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Report on the Tectonic Studies Group A.G.M. 18–19 December 1980, University of Keele

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THE ANNUAL General Meeting of the Group for 1980 was held at Keele University on 18 and 19 December. There were 216 registered participants. The meeting was followed by two field excursions; the first, on 20 December, to examine the structure of the Cambrian slate belt at Nantlle quarries was led by Barry Webb of I.G.S., Leeds, and the second, on 21 December, to investigate the stratigraphy and structure of the Mona complex of the Lleyn peninsula, was led by Wes Gibbons of U.C.W., Cardiff.

The meeting itself attracted a large number of papers of good quality and 44 papers were read. In accordance with normal TSG practice there was no theme to the annual meeting, but the various sessions were roughly separated on thematic lines. Field-based, theoretical and experimental studies were all well represented.

In a departure from traditional TSG practice it was decided to publish the abstracts of papers read at this meeting so that they might reach a wider audience. Abstracts of those authors who have agreed to publication are included below.

ABSTRACTS OF PAPERS PRESENTED

Triggering mechanisms of salt movement in a sector of the Hellenic Trench system, south of Crete, Eastern Mediterranean. G. Anastasakis and G. Kelling, Department of Geology, University of Keele, England.

The Ptolemy Mountains, between the central Hellenic Trench system and Crete, form part of an accretionary prism of the Hellenic subduction system. This region includes a series of basins that with increasing distance from the trench evolve from accretionary type to perched basins to graben-like depressions and fault valleys.

Seismic reflection profiles reveal that the observed acoustic basement is the Pan-Mediterranean reflector M, marking the top of the evaporitic Messinian sequence. On the basis of the available seismic data four triggering mechanisms of mobilization of the evaporitic substratum are recognised: (1) halokinesis initiated directly by the compressional stress of the subduction process, causing updoming along zones trending parallel to the compressive stress vectors; (2) vertical flow along faults triggered by differential block uplift, or above the downward terminations of reverse faults triggered by the differential stress; (3) salt doming triggered by a substantial thickness of overlying sediment with a mean density that surpasses that of the salt layer (buoyancy effect) and (4) lateral flow of salt due to asymmetric loading of the overlying sediment.

Once the salt movement has been triggered by one of these mechanisms the process appears to be self-perpetuating and demonstrably affects even the most recent sediments. It is suggested that in tectonically controlled sedimentary regimes of this kind, more than one mechanism is likely to be responsible for the observed halokinetic phenomena.

Intrabasinal deformation in the Back Cove Olistostrome, New World Island, Newfoundland. R. J. Arnott, Department of Geology and Mineralogy, Parks Road, Oxford OX1 3PR, England.

The Silurian Back Cove Olistostrome is composed of exotic blocks of limestone, basalt and black shale that have been emplaced into a thick sequence of sandstone turbidites. Sequences of thick-, and thin-bedded turbidites record an intrabasinal deformational event. Structures associated with the regional Acadian tectonism are only locally developed within the olistostrome, and clearly post-date the earlier deformation.

Sandstone layers show a complete spectrum of deformational features that are related to the degree of consolidation and include: (1) homogenization of sand and mud layers; (2) pinch and swell structures and boudinage and (3) parallel sets of extensional fractures inclined to bedding. Most of the disturbed strata can be traced laterally and vertically into undisturbed strata. More intense deformation is usually found around the exotic blocks.

Mudstone has been deformed in a ductile manner. Fractures within the sandstone layers are mud-filled and the greatest amount of stratal disruption is confined to layers with a low sand-shale ratio. A fabric developed within the disturbed mudstone 'wraps' around the exotic blocks. This fabric is not developed within the undeformed turbidite sequences as would be expected if the feature was a loading or regional tectonic phenomenon. This fabric has been tightly folded by the Acadian deformation.

Layers that display ductile deformation are interbedded with layers that display brittle fracturing and these structures may have formed at the same time. Differing degrees of consolidation is the most likely explanation for the varied deformation and this could be related to local differences in water content. Unconsolidated sand with a high water content deformed in a ductile manner whilst brittle fractures developed in more consolidated sands with a lower water content.

These early deformation features were caused by slumping, sliding and intrastratal shear on an unstable slope and locally by emplacement of exotic blocks.

Cover-, basement- and crustal-shortening in a section of the French Alps. A. Beach, Department of Geology, University of Liverpool, L69 3BX, England.

In the French Alps, the Ultradauphinois zone is a thrust zone of Dauphinois cover rocks lying structurally below the Briançonnais nappes. From measured stratigraphic thicknesses and amounts of strain, a structural cross-section has been restored at constant cross-sectional area, providing an estimate of 70 km cover shortening. The cover imbricates are the result of two major basement thrusts climbing section from basement into cover. The offset of the unconformity along a known movement direction provides an estimate of 35 km displacement along one of the basement thrusts. An E–W crustal cross-section across the Alps from Grenoble to the Po plain has been constructed from seismic data, and again restored at constant cross-sectional area to a uniform crustal thickness of 30 km, which is the thickness observed to the west of the Alpine deformation front between Grenoble and the Rhone valley. This provides an estimate of 30 km for the Alpine crustal shortening, i.e. a figure similar to that measured on one basement thrust alone. The discrepancy in the results suggests that prior to the Alpine orogeny, the crust had been much thinner than the average 30 km of the undeformed crust. If it had been thinned to an average 10 km a crustal shortening of 300 km is implied for the profile shown. This seems more compatible with the magnitude of displacements on and the number of the basement thrusts that are observed in the external Alps.

Syntectonic vein development in a thrust sheet. A. Beach, Department of Geology, University of Liverpool, L69 3BX, England.

The development of syntectonic veins in one of the thrust sheets in the Ultradauphinois zone of the French Alps close to La Grave has been studied in detail. The thrust sheet is one of a complex series of imbricates consisting largely of alternations of limestone and shale, is about 60 m thick and can be traced for a strike length of about 7 km. The rocks record large ductile strain with a strain ratio of approximately 10/1/0.2 and with the maximum extension $1 + e_1 = 6.0$. The first veins developed during this extension as short cross-cleavage fractures in the slates which then underwent considerable extension to produce thin, cleavage-subparallel veins. However, the bulk of the veins developed as late stage features of the deformation, truncating slaty and crenulation cleavages, as well as pyrite pressure shadows and extended belemnites. Narrow boudin-necks in the limestone beds developed asymmetrically with respect to slight ductile pinching of the beds. Continued separation of the limestone boudins occurred obliquely and infilling by calcite kept pace with separation to produce asymmetric bow-tie type veins. After a small amount of oblique separation, shear zones developed outwards from the boudin neck, involving boudin necks in beds above and below. The shear zones form a conjugate set with normal fault type geometry and range from 0.5 to 15 m in length. They are curved in profile as each zone flattens upwards and downwards to die out parallel to bedding. Numerous upright extension veins develop from the shear zones, often forming systematic en echelon sets. The early ductile deformation etc. appears to be related to the dynamics of thrust sheet emplacement, while the late brittle structures relate more clearly to increased overburden produced by thrusting.

The kinematic significance of deformed quartz polycrystal fabrics, deduced from a geological example. J. H. Behrmann and J. P. Platt, Department of Geology and Mineralogy, Oxford University, England.

