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Conference Report

Tectonic studies group: 14th annual meeting

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Report of a meeting of the Tectonic Studies Group held at the University of Glasgow, 18–21 December 1983. The meeting was organized by Drs P. W. G. Tanner and C. Farrow (Glasgow), I. Allison (Strathclyde) and A. D. Gibbs (Britoil).

After a decade of sustained growth, the Tectonic Studies Group has acquired international status and the 14th Annual Meeting attracted nearly 300 participants, many of whom were from the European continent and North America. Papers on any structural topic were invited and for the first time the number of contributions (92) far exceeded the number of papers (51) which could be given in two days. The organizers were faced with the unwelcome task of selecting speakers and also had to reduce discussion time to less than was desirable. John Underhill was awarded the prize for the best postgraduate contribution.

The meeting began with a 2-day workshop (18 and 19 December) on the interpretation of seismic reflection sections, organized by G. K. Westbrook (Durham) and J. Hall (Glasgow). A basic course in the techniques of reflection seismology was followed by a series of presentations by researchers from the universities and from industry on applications to different tectonic environments.

On 19 December, three field excursions were held. P. R. Thomas (Paisley) led an excursion to look at structures in the Central Highland Moine as exposed in new road cuttings on the A9; W. G. Henderson (BGS) led a party to North Glen Sannox on the Isle of Arran to examine Dalradian–Highland Border complex relationships; and J. Warrender, L. A. D. Fernandes and K. C. Lawrie (Glasgow) demonstrated new evidence for the D1 age of the Cuil Bay synform, Ballachulish.

The meeting on 20 December began with a welcome from B. E. Leake. The first session was mainly concerned with tectonics. J. K. Leggett (Imperial College) described extensional tectonics from the Honshu fore-arc in Japan based on results from Deep Sea Drilling Project Leg 87. He identified two problems: an anomalously narrow Late Oligocene arc-trench gap and trench-ward dipping sediments. The former is explained by subduction erosion; the latter as the result of land-ward dipping growth faults. The termination of the Irumide belt of central Africa against the older Ubendian fold belt was discussed by M. Daly (Leeds), who suggested that the presence of syntectonic granites of Irumide age in the Ubendian belt and parallelism of extension lineations in the two belts indicated that part of the Ubendian belt is Irumide in age. J. Crespi and R. Kligfield (Colorado) described the geometry of large-scale shear zones in the extensional terranes of the North American Cordillera in Arizona. They presented mathematical models for such zones, expressed in terms of simple shear, pure shear and volume change, and emphasized the compatibility problems which arise at shear zone boundaries. G. K. Westbrook (Durham) displayed some fine seismic sections across the leading edge of the Barbados Ridge Complex. He showed that the ratio of the initial spacing of thrusts to the thickness of the thrust layer, above a décollement, is almost constant, and that folds form as a *consequence* of deformation associated with the thrust movement. J. Grocott (Amsterdam) then described a remarkable pattern of superimposed colinear deformations from the Early Proterozoic Rinkian mobile belt of central West Greenland. Four distinct deformation phases show near parallelism of fold axes and the X direction of the strain concerned, and Grocott concluded that, as the structure evolved and metamorphic grade declined, both planar and linear (bending) anisotropies became active in controlling the geometry. J. Hossack (City of London Polytechnic) presented some beautiful sections from the southern Pyrenees that demonstrated the geometry of buried and eroded thrust-front tip lines. The emergent imbricates are cut by erosion surfaces which are later cut by thrusts, and both emergent and buried frontal tips have important consequences for the provenance of molasse sediments accumulating above and in front of them.

The next session included papers on interrelationships between thrusting and sedimentation, and soft sediment deformation. S. Cosgrove (Swansea) described relationships between tectonics and sedimentation in the Peloritani Mountains of NE Sicily where a fragment of the Alpine orogenic belt has been overthrust onto the foreland-verging thrust zone of the Apennine–Maghrebide system. In a talk held over from the first session, A. E. S. Kemp (Edinburgh) presented the results of a detailed structural and metamorphic study of uppermost Llandovery and Wenlock strata in the Southern Uplands accretionary prism. He identified four sequentially accreted packets in which the intensity of the D1 accretion-related folding and fabric is related to structural level in the accretionary pile. Returning to the Pyrenees, G. D. Williams (Cardiff) and C. Atkinson (Shell) used their study of the Montsec thrust sheet to show how detailed stratigraphic and sedimentological research in syn-thrusting sedimentary basins may be useful in predicting the presence of buried culminations and blind thrusts. Such work may also be used to determine the evolutionary history of the thrust system. Small-scale gravity gliding structures which developed after diagenesis, but before the main deformation, were reported by J. Craig (Geomorphological Services), W. R. Fitches and A. J. Maltman (University College of Wales) from the Lower Palaeozoic rocks of Cardiganshire. A more detailed analysis of soft sediment slump sheets as seen in the Ainsa basin, southern Pyrenees was presented by S. Farrell (Cardiff). These sheets show contractional and extensional strain features, strain overprinting, and clastic dykes, all features that can be explained in terms of a model of progressive slope failure. The session concluded with a structural and economic study by L. I. Wright (Leeds) of the Cambrian Hazara phosphate deposits found near Abbottabad in the North West Frontier Province of Pakistan. The 3-D distribution of the phosphorite is due partly to variations in sedimentary facies but mainly to the effects of two phases of 'Himalayan' deformation.

