaction and diagenesis, fault kinematics plus seismic, gravity and magnetic data. If using a reasonable spread of seismic or field data, it is important to contour bed and fault surfaces and produce cut-off and branch-line maps (Coward 1984). In regions of consistent or only slightly variable plunge, it is possible to attempt down-plunge projections. However, as faults and their associated buckle or ramp-induced folds do vary in geometry along strike, such projections can lead to serious errors and this method must not be relied on. Section construction is not a quick slap-dash method, but a rigorous discipline, based on established structural principals. It certainly should encourage, not discourage, detailed field observations among its protagonists.

Further, it is important to determine the fault-slip direction. All the simple balancing techniques involve an assumption of plane strain, or a knowledge of the area change that has affected the particular section. Sections drawn oblique to the fault-slip direction always have material that has moved in or out of section and it is questionable as to whether such sections maintain constant area during deformation. In Pakistan, there are variable thrust movement directions in the eastern parts of the Salt Ranges and near the Hazara syntaxis (Coward *et al.*, this symposium) and hence here, simple two-dimensional (2D) balancing techniques should not be used. Three-dimensional (3D) balancing or sequential partial restoration should be attempted.

Apart from encouraging a rigorous approach to structural geology, balanced section construction has several uses. Predictions can be made and tested with extra surface or seismic data (or well data in exploration!). Estimates can be made of detachment depths and amounts of displacement. Indeed the concept of necessary basal detachment essentially came from early balanced section work (Chamberlain 1910). Before and often since then, many geologists have drawn sections with fold or fault geometry that clearly cannot work. If a section does not balance then that particular section or some of its assumptions are wrong. A balanced section need not be wrong. However, section-balancing techniques are iterative and rarely result in a unique solution, especially as they depend largely on the amount of input data. Details of the sections will change as more data are forthcoming. Thus, as claimed by Ramsay & Huber (1987) 'beware of the geologist who announces ... that his sections are "perfectly balanced" and who gives the impression that these sections are above reproach from any source. If you meet such a character you can be pretty sure that he is naïve, dishonest, or combines these traits.' The only sections that are 'beyond reproach' are those that can be photographed on hillsides or cliffs, and it is surprising how many geologists copy these incorrectly!

Certainly, as Professor Ramsay claims, the internal parts of orogenic belts have a complex history and it is difficult to produce reliable and reproduceable sections in these regions. Professor Ramsay seems concerned about fold shapes and 2D ductile strains in internal regions. It is possible to deal with some problems using area balancing methods. Kink-band methods are clearly not applicable to internal zones and line-length balancing methods need to take into account rock strain. Far more problematical are complex 3D strain histories involving rotations and thrust movements in more than one direction. These problems are certainly encountered in the internal zones of the western Himalayas (see Coward *et al.*, this symposium) and any sections to depth through these areas, or similar sections through, say, the internal zones of the Caledonides or western Alps, must be considered only as educated tectonic sketches. The sections can be balanced; there is no point in producing a section that looks glaringly ridiculous without discussing why, but the balancing is only as good as the input.

Section balancing is similar to many other techniques and concepts in structural geology, such as plate-tectonic modelling, fold analysis, finite and incremental strain measurement. It can be done well or badly. As with the other techniques, it can lead to tremendous increases in knowledge of 2D and 3D structural geology, but can also be abused. The structural geologist should attempt to understand and use all the techniques available.

References

Chamberlain, R. T. 1910 *J. Geol.* **18**, 228–251.

Coward, M. P. 1984 *Scott. J. Geol.* **20**, 87–106.

Ramsay, J. G. & Huber, M. 1986 *The techniques of modern structural geology, Volume 2. Folds and fractures.* London: Academic Press.

Suppe, J. 1983 *Am. J. Sci.* **283**, 684–721.

Verrall, P. 1981 *Structural interpretation with application to North Sea problems* (Joint Association for Petroleum Exploration Courses (U.K.), vol. 3.

Wheeler, J. 1987 *J. struct. Geol.* **9**, 1047–1049.

Williams, G. D. & Vann, I. 1987 *J. struct. Geol.* **9**, 789–795.