Quartzites within a zone of mylonitic schists beneath the higher Betic nappe complex (Betic orogen, Southern Spain) have been deformed by dislocation creep mechanisms. A north-closing fold nappe at the base of the nappe complex suggests northward sense of emplacement. Microstructure development involves dynamic recrystallization and recovery processes.

The standard c-axis fabric produced during thrusting is a type I crossed girdle, with pole-free areas around the directions of maximum finite elongation. Skeleton asymmetries of complete fabrics (Lister & Williams 1979) consistently indicate northeast directed shear. Results from a-axis fabrics (Bouchez 1978) and basal trace plots in the XZ plane of the finite strain ellipsoid (Bouchez & Pecher 1976) yield internally conflicting conclusions.

Some fabrics are incomplete, and are difficult to interpret, possibly as a result of initial non-random orientations.

We conclude that the sense of vorticity in non-coaxial deformation of rocks can be independently determined from fabric skeleton asymmetry, provided that the fabrics are complete, and have a well defined outline.

The structural evolution of the Moine Thrust Zone between Loch Eriboll and Fionaven, N.W. Scotland. Robert W. H. Butler, Department of Earth Sciences, The University, Leeds, England.

The Moine Thrust Zone immediately South of Loch Eriboll, despite excellent exposure, has been comparatively ignored for a number of years. The area was important in the recognition by early workers that the Moine Rocks had been translated over a foreland of Cambro–Ordovician cover on Lewisian basement. Since then there has been some debate as to whether thrusting was propagated in or against the tectonic transport direction.

Studies of the critical areas around Creag Shomhairle (NC 383507.) show that thrusting of Moine Rocks over Lewisian was followed by the two distinct sheets of Moine and Lewisian being thrust over the pipe-rock member of the Eriboll Quartzite. This three-component sheet was then imbricated while being thrust over the An t'Sron Formation. The whole complex was subsequently folded by imbrication, initially of the An t'Sron Formation and later the Eriboll Quartzite. This succession of thrusting, from top to bottom, implies that thrusting was propagated in the tectonic transport direction. A corollary of this is the concept of net accretion onto the overriding thrust sheet. Hanging wall and cross section evolution diagrams were presented to illustrate this model.

Along strike of the Thrust Zone there is considerable structural variety due to footwall corrugations and hanging wall culminations. The interference of these structures at the lateral termination of duplexes, coupled with oblique ramp-climb, can complicate the thrust rules as listed by Elliott & Johnson (1980). For this reason it may not be prudent to correlate structures laterally along the Thrust Zone.

Strain removal in two and three dimensions: theory and regional applications. P. R. Cobbold and M. N. Percevault, C.A.E.S.S., Université de Rennes, France.

The simplest techniques of strain removal so far developed make use of finite elements, within each of which, components of strain, rigid rotation and translation are assumed constant. Elements are unstrained individually, then reassembled so as to minimize gaps and overlaps.

In two dimensions, a numerical method exists whereby elements are reassembled by minimizing the sum of the squares of internodal distances. We have applied this method to regional strain data from South-Central Brittany. The results indicate that the region underwent a dextral transcurrent shear parallel to major shear faults. Other structural evidence also leads to the same conclusion. The method is applicable here because strains are essentially two-dimensional.

In three dimensions, we have extended the method to treat rectangular prisms (parallel to strain trajectories) and also parallelepipeds. Our minimization technique leads to unique and exact expressions for the rigid translations and rotations of the elements. For regional applications we suggest dividing a surface layer into cubes using a Cartesian grid. After unstraining, the cubes become parallelepipeds, which we reassemble using the minimization technique. For graphical representation, we favour an isometric projection and automatic (computer) plotting.

Gravity spreading in the Moine Thrust Zone. M. P. Coward, Department of Earth Sciences, Leeds University, England.

The Caledonian thrust zones of Assynt show several examples of large fault bounded, gravity spreading structures, 'surge zones', some 5 km^2 in extent. Extensional faults can be traced into strike slip and then to compressional faults. There are extensional and compressional imbricate faults and zones of extensional and compressional ductile flow, as shown by strained Cambrian pipe-rock. Differential movement of late surge zones caused folding of earlier surge faults and hence the sequence of structures can be deduced.

Recognition of the surge zones has solved several local problems, such as the lack of continuity of the Glencoul thrust. It also means that many of the rules of thrust geometry and propagation need to be rewritten. For example, hanging wall sections with extensional fault geometry pass over footwall sections with compressional fault geometry and hence young rocks can be thrust over old rocks. Several other probable surge zones have been identified along the length of the Moine Thrust suggesting that gravity spreading has been an important driving mechanism during at least the late stages of movement. This raises interesting problems concerning the continuation of the major thrusts at depth.

An attempt at a kinematic interpretation of the root zone of the Helvetic nappes, Western Switzerland. D. Dietrich, Song Honglin and M. Casey, Geologisches Institut, ETH Zentrum, CH 8092 Zürich, Switzerland.

Observations of fold axes, cleavages, lineations, pressure shadows, calcite preferred orientation and microstructure were made in the root zone of the Helvetic nappes in order to obtain a better understanding of its deformation history. The fold axes form a slight arc between the Aiguilles Rouges massif and the Aar massif. In the root zone the dip direction of the well developed slaty cleavage changes gradually from E in the west to S in the east. The crystallographic preferred orientation of calcite changes correspondingly, but to a lesser extent. The c-axes are oblique to the macroscopic fabric and this is used to infer the direction of a late shear movement, responsible for the arcuate pattern of the nappe pile. The shear zone boundary is approximately cone shaped, dipping slightly to the SE, and the shear movement is overthrust towards the NW.

The macroscopic fabric in the root zone is characterized by two lineations in the cleavage. Well developed pressure shadows, common in the limestones, show fibre patterns with two main elongations parallel to each of the lineations, from which the relative ages of the lineations can be deduced. The earlier lineation, at a high angle relative to the fold axes, is a stretching lineation. The corresponding increment of the pressure shadows shows an extension parallel to the X axis of the finite strain ellipsoid. This lineation was the result of intense shear strain in the nappe pile during its emplacement. The second lineation, sub-parallel to the fold axes of the major folds, is not a stretching lineation, but the corresponding increment of the pressure shadows shows a slight elongation parallel to it. It is proposed that this lineation is associated with the late shear movements inferred from the calcite preferred orientations and that the extensions recorded by the pressure shadows are the result of the formation of the arc.

The Caledonian evolution of the Jotun Nappe of central southern Norway. T. F. Emmett, Department of Geology, University of Keele, England.

The Jotun Nappe, which forms the highest structural unit of the Caledonide Orogen of central S Norway, is predominantly composed of amphibolite- and granulite-facies orthogneisses of Sveconorwegian and Svecofennian age (Schäer 1980). It is preserved along the axis of a regional synform, the Faltungsgraben, and the SE margin of this depression is marked by the Tyin Gjende Fault, a major post-thrust shear zone. Structural studies from the sub-Jotun units (e.g. Roberts 1977, Hossack 1978), and the presence of Jotun-type rocks in the Caledonised Western Gneisses (Bryhni 1966) indicates that the Jotun Nappe was thrust into position from the NW. Such a model is in apparent conflict with gravity anomaly models (Smithson *et al.* 1974) and the structure of the central part of the nappe where Caledonian deformation is confined to thrusts, lag-faults, and steep normal and reverse faults. The interrelationship between these structures and the distribution of the various petrogenetically distinct units within the nappe requires that vertical movements which post-date the cessation of thrusting are important in establishing the present-day form of the nappe. Previous models for the emplacement of the Jotun Nappe have generally concentrated on either horizontal movements or vertical movements (for review see Smithson *et al.* 1974).