The session which followed lunch was mainly devoted to studies of fold structures and the origin of steep belts. J. Ridley (ETH, Zurich) began by examining aspects of the development of folds in shear regimes, using examples from well-layered metasedimentary rocks of blueschist facies from the Aegean. Different microstructures in the short limbs and in the long limbs of small-scale asymmetric folds suggest either a higher differential stress, or fabric softening, in the short limbs. P. Huggenberger and M. Casey discussed the problem of estimating the bulk strain for a complex fold structure. They described two possible methods and illustrated their use with respect to folds and deformation in the Morcles nappe (Western Helvetics) of Switzerland. Continuing in the Alps, P. Cobbold (Rennes) presented new data from the so-called 'root zone' of the Pennine nappes in the southern Central Alps. He used the prominent rodding lineation, which changes plunge from horizontal to vertical *within* the steep belt, and the foliation to construct strain trajectories and inferred a complex collision model for the region. Dealing with the origin of the steep belt in the Central Highlands of Scotland, S. Temperley (Hull) presented a comprehensive structural analysis of the Glenbanchor area in Inverness-shire. He concluded that the main steep belt–flat belt geometry developed during a secondary Palaeozoic deformation and that the steep belt did not represent a primary root zone. Turning to the deformation of the Upper Carboniferous Bude Formation in N Cornwall, J. S. Whalley (Portsmouth) and G. E. Lloyd (Birmingham) argued for a reappraisal of the current model of a regional, southerly directed dextral simple shear followed by normal faulting. They concluded that the tectonics of the Bude Formation must initially have involved the large-scale gravitational sliding of wet sediment and also included a later period of thrusting. B. Murphy (Trinity, Dublin) presented structural data from the Silurian rocks of the Balbriggan inlier (Dublin and Meath). Initial compression across the Iapetus suture zone in this area was followed by strike-slip motion which generated clockwise transected folds within a regional transpressive regime. The existence of anticlockwise transected folds was attributed to local dextral shear adjacent to an uplifted rigid block in the shear zone. Tietzsch-Tyler (University College, Dublin) described structures from farther south in the paratectonic Caledonides of Co. Wexford in SE Ireland. The rocks include the Cullenstown Formation (equated with the Mona Complex of Anglesey) and a Lower–Middle Cambrian sequence which together appear to have been thrust SE onto the Rosslare Complex.

In the final session on 19 December the main theme was thrust tectonics. G. Mäkel and J. Walters (Shell) used finite element techniques to investigate the mechanics of thrust fault formation in a homogeneous wedge-shaped thrust sheet overlying a weak substratum. They reported that, contrary to the usual assumptions, a backthrust initially determines the position of the thrust fault and then accommodates the movement of the thrust sheet along a basal slip plane and up the ramp created by a reverse fault. T. J. Chapman (Plymouth) and G. D. Williams (Cardiff) described a new method, the cumulative displacement–distance diagram, for calculating absolute shortening or extension accommodated above a single décollement in a linked-fault system. The method can be used as an alternative to, or in conjunction with, a balanced cross-section. Following this more theoretical work, C. Townsend (Cardiff) described an exceptionally well exposed 5.5-km transverse section through the Finnmarkian Caledonides of northern Norway. He proposed a thin-skinned tectonic model for this portion of the Caledonides with a depth of burial estimated at 5–10 km and a total shortening possibly well in excess of 150 km. Thrust wedges are contractional dislocations of small displacement which occur in competent units within alternating competent and incompetent beds or, for example, in well-bedded limestones. C. K. Morley (Swansea) described two types of thrust wedge from the Oslo graben and Mjosa areas of southern Norway: those resulting from an initial compressional event at the sole thrust tip, and those which formed at the same time as folds and second order thrusts and which display less shortening. N. Fry, V. Davies and M. Jones (Swansea) presented a report on their summer's fieldwork in the Pennine front around Bersezio in Haute Provence. They recognized a common tectonic history for all of the Internal Zone rocks in this area, rocks previously divided into three discrete units, the Parpaillon Flysch Nappe, Briançonnais Zone and Sub-Briançonnais Zone. Moving to North America, N. B. Woodward (Tennessee) emphasized the changes in structural geometry of folds and thrusts, both from hinterland to foreland and along strike, within the northern Idaho–Wyoming–Utah thrust belt. Major features besides normal stair-step thrusts are blind imbricates and lateral ramps; the latter not only suggest longitudinal changes within the deforming packages but can prevent the use of down-plunge methods. The last contribution of the day was given by J. Underhill (Cardiff) who described thrust events in the Neogene of the so-called Hellenic 'foreland' of Kephalinia and Zakinthos in western Greece. He described how olistoliths were supplied by emergent thrust faults, as was the detritus which produced Pliocene mega cross-beds, and how, at a very late stage, small backthrusts displaced Quaternary raised beaches on both of the islands. A reception was held in the Hunterian Museum followed by a buffet dinner in the University College Club.