To explain the field evidence and to accommodate the geophysical models, the following model is proposed. (1) Emplacement from the NW of a thrust-nappe of dense Jotun rocks over continental crust. (2) Gravitational sagging and the consequent thickening of the central part of the nappe. (3) Renewed SE-directed compression which resulted in the underthrusting and up-wedging of Jotun rocks along steep major faults, and the formation of the Faltungsgraben.

The structural history of the West African Basement Complex. S. J. Freeth and A. E. Annor, Department of Geology, University College of Swansea, Wales.

Three major episodes of deformation can be recognised in the Basement Complex of south-western Nigeria.

The first major tectonic event resulted in the development of a strong metamorphic–tectonic fabric (D1) within a suite of what are now banded gneisses. This event transformed a sequence of rocks which had a mixed volcano-sedimentary origin and superimposed the present, strongly banded, fabric. By comparison with observations made elsewhere in the Nigerian Basement Complex we infer that this event occurred towards the end of the Archaean and can be correlated with the Liberian orogeny (2700 ± 200 Ma).

Prior to the onset of the second major tectonic event a sequence of pelitic and psammitic sediments were deposited in the Okene area. Early in the second tectonic event these sediments and the underlying gneisses were extensively invaded by tonalitic magmas. The rocks were then intruded by a sequence of dykes of intermediate composition. These dykes, which have previously been observed elsewhere in southern Nigeria (Burke *et al.*, 1976), clearly cross-cut the D1 fabric and therefore provide an excellent structural marker. The metamorphic–tectonic fabric (D2) developed during this event modifies the earlier (D1) fabric and is well developed in all the post-D1 rocks. Granites which post-date the intermediate dykes but contain a well developed D2 fabric were intruded towards the end of the second event. One of these granites, from Ibadan, has yielded a radiometric age of 2300 Ma. We therefore infer that our second tectonic event occurred early in the Proterozoic and can be correlated with the Eburnean orogeny observed elsewhere in West Africa.

The third tectonic event produced large open folds with localised zones of high deformation (D3). During this event pyroxene diorites and granites were intruded. The extent to which these intrusives are foliated depends entirely on their position relative to the level of D3 deformation. This event can be correlated with the Pan-African thermo-tectonic event which affected large areas of Africa during the Late Proterozoic–Early Phanerozoic.

Experimental study of cataclastic deformation of a quartzite. J. Hadizadeh and E. H. Rutter, Geology Department, Imperial College, London SW7, England.

The problem of the development of peak stress and fault zone localisation in a quartz cemented sandstone (Oughtibridge Ganister) has been investigated through detailed microstructural study of samples deformed to various strain levels up to and beyond the peak stress. Experiments were carried out at 200 MPa confining pressure, 20°C and at 10^{-5} $\sec^{-1}$ strain rate.

Progressive loosening of the rock structure occurs by the formation of grain boundary cracks which are initiated at the sharp corners of pores. This process continues through the peak stress and it is only when well into the post-peak region that axial transgranular cracks start to develop. This is the first stage in the localisation of a fault zone.

From crack maps prepared for various levels of permanent strain, a plot of integrated crack length versus permanent strain was prepared. This plot has the characteristics theoretically expected for a material which exhibits a peak strength as a geometric consequence of the way in which permanent strain is accumulated through crack growth. Most of the resistance to deformation for this rock appears to arise from sliding friction between microcrack faces. This study suggests that the mode of failure of brittle rocks may depend on the initial microstructure.

Post-alpine tectonic evolution of South-east Spain and the structure and microstructure of fault rocks. S. H. Hall and E. H. Rutter, Geology Department, Imperial College, London SW7, England.

The microstructures and mineralogies occurring in major NE–SW trending fault zones (≃400 km outcrop length) in SE Spain have been investigated. The movement history of the faults has been inferred from studies of the sediments within the basins which formed as a result of faulting. Three main periods of movement, of decreasing intensity with time, can be deduced to have occurred from the M. Miocene to the present. These are (a) Serravallian, (b) Messinian and (c) Upper Pliocene.

The structures within the fault products themselves have been studied in detail. Fault gouges possess two foliations, one (R_1) at about 20° to the gouge/country rock interface and one (Y) parallel to it. The latter crenulates the former. From the orientation of the intersection of the foliations a movement direction may be deduced. This technique provides data consistent with other movement direction indicators. The main fault zones are left-lateral wrench with a reverse component overthrusting to the south. Mineralogical studies of two major faults showed one to be dominated by kaolinite and the other by chlorite as the principal secondary phyllosilicate gouge minerals.

New/Old Moine relationships between Fort Augustus and Inverness. A. L. Harris, Department of Geology, University of Liverpool, England, L. M. Parsons, Institute of Oceanographic Sciences, Brook Rd., Wormley, Surrey, England, A. J. Highton, Department of Geology, University of Liverpool, England and D. I. Smith, I.G.S., Edinburgh, Scotland.

Between Fort Augustus and Inverness on the southeast side of the Great Glen hitherto undescribed Moine/Dalradian rocks offer an insight into the nature of cover and basement rocks in the Highlands.

To the NE of the Foyers Granite much of the ground is underlain by coarse-grained psammitic and pelitic gneisses with calc-silicates and garnetiferous amphibolites. These rocks, which closely resemble parts of the Glenfinnan Division (Johnstone 1975) of the N. Highland Moines, reached sillimanite-grade metamorphism. They carry evidence of four episodes of deformation, of which at least two postdated the peak of metamorphism.

To the SW of the Foyers Granite a sequence of variably deformed pebbly schists of low metamorphic grade, now up to 3 km thick, dips approximately south and east at about 60° and youngs upwards. The top of this sequence is marked by a zone of strong deformation (? slide) which carries platy quartzite and which underlies semipelitic schists of Dalradian aspect.

The relationships of this sequence to the high-grade gneisses described above is partly obscured by faulting and by the Foyers Granite itself; recent work near Loch Mhor (NH 525175) and in the vicinity of Torness (NH 582270) has, however, clarified the original relationships between the low-grade pebbly schists and the high-grade gneisses.

In an ?enclave of the granite near Loch Mhor, pebbly schists, closely resembling those at Fort Augustus, pass upwards stratigraphically into siliceous cross-bedded psammites of low tectonic strain and low metamorphic grade. These in turn pass up into semipelitic schists (now hornfelsed). In the vicinity of Torness, similar cross-bedded siliceous psammites of low strain and low metamorphic grade are in contact with high-grade pelitic gneisses. These siliceous psammites carry a single cleavage, axial planar to upward-facing folds of moderate plunge. Folds of the same generation in the gneisses below and adjacent are steeply plunging but are phase-3 in the basement tectonic sequence and post-date the peak of metamorphism. Analysis of the sense of overturning of folds in the siliceous cross-bedded psammites suggests that they occupy the core of a major upward-facing synform which trends approximately NNE. The contact between the cross-bedded psammite and the gneisses is marked by a platy zone indicative of high tectonic strain about 150 m wide. This is inferred to relate to ductility contrasts between the cover sequence of psammites and the coarsely crystalline pelitic gneisses which are severely retrograded at the contact. Although the possibility cannot be ruled out that these platy rocks are an extension to the SE of the Great Glen of the Sgurr Beag Slide (Rathbone & Harris 1979), the authors believe that they have recorded a modified original unconformity between a cover sequence of "New Moine" rocks which passes up into Dalradian, and the considerably older Grenville or Morarian gneisses of the "Old Moine" which occupy much of the Northern and Central Highlands.

These results provide further confirmation of the reality of a cover sequence postulated by Piasecki & van Breemen (1979).

A zone of high strain within the Grampian Division of the Southern Monadhliath Mountains Inverness-shire. P. J. Haselock, Department of Geology, University of Keele, Staffs, England.

Two distinct lithostratigraphic successions, separated by a zone of high strain, have been recognized in an area east of the Corrieyairack Pass, Inverness-shire.

Minimum finite strain values, which show a maximum elongation in a NW–SE direction, have been calculated from deformed pebbles in a pebbly psammite from the top of the lower succession.

Structural evidence obtained from minor structures suggests that the principal deformation of the pebbles, associated with the development of the zone of high strain, occurred early in the structural history of the area.

Contemporaneous local migmatization occurs in the overlying semipelites.

Sequence of hanging-wall imbrication in the Valdres Thrust, Djuptjernskampen, Norway. John R. Hossack, Geology Department, City of London Polytechnic, Walburgh House, Bigland Street, London E1 2NG, England.

The sequence of imbrication in foot-wall imbricates (duplexes) is unequivocally from hinterland towards foreland in the direction of displacement of the floor and roof thrusts. Dahlstrom (1970) suggested that hanging-wall imbricates propagate in the same sense but had no evidence to support this view. Imbricate thrusts in the hanging-wall of the Valdres Thrust repeat older basement gneisses over their cover of Cambrian quartzites. The higher imbricates are displaced by a Caledonian normal fault which formed above a side-wall ramp of the Valdres Thrust. The lower imbricates are not displaced by this fault and are hence younger. A hanging-wall sequence diagram (Elliott & Johnson 1980) clearly shows the sequence of imbrication was from top to bottom, or hinterland to foreland. A similar side-wall ramp fault exists 6 km to the east of Djuptjernskampen. The direction of thrust displacement was probably parallel to the 130° strike of the side-wall ramp faults. This direction is parallel to quartz fibres on thrust surfaces of the foot-wall imbricates beneath.

The erosion factor in the emplacement of the Keystone thrust sheet across a land surface. M. R. W. Johnson, Grant Institute of Geology, University of Edinburgh, Scotland.

The Keystone/Muddy Mountain thrust of SE Nevada provides a spectacular example of a thrust sheet that has travelled across the earth's surface for a distance of at least 25 km, probably as much as 50 km. Along the thrust a Palaeozoic to early Mesozoic succession (>4 km thick) has moved over a channelled erosion surface cut into Jurassic aeolian sandstone. Clasts in the channels are stratified, with those in upper layers being easily matched with the rocks in the thrust sheet—thus the clasts 'herald' the approach of the sheet. The clasts are only weakly deformed by the thrusting which belongs to the Sevier–Laramide orogeny.

Erosion appears to be a significant if not crucial factor in the emplacement of the Keystone thrust sheet. Adopting an erosion rate of 1 mm a^{-1} (in accord with Alpine and Himalayan estimates) and a rate of thrusting of 5 mm a^{-1} (in accord with estimates from the Canadian Rockies) it follows that the thrust sheet was 'half-eroded' after travelling about 25 km. From a stress analysis it is concluded that large displacement (i.e. >25 km) is impossible without erosion, and one of two 'erosion models' would greatly facilitate transport up to 50 km which is the likely maximum displacement.

Despite the high permeability of the rocks in the footwall the analysis requires a moderately elevated fluid pressure which is not inconceivable in the thin zone of deformed, indurated, sandstones found immediately beneath the thrust plane.

The analysis differs from Raleigh & Griggs' study of the erosion factor in thrusting firstly in the assumption of only modest fluid pressure and, secondly, in the attempt to quantify the erosion factor. For these reasons the present conclusions may have a fairly wide application in the study of thrusting mechanisms.

Structures, deformation and metamorphism of the northern Maggia Zone (Ticino) Switzerland. Eva M. Klaper, Geologisches Institut, ETH Zurich, Switzerland.

The area investigated in this paper is situated in the Northern Penninic realm of the central Swiss Alps (Ticino).

The structural history of the area can be divided into three main events: (1) Nappe formation and northwards transport. Formation of isoclinal folds with a mineral elongation lineation parallel to fold axes. (2) Regional folding of the nappe pile. Isoclinal refolding of F_1 folds with strong shearing on most fold limbs. Axial planar schistosity parallel to earlier schistosity and compositional banding. (3) 'Backfolding' of the nappe pile and crenulation of all earlier schistosities.

An amphibolite facies metamorphism can be correlated with the 2nd and 3rd phases of deformation through the formation of garnet, staurolite and kyanite porphyroblasts in carbonate-micaschists and the existence of talc and tremolite in marbles. Temperature of metamorphism between 550–580°C and pressures of 5.5–6.0 kbar have been determined and evidence is presented for the existence of a CO_2 rich fluid. A constant sense of rotation of synkinematic prophyroblastic garnets over the entire area suggests that they formed during the last phase of deformation.

The strain field of a ductile shear zone in the Northern Apennines. Roy Kligfield, Geologisches Institut, ETH Zentrum, Zürich, Switzerland, L. Carmignani, Istituto di Geologia, Pisa, Italy, and W. H. Owens, Department of Geological Sciences, Birmingham, England.

The Apuane Alps region of the Northern Apennines appears to have been deformed and metamorphosed within a large scale, low angle crustal shear zone with an overthrust sense of movement. The presence of mineral stretching lineations, fold axes progressively rotated into the X direction and schistosities which intersect the nappe boundaries at 45°, suggest that the deformation was due largely to simple shear.

The strain ratios and orientations on two-dimensional sections have been determined from deformed marble breccias, reduction spots and oncalites. Data from three or more non-perpendicular, non-principal sections have been combined to determine the finite strain values. A general relationship is found between the amount of simple shear as determined by degree of fold axis rotation and the type of strain. On a logarithmic deformation plot, the strain values at areas with non-rotated fold axes generally lie within the flattening field ($0 < k < 1$); the strain values at sites where the fold axes are parallel to stretching lineation are along the plane strain field (parallel to $k = 1$) with about 20% volume loss.

These results can be integrated together with the total time of deformation (15 Ma from K/Ar and Ar^{40}/Ar^{39} studies) to arrive at 'average' strain rates of $1.5 - 5.7 \times 10^{-15}$ sec^{-1} for extension and $1.0 - 1.6 \times 10^{-15}$ sec^{-1} for shortening.

In situ *development of deformation microstructures under the optical microscope.* R. J. Knipe, Department of Earth Sciences, Leeds University, England.