The first session on 20 December covered a variety of topics from African greenstone belt tectonics to methods of measuring finite strain in rocks. J. R. Vearncombe and J. M. Barton (Witwatersrand) reported new data on the structure and geochronology of the Rooiwater igneous complex and part of the Murchison greenstone belt in the Kaapvaal craton of South Africa. The tectonic units were interpreted as thrust sheets, and the authors challenged the validity of the Barberton type stratigraphy and the existence of the Murchison synclinal keel. S. H. Lamb (Cambridge) recognized a new phase of deformation within the Barberton greenstone belt of NW Swaziland: high-level syn-sedimentary folding and faulting, followed by the development of a complex of thrust sheets up to 1 km thick, some of which have been transported over 10 km. This deformation is older than three billion years and postdates an earlier phase of stratigraphic inversion and nappe tectonics reported from the central part of the greenstone belt. The paper by R. J. Lisle (Swansea) which followed represented a complete change in scale and topic. He had investigated the variation in fabric intensity with strain magnitude shown by 30 pebbles from a single exposure. The results cast doubt on any conclusions about strain magnitude which are based on fabric strength, for he showed that pure, coarse quartzite pebbles have better developed fabrics than impure, finer-grained ones, and predicted that pebbles with more than 25% non-quartz content will have a fabric statistically indistinguishable from uniform. J. Behrmann (BP) described a volume balance method for the analysis of finite deformation. The technique does not require geometric markers but relies upon an immobile marker material to provide a quantitative measure of diffusional mass transfer. In contrast, M. Ford (Cork) and C. C. Ferguson (Kansas) reported strain estimates from the Variscan fold belt in SW Ireland. A modified strain reversal method was used to calculate crystal extension on cleavage planes of stretched arsenopyrite crystals; this method showed that the strain was a pure shear with an average area increase on the cleavage plane of 190%. Turning to mechanisms of boudinage, R. Nicholson (Manchester) presented a case for considering that fracture boudins do not necessarily arise through the independent formation and dilation of cracks that form the ends of boudins, but can result from the growth and dilation of fracture arrays. Thus, for example, fracture boudins can be cross-sections of strips of rock defined by sigmoidally curving cracks of *en echelon* arrays. T. G. Bevan (Bristol) presented a new interpretation of the mesofracture systems in the Upper Cretaceous rocks of the steep zone in the Purbeck Wight monocline in Dorset. Fractures previously considered to have been generated during complex thrusting were shown to be the result of layer-parallel extension during flexuring. Thus structures in the steep zone of the monocline result from stretching during rotation and not from horizontal compression.

The second session was devoted to problems associated with the subduction process, faulting and the development of mylonites. D. C. Rubie (Bern) examined the possible effect of the olivine–spinel transformation on the rheology of subducting lithosphere. He identified three types of subducting slab and proposed that the above transformation, which occurs at a depth of about 300 km in a subducting slab, could be the cause of some slabs becoming aseismic at this depth. Also, certain slabs initially deform superplastically below the phase boundary but, due to the process of grain growth of spinel, the flow stress then increases with depth and these again become seismically active at a depth of around 500 km. N. J. Kusznir and J. M. Lockett (Keele) reported the results of experiments carried out to study the accumulation of strain energy and its subsequent release within a viscoelastic material with quartz and olivine dislocation creep mechanisms, subjected to constant shear velocity conditions. They concluded that the thermomechanical shear instability process, which may cause either slow running or fast running shear instabilities, may be an important deformation mechanism in the region of the brittle–ductile transition zone of major strike-slip faults. R. H. Sibson (California) looked for the causes of the varying depth of frictional interaction in fault zones and its consequences, The microseismic cut-out depth is believed to correspond to the transition with depth from friction-dominated faulting to mylonitization in quasiplastic shear belts, and Sibson recognized two main factors affecting the depth of the transition: compositional change and regional variations in heat flow. Turning to detailed field and microstructural work, P. G. Bretan and S. H. White (Imperial) reported on a study of mylonites associated with the Darling Fault, which runs for 1000 km along the SW margin of the Australian continent. They demonstrated the existence of a 'proto Darling Fault' along which sinistral transcurrent displacement occurred during late Proterozoic times. T. G. Blenkinsop (Keele) had examined Cambrian quartzites in the vicinity of the Ord Thrust on Skye under cathodoluminescence in the SEM to ascertain deformation mechanisms. He concluded that the dominant mechanism for both folding and thrusting was cataclasis and described a progressive deformation sequence from intact quartzite through protobreccia to breccia and ultrabreccia. The session concluded with a report by C. W. Passhier (Swansea) on new work from the southern part of the Proterozoic Mount Isa inlier in Queensland, Australia. Thrust zones with south-directed movement appear to be limited to the northern half of the inlier, whereas transcurrent faults extend the entire length of the inlier. Intrusion of granitoid bodies then precedes an intense phase (D2) of regional shortening.