The recent development of *in-situ* deformation experiments under the optical microscope using camphor and para-dichlorobenzene allows the direct observation of the evolution of many microstructures characteristic of deformed minerals (Urai *et al.* 1980, Means 1980). Examples of the deformation processes which can be studied, in these and other materials, in a simple apparatus (designed by Win Means, Albany) have not been widely demonstrated here. Direct observation of the microstructural evolution of mylonites is possible within minutes or hours. Processes which can be observed include kinking, grain boundary sliding, grain boundary migration, sub-grain development and recrystallization.

Lithosphere response to externally and internally derived stresses.

N. J. Kusznir, Department of Geology, University of Keele, Staffs., England.

Non-lithostatic stresses may be generated internally within a section of lithosphere (Turcotte 1976) or may be stress-guided to a particular section of lithosphere from an adjacent lithosphere source. Walcott (1970), Watts *et al.* (1975) and others have shown that the lithosphere, as conventionally defined by seismology and post-glacial rebound studies, behaves as a non-elastic structure. For externally or internally derived stresses the non-elastic lithosphere results in stress decay at depth with associated stress amplification in the upper lithosphere (Kusznir & Bott, 1977). The stress response of lithosphere with power law stress and temperature dependent viscoelastic properties has been investigated.

For lithosphere with an oceanic geotherm and thickness 80 km, subject to an externally derived applied lateral stress of ± 0.1 kbar, stress in the upper lithosphere is amplified by 1.5, 1.8 and 2 times at 10^4, 10^6 and 10^8 yr respectively. At 10^6 yr the effective thickness of lithosphere still carrying stress is reduced to approximately 40 km. For an applied stress of ± 1.0 kbar the stress amplification and decay proceeds more rapidly resulting in extensive brittle fracture of lithosphere for a tensile applied stress.

For continental lithosphere with thickness 150 km the stress amplification in upper lithosphere of an applied lateral stress of ± 0.1 kbar is 1.6, 2 and 2.5 times at 10^4, 10^6 and 10^8 yr. The thickness of lithosphere carrying stress at 10^6 yr is about 70 km. Again an applied stress of ± 1.0 kbar results in faster stress transfer to the upper lithosphere which results in extensive brittle failure for tensile stress.

The decay of stress in the lower lithosphere and associated amplification above, is extremely rapid for lithosphere with a Basin and Range type geotherm. An initial lithosphere thickness of 150 km is used. For an applied stress of ± 0.1 kbar, stress amplification at 10^4, 10^6 and 10^8 yr is 5, 6 and 7 times respectively. For an applied tension of 0.1 kbar brittle fracture results after 10^4 yr. The effective lithosphere thickness at 10^6 yr is 30 km. For an applied stress of ± 1.0 kbar, by 10^3 yr both tensile and compressive applied stresses have been amplified sufficiently to result in brittle failure and by 10^5 yr this brittle failure has penetrated the whole of the elastic component of the lithosphere. This results in a situation where upper lithosphere cannot sustain the applied stress, but its transfer to lower lithosphere, after faulting, results in its rapid transfer back to upper lithosphere because of lower lithosphere creep. Thus periodic faulting results and associated crustal attenuation for tensile applied stresses.

The behaviour of stress generated by lateral density contrasts within lithosphere has been examined for the stress fields associated with continental margins and the low density mantle feature underlying the plateau uplift of the Basin and Range area. While the elastic solution of the Basin and Range stress field gives a maximum deviatoric stress of 0.3 kbar the viscoelastic solution at 10^6 yr gives 1.2 kbar at upper crystal levels. This is sufficient to cause tensional brittle failure.

Relationships between strain and quartz optic axis fabrics in the Roche Maurice Quartzites of Western Brittany.

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A petrofabric study has been made of the Roche Maurice Quartzites which crop out along the southern bank of the Elorn estuary in Western Brittany. The quartzites are folded and exhibit a penetrative cleavage of variable intensity which fans about the hinge surfaces of minor folds. Bedding–cleavage intersection lineations (*L*), are parallel to local fold hinges.

At low strains, quartz grains exhibit undulose extinction and occasional lobate boundaries, whilst with increasing strain, grains become flattened and may display 'core and mantle' structures (White 1976). In the most highly deformed specimens old grains are seen to be widely separated in a matrix of small new grains. Ribbon-like grains are also seen in the more highly deformed specimens; a few quartz grains in these specimens appear to be undeformed and flattened grains may anastomose around these augen.

A simple strain analysis, using the Rf/ϕ technique of Dunnet (1969), was performed on a series of orientated specimens, using the deformed detrital grains as strain markers. Ribbon grains were not included in this analysis. Three orientated, mutually perpendicular thin sections were prepared from each specimen, the Rf/ϕ analysis applied to each section, and the results combined to estimate the strain ellipsoid for each specimen. It was found that the principal extension axis (*X* axis) of the calculated strain ellipsoid was parallel to *L*, whilst the principal shortening axis (*Z* axis) was perpendicular to cleavage.

'*U*' stage work revealed that variation in symmetry and magnitude of strain was reflected in the quartz optic axis fabrics; the degree of preferred orientation being proportional to strain magnitude. c-axes of quartz augen are sub-parallel to *Z*.

In specimens with calculated flattening strains, c-axes lie on a small circle girdle (opening angle 25°–35°), about *Z*. For specimens that exhibit approximate plane strain a cross girdle pattern was detected, consisting of a small circle connected through *Y* and containing triangular maxima in the most highly deformed specimen. These fabrics are very similar to those predicted by Lister *et al.* (1978) when basal ⟨**a**⟩ is the easiest slip system to operate, and the r and z rhomb systems have equal but higher critical stresses. In specimens of low strain magnitude, c-axes of ribbon grains are scattered around *Y*, whilst in the most highly deformed specimens they form a well defined cross girdle fabric intersecting in *Y*. Fabrics from ribbon grains in the two most highly deformed specimens are similar to those predicted by Lister *et al.* (1978) when prism ⟨**c**⟩ glide is considerably easier to activate than glide on basal ⟨**a**⟩ and combined rhomb glide systems. Quartz optic axis fabrics of recrystallised grains are similar to those of deformed detrital grains for a given specimen.

It has proved difficult to estimate the metamorphic grade of these essentially monomineralic rocks. A little white mica is present as beards in slightly deformed specimens; the quartz optic axis fabrics discovered have been previously described in tectonites deformed under greenschist facies conditions (Tullis 1977).

The exact shape of deformed pebbles.

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The shape and internal structure of deformed pebbles are compared with theoretical predictions about the deformation of a viscous circular or elliptical inclusion in a matrix of lower viscosity (Eshelby 1957, Ghosh & Sengupta 1973, Bilby *et al.* 1975). A geologically important prediction supported by the finite element calculations of Shimamoto (1975) is that the finite strain within the pebble is homogeneous and remains so during continued deformation. The deformed inclusion retains an elliptical shape.

Pebbles from conglomerates in Artfjall (Swedish Caledonides) closely approximate to ellipses, whilst other pebbles from neighbouring areas, the Swiss Alps (Ramsay 1967, fig. 5–44) and grains from deformed grits from the Appalachians possess outlines with a systematic deviation from an elliptical shape. Fitting members of the superellipse–subellipse series which are shapes described by the equation

$$\frac{x^n}{a^n} + \frac{y^n}{b^n} = 1 \quad (a \text{ and } b \text{ are the lengths of the semi-axes})$$

to these shapes yields values of n between 2 and 1 signifying that the shapes are intermediate between ellipses and lozenges (subellipses). This tendency for pebble shape with pointed ends is found to be common.

Fourier analysis (Ehrlich & Weinberg 1970) of pebble shapes has been carried out to distinguish shape 'components' which can be used in classification. The second and fourth harmonic amplitudes provide a means of classification comparable to the classification of superellipses in terms of the power, n.

Several explanations can be offered for the occurrence of 'subelliptical' pebble shapes.

(a) The shapes are the product of close packing of pebbles so that neighbouring pebbles in a less competent matrix mutually interfere to give a tendency for straight faces on juxtaposed pebble contacts.

(b) The pebbles are in fact boudins with a 'pinched' shape predicted by Smith (1975) to develop in pebbles when their axial ratios become large.

(c) The core of the pebble is deformed less than their margins in which case Tan's (1974) experimental simulation of oolite deformation may be relevant.

The first explanation is envisaged as an important reason for non-elliptical pebble shapes in a wide variety of conglomerates, explanation (b) is doubtless important in certain strongly deformed conglomerates but the relevance of (c) is still uncertain.

Theoretical aspects of shear zone initiation and development. J. M. Lockett and N. J. Kusznir, Department of Geology, University of Keele, Staffs., England.

A theoretical examination of shear zones is necessary in order to provide an insight into the thermal and mechanical processes involved. Such information cannot be determined from field observations alone.

Yuen *et al.* (1978) have described a one dimensional mathematical model of a shear zone. They show that shear zone width, shear heating temperature anomaly and shear stress magnitude depend on ambient temperature, the velocity of relative motion of the shear zone and time.

Yuen *et al.* (1978) have described a one-dimensional mathematical initiation and early evolution of the shear zone and is not suitable for small shear zones. An alternative solution technique is presented here which overcomes these limitations.

The fundamental equations (Yuen *et al.* 1978) describing the shear zone are:

$$\rho\sigma\frac{dT}{dt} = \kappa\frac{d^2T}{dy^2} + \frac{du}{dy}\tau \qquad (1)$$

and

$$\rho\frac{du}{dt} = \frac{d\tau}{dy}, \qquad (2)$$

in addition

$$\frac{du}{dy} = \frac{\tau^n}{A\exp(BTm/T)}. \qquad (3)$$

For earth material thermal diffusion occurs over a much larger time scale than viscous diffusion and consequently the inertial term $\rho du/dt$ of equation (2) can be neglected. A coupled numerical solution of differential equations (1) and (2) confirms that this assumption is everywhere valid. From equation (3) we therefore obtain

$$u(y) = \tau^n \int_0^y 1/A \exp(BTm/T)\,dy', \qquad (4)$$

which for a constant differential slip velocity of U_0 across the shear zone becomes

$$u(y) = U_0/2\,\frac{\int_0^y 1/\exp(BTm/T)\,dy'}{\int_0^\infty 1/\exp(BTm/T)\,dy'}. \qquad (5)$$

The problem thus simplifies to the solution of equation (1) together with either (4) or (5) for either constant stress or velocity boundary conditions.

The results of our constant velocity model agree closely with those of Yuen *et al.* (1978). However, for a given time our shear zone, as defined by the velocity profile is narrower than that of the Yuen *et al.* (1978) model. A further fundamental difference is that while the initial velocity profile of Yuen *et al.* (1978) is a Heaviside function with $U = Uo/2$ everywhere except at the origin, our model has a uniform shear velocity gradient. The other significant difference is that the positive temperature anomaly at the shear zone centre is shown to increase gradually and continuously and does not reach an asymptotic or steady state value. Temperatures are however not sufficient to cause significant partial melting within a reasonable time scale. The shear zone can also be shown to broaden with depth. Similar conclusions have been reached by Fleitout & Froidevaux (1980).

The constant stress boundary condition gives rise to constant gradient velocity profiles across the shear zone. The values for velocity are very small until a critical value for temperature or shear stress is reached. At this point shear localizes in the centre of the shear zone producing large velocities. Subsequent shear heating gives rise to thermal runaway and melting. The critical value of shear stress and/or ambient temperature required for shear zone initiation have been found. Relatively high shear stresses are required to initiate thermal runaway at low temperatures.

The constant stress boundary condition may be applicable to small shear zones of the order of metres or centimetres in width and to the initiation stages of larger scale shear zones. In contrast the constant velocity model may be more applicable to plate boundaries.

Primary bedding-parallel fabrics in structural geology. Alex Maltman, Department of Geology, University College of Wales, Aberystwyth, Wales.

During sedimentation, phyllosilicates attain mechanical stability by orienting themselves parallel to bedding, although any quartz grains present may restrict this tendency and some pure clays may prefer 'card-house' arrangements. Loss of water during the initial stages of compaction also promotes a bedding-parallel alignment. This 'primary fabric' will be most efficiently achieved during shallow burial, where the compactional force is virtually uniaxial, and there is relatively little constraint on rotation of the plates. Observations on laboratory materials and on rocks, such as the displacement of the fabric by sedimentary dykes and re-orientation around slump folds, support this idea in preference to the fabric arising through substantial burial. Diagenetic processes such as the growth of chlorite–mica stacks enhance and 'lock-in' the already-produced fabric. If the material is buried to the extent that metamorphism takes place, but in the absence of tectonic stress, static mimetic recrystallization will cause the fabric to become metamorphic in appearance, while maintaining its bedding-parallel orientation.

Such fabrics, in their various stages of evolution, appear not to have received due attention in structural geology. Three examples follow to show how their recognition may aid understanding of structural problems.

(a) The question of how the slump-folds of the Powys Trough, E. Wales, produced an axial-planar cleavage is resolved if the cleavage is interpreted as a primary fabric due to compaction immediately following slumping. The geometrical relationship between the cleavage and the ubiquitously flat-lying folds is therefore only fortuitous. (b) The difficulty of generating suitably-oriented nuclei for production of a first cleavage is avoided if there is a primary fabric available for crenulation. This appears to have taken place in the Aberystwyth Grits of W. Wales. (c) As another example there has been debate on the sequence of events in the Ballachulish Slates of W. Scotland. The widely-accepted view regards the major cleavage, axial-planar to the regional folds, as a 'first' deformation structure, but there is preserved in certain lithologies an earlier metamorphic fabric. If the latter is interpreted as a product of mimetic recrystallization of a primary fabric, then the conventional sequence of deformation can be retained. The presence of a metamorphic fabric in rocks does not in itself denote a period of deformation.

On the age of the 'root zone' of the internal, north-western Alps. B. A. Martin, Institute of Geological Sciences, Environmental Protection Unit, Harwell Laboratory, Didcot, Oxfordshire, England.

The Penninic and Austroalpine nappe pile of the internal, north-western Alps is overturned and attenuated into a steep zone adjacent to the Canavese Line, a part of the Insubric fault system. According to Argand's (1911, 1934) classic concept of Alpine structure, the fold nappes originated from this 'root zone'.

The label 'root zone' has since been generally applied, in thrust nappe terrain, to zones which, in comparison to adjacent parts of the sheets, are steep, narrow and exhibit a higher degree of deformation, and where the rearmost exposed part of the nappes turn down to depth.