The afternoon session began with a fascinating demonstration by D. J. Sanderson of the use of a microcomputer to obtain geometrically corrected data from field photographs of planar surfaces. For any quadrilateral, a matrix can be found which transforms it to its original known shape; other lines and points on the same surface can then be restored using the same transformation. Sanderson illustrated the method using photographs of fracture traces and strained objects, and a digitizing pad for data input. R. J. Knipe (Leeds) discussed the patterns of straining created in mylonites along thrusts as rocks are moved from depths where the accommodation of deformation may be continuous and distributed over the whole shear zone, to crustaul levels where the deformation becomes discontinuous and heterogeneous. Analysis of the strain-rate patterns developed as the rocks experience a syntectonic temperature decrease was illustrated with reference to Lewisian mylonites and experimentally produced mylonites in paradichlorobenzene. M. A. Ellis (West Chester, USA) then discussed the criteria for using syntectonic crystal fibres of the continuous type to determine strain histories. He concluded that accurate strain histories may be determined only if the incremental strains were homogeneous over the scale of the rigid particle–fibre couple, and if the full lengths of the fibres are preserved and can be observed. Turning to quartz c-axis fabric diagrams, D. Saha (Imperial) suggested that point-densities on such diagrams should be estimated by comparing the actual fabric with a random fabric. Using the coefficient of skewness of the distribution, η_3, as a measure of preferred orientation of the fabric, he found that 20 samples of deformed quartzite gave a linear correlation between η_3 and strain intensity. This suggests that under suitable circumstances η_3 can be used as a measure of strain intensity in quartz tectonites. D. G. De Paor (Johns Hopkins) made a plea for the use of general tensors rather than cartesian tensors for the quantitative description of structures. He presented several examples to illustrate the elegance of the general tensor approach. R. K. Morgan (Leeds) then reported new work on the Cambrian quartzites of the Kishorn area, Ross-shire where pipes in the quartzite remain circular in cross-section and orthogonal to bedding around hanging-wall folds. Large fractures divide the beds into blocks, and he considered that deformation of these blocks by microfracturing, accompanied by some crystal-plastic deformation, permitted folding to take place whilst coherence of the beds around the folds was retained. A. M. Bell (Galway) then examined possible theoretical strain paths which are followed during slaty cleavage formation, in particular a deformation involving plane strain and volume loss superimposed upon an initial shape generated by diagenetic flattening. He concluded that initial layer-parallel shortening may play an important part during cleavage development in slates.

The final session of the meeting was opened by E. H. Rutter (Imperial), who gave a contribution at short notice on the relations between deformation and metamorphism, with particular reference to the importance of dehydration reactions. J. P. Platt (Oxford) and J. K. Leggett (Imperial) then presented an analysis of fracture patterns and slip directions in the Makran accretionary terrain of Tertiary age in SE Pakistan. They described the determination of slip vectors from gouge fabrics, tectoglyphs, vein fibre lineations, and synthetic and antithetic fractures, and concluded that, in the last case, the standard interpretation of steps in fibre-lineated veins invariably gave the 'wrong' sense of slip. S. S. Hanna (Swansea) reported field observations from the Central Oman Mountains thrust belt where a series of culminations are developed above a sole thrust associated with the southward emplacement of an ophiolite. Thrusting was followed by culmination collapse, which is believed to be responsible for the extensional nature of the so-called 'Semail Thrust'. M. P. Coward (Leeds) described the evidence for low-angle extensional faulting associated with late movements on the Moine thrust zone and considered two possible causes: spreading from a thickened Caledonian crust or late-phase regional crustal extension analogous to that reported from the western USA. The meeting closed with a paper by D. Barr (BGS), R. W. H. Butler and R. E. Holdsworth (Leeds) on a thrust tectonic model to explain the internal geometry of the Moine thrust sheet. Estimates of pre-Caledonian P, T conditions were used to constrain the relative positions of major slide-bounded sheets prior to sliding.