Modern Alpine work has demonstrated part of the 'root zone' in the Central Alps to be a late Alpine structure (e.g. Milnes 1974, 1978). A similar interpretation can be applied to the classic area in the Ossola valley of northern Italy: From structural overprinting relationships the 'root zone' feature is demonstrated to be a third generation (D_3) structure, as it folds the Monte Rosa fold nappe (F_2) which itself folds the ubiquitous S_1 planar fabric. The zone is dominated by tight, asymmetrical F_3 folds which are contemporaneous with the attenuation of all units in this steep belt. Late faulting, box folds (F_4), kink bands and a conjugate crenulation cleavage (set) (S_4) are of only very local significance.

Thus, the strong deformation state of the so-called 'root zone' post-dates the nappe formation. The traditional idea that the nappes originated from this zone has led to uncertainty over the geometry of the nappe boundaries beneath the 'root zone', which is reflected even in recent structural profiles (e.g. Dal Piaz & Ernst 1978, Gosso *et al.* 1979). Mapping of the F_3 folds in the Ossola valley indicates that the nappes do not appear to terminate in this zone, but are simply folded within it and continue eastwards at depth, although presumably offset by the Canavese Line.

The features commonly thought to be indicative of a root zone appear, in the Alpine case, to have been generated after nappe emplacement. It is possible that these features may have been impressed on a pre-existing root zone as the zone is juxtaposed to, and deforms part of, the regional suture. However, it is suggested, as employed by Milnes (1974), that this zone should be referred to as a 'steep belt'.

Late Precambrian to early Cambrian sediments and volcanics southeast of the Rosslare Complex, S.E. Wexford, Ireland. M. D. Max, Geological Survey of Ireland and P. Grant, Department of Geology, Imperial College, London, England.

A newly recognized assemblage of greywackes, siliceous pelites, black slates, psammites, basaltic pillowed lavas and other submarine volcanic and igneous rocks occurs in the sea area around the Tuskar Rocks and immediately to the east of, and at Carnsore Point. Strike of bedding is E–W to NE–SW. Younging, where recognized, is consistently toward the north and a single upright penetrative to fracture cleavage is more steeply dipping to the south; a major upward facing anticline is indicated to the south. These rocks are termed the Tuskar Group.

The Tuskar Group does not display the migmatization or the complex, high grade tectono-thermal history of the Rosslare Complex. There is a clear structural and metamorphic break and it is likely that the Tuskar Group is entirely younger than the Rosslare Complex in which the last major metamorphism has been dated at about 640 Ma (Ar/39–40 step heat). The Tuskar Group and its deformation is older than 535 Ma (Rb/Sr, = 1.42) as it is hornfelsed by the dated Carnsore Granite. It is therefore of latest Precambrian to early Cambrian in age.

Correlations can be made with parts of the Gwna Group of the Bedded Succession on Anglesey. The Tuskar Group is nearly on strike with Anglesey, contains similar lithologies and displays a comparable tectonothermal history to parts of the Bedded Succession. Deposition of both groups and possibly much of their respective structural histories appear to be closely related in time. Although there is no evidence of exact comparability, it is clear that both Anglesey and the Rosslare area must be considered together in assessing the late Precambrian and early Lower Palaeozoic history of the central Irish Sea region.

A model for the formation of ophiolite dynamothermal aureoles. A. M. McCaig, Department of Earth Sciences, Downing Street, Cambridge, England.

The dynamothermal aureole of the Bay of Islands Ophiolite Complex (Malpas 1979) shows the following features:

(1) High temperatures (780–850°C) at the contact with peridotite and steep inverted metamorphic gradients (1000–2000°C/km);

(2) High pressures (>7 kbar) in the uppermost part of the aureole;

(3) Metasomatic Ti-rich amphibole and phlogopite in the basal mylonites of the peridotite;

(4) A distribution of lithologies consistent with overturning and thinning of an oceanic crustal sequence (cf. Jamieson 1980).

All these observations except for the high pressures can be explained by a model involving emplacement of a hot ophiolite slab along an approximately isothermal shear zone at a ridge crest, where the isotherms cut up towards the surface. Steep gradients may be preserved by continued shearing over cold rocks (McCaig & Church 1980), while metasomatism may result from overriding of a pre-existing mid-ocean ridge hydrothermal circulation system.

The high-pressure assemblages occur in metagabbroic rocks which are in high temperature, partially annealed contact with the basal lherzolites of the ophiolite. Hence they cannot be explained as 'accidentally' incorporated slices similar to Franciscan 'knockers'. Nor are they accretions onto the hanging wall of a subduction zone, since the stratigraphic thickness of the ophiolite is at most 12 km. The most likely explanation is that the ophiolite was overlain in an early stage of its emplacement by additional nappes, now eroded away.

The practical use of microstructural parameters in the estimation of palaeostresses. M. G. Norton and S. H. White, Department of Geology, Imperial College, London, England.

Recent studies have used a variety of theoretically and empirically based equations to relate dislocation density (ρ), sub-grain size (d_{SG}), and recrystallized grain size (d_{RG}) to the flow stresses obtaining during deformation. No two authors have used exactly the same equations leading to a great deal of uncertainty regarding the stresses estimated.

A series of quartz tectonites have been studied using etch-pit techniques to determine the microstructural parameters described above. These data have been compared with published data for quartz and olivine in an attempt to produce an internally consistent set of equations for these minerals.

Good experimental data are available for the relationship of dislocation density with differential stress (Kohlstedt 1980) giving the equation for both quartz and olivine:

$$\sigma_1 - \sigma_3 = 1\,\mu b \rho^{u} \qquad (1)$$

where μ is the shear modulus, b is the Burgers vector, k is a constant $\sim 3 - 4 \times 10^{-2}$, u is a constant $\sim$0.6–0.7 (N.B. all units in this and subsequent equations are S.I.)

For sub-grain size, and grain size, equations of the form

$$\sigma_1 - \sigma_3 = 1\,\mu b\, d_{SG}^{-v} \qquad (2)$$

where m, l, v, w are constants

$$= m d_{RG}^{-w} \qquad (3)$$

have been proposed. Plots have been made of $\log_{10}\rho v.\ \log_{10} d_{SG}$, and $\log_{10} d_{RG}\ v.\ \log_{10} d_{SG}$ for both minerals. The first of these is explained in terms of a linear relationship for which both sub-grain size and dislocation density are in equilibrium with the flow stress, the other fields of data being due to partial readjustment to new stress and/or temperature regimes. In the case of olivine, data from mantle xenoliths in basaltic lavas show a spread away from a line, defined by Alpine type peridotites, that is interpreted as being due to partial annealing under very low to hydrostatic stresses during the period from incorporation in the magma to extrusion. Data for quartz scatter to both sides of an assumed equilibrium line, which is thought to be due to resetting of sub-grain size to higher stresses without the strain necessary to produce recrystallization.

Quartz and olivine are both known to recrystallize by two distinct mechanisms, sub-grain rotation and grain boundary migration. Recent work (Guillope & Poirier 1979) has shown that these two mechanisms may give rise to quite different grain sizes for the same stress with varying temperature, and vice versa. The effect of this on the interpretation of recrystallized grain size data is considered, and practical methods are outlined to enable the thermal and mechanical history of a rock to be at least partly deciphered.

The linear relationships derived from the log-log plots give rise to the following values for the constants in equations (2) and (3):

For olivine $1 \sim 25$–30, $v \sim 1.0$; $m \sim 2$–3×10^4, $w \sim 0.9$–1.0.

For quartz $1 \sim 100$–110, $v \sim 0.9$; $m \sim 1$–2×10^5, $w \sim 0.6$–0.7.

The Gortenfern Disturbance: an example of a thrust-like reactivation of a primary dislocation in the Moine schists of Ardnamurchan, West Highlands, Scotland. Brian H. O'Brien, Department of Geology, The University, Liverpool L69 3BX, England.

The Gortenfern Disturbance was originally mapped as a N–S trending, sub-vertical, narrow zone of highly strained Moine rocks which extended for some 4 km S of the northern coastline of the peninsula. Across this zone adjacent lithostratigraphic units structurally converge such that to the west of the 'disturbance' a stratigraphic succession of psammitic schists strikes NW–SE, while to the east folded pelitic schists trend NE–SW.

A sequence of superimposed, inhomogeneous deformations, D1–D4, can be recognised in the area. D1 and D3 produced originally gently inclined fold axial surfaces and fabrics, while D2 and D4 are steep. The Gortenfern Disturbances is reinterpreted as a primary dislocation (D1) which was probably sub-horizontal at the time of its formation. It is now recognised that it extends with variable orientations for a further 8 km south of the steeply dipping rocks near Gortenfern. Over the entire 12 km it is coincident with the lithostratigraphic boundary between the psammitic and pelitic schists. The dislocation itself (i.e. the psammite/pelite contact) together with the adjacent and consanguineous, highly strained D1 tectonites occur either in (1) steep belts where they are severely modified in gently plunging, asymmetric F2 'pinch' or 'cuspate' isoclinal folds, or in (2) flat belts where they are intensely deformed during D3 and reworked to take on the appearance of zones of late ductile thrusting.

Numerical modelling of stresses in accretionary prisms and thrust wedges. M. J. M. Park, Department of Geological Sciences, University of Durham, England.

The deformation in a model of an accretionary prism, based on the dimensions and structures of the Middle America Trench (Moore *et al.* 1979) was investigated using visco-elastic finite element analysis (with material properties: density, 2500 kgm^{-3}, Young's modulus, 10 G Pa, Poisson's ratio 0.27, viscosity 10^{22} Pa).

In order to find the shear stress at the base of the wedge necessary to counteract gravitational spreading and so maintain its surface gradient, two types of model were employed: one in which the basal stress was transmitted through a shear zone of weak material between the subducted oceanic crust and the overlying wedge, the other in which there was a direct frictional contact between the two. Both models, which could not be distinguished on the basis of surface displacement, or from their stress or strain distributions, indicate that the average shear stress needed to support the wedge in equilibrium is 12 MPa. This represents a minimum value, since a larger stress would be needed to increase the size of the wedge. A shear zone of thickness 100 m and motion of 70 mm yr^{-1} has a viscosity of 10^{18} Pa.

The strains at equilibrium in the accretionary wedge were less than 5%, consistent with the observation that most of the deformation in the accreted sediments occurs as they are added to the toe of the prism.

Variation of the model parameters and analysis of the potential energy of a wedge has been used to show that gravitationally induced flow of a wedge, up the basal slope, is only possible when the shear resistance to motion on the base is less than a critical value dependent on the gradients of the base and surface, and when horizontal stresses are applied at the thick end of the wedge sufficient to hold that end still (approx. lithostatic). These applied stresses must be larger for whole-body motion of the thrust wedge.

The transformation of pseudotachylyte to ultramylonite in a mylonite zone. C. W. Passchier, Geological Institute, University of Amsterdam, Netherlands.

In the St. Barthélémy massif (French Pyrenees) a mylonite zone is developed in a gneiss with amphibolite facies paragenesis. Deformation took place during retrogression under upper greenschist facies conditions. In the mylonite zone isolated, dark bands with sharp contacts crosscut the mylonitic foliation in the gneiss at a shallow angle. The bands have constant thickness (1–5 mm) over several tens of metres. A stretching lineation is developed in the gneiss and usually in the bands. Both have an identical orientation. Along some of the bands a displacement of markers has been measured of several metres parallel to the lineation. In thin section most dark bands display a microstructure typical of an ultramylonite. It consists of a homogeneous matrix of fine grained (1–5 μm) quartz, plagioclase and biotite with a distinct layering and few ductilely deformed included lenses. A strong preferred orientation is developed in biotite. A number of data suggest that these dark bands are in fact ductilely deformed crystallized pseudotachylyte. An emphasis is laid on the microstructural criteria to distinguish deformed pseudotachylyte from ultramylonite.

Some dark bands lack a stretching lineation and display a number of features which have been described from crystallized pseudotachylyte: (1) intrusion veins penetrating the country rock; (2) a dark, fine grained matrix of plagioclase, biotite and quartz (1–10 μm) lacking a preferred orientation; (3) an irregular striping resembling a flow banding in the matrix; (4) plagioclase microlites with random orientation; (5) spherulites and (6) very angular fragments of quartz and feldspar, some with corroded boundaries suggesting partial melting. The mylonite fabric in the gneiss is obliquely cut off by the dark bands.

Locally evidence exists for ductile deformation of these dark bands. In the centre of the band a biotite preferred orientation is developed and angular rock fragments have been ductilely deformed. In embayments and intrusion veins in the edges of the band this preferred orientation is lacking. Apparently these patches were protected from ductile deformation by the surrounding gneiss. A stretching lineation of common orientation is developed.

All dark bands are interpreted as crystallized pseudotachylyte bands that were ductilely deformed with varying intensity. During the closing stage of mylonite deformation in the gneiss, pseudotachylyte formed and crystallized into a very fine grained polymineral aggregate. This acted as a zone of weakness in the gneiss and the small grain size favoured a grain boundary sliding mechanism. Subsequent ductile deformation was concentrated along the bands. The constant orientation of the lineation testifies to the continuous progression of the deformation process.

Subduction complexes: a dynamic model. J. P. Platt, Department of Geology and Mineralogy, Oxford University, Oxford, England.

Any model for the tectonics of subduction complexes must account for the following.

(1) The frontal zone of an accretionary prism typically consists of rotated fold-fault packets of unmetamorphosed clastic trench-sediments.

(2) Oceanic basement and pelagic sediments are preferentially subducted; but their metamorphic equivalents may outcrop in the rear of the prism.

(3) The oldest rocks generally show the highest pressures of metamorphism, outcrop in the rear of the prism, and form thrust sheets overlying younger lower-grade rocks.

A dynamic model accounting for these features includes the following processes.

(1) Accretion of fold-fault packets of unconsolidated trench-sediments by bulldozing.

(2) Fast underflow of oceanic crust and consolidated pelagic sediments. The lower part of the frontal accretion zone may also be scraped off and subducted.

(3) 'Deep accretion' of (2) beneath the rear part of the prism, at depths of 30–40 km, accompanied by high-pressure metamorphism.

(4) Isostatic uplift of the rear part of the prism, thickened by deep accretion.

(5) Oceanward gravitational spreading of the complex under the influence of the topographic slope. This will cause: (a) listric normal faulting and tectonic denudation in the rear, allowing further uplift of high-pressure rocks; (b) oceanward emplacement of thrust sheets of metamorphic rocks from the uplifted rear and (c) listric thrust-faulting of the compressed prism front. These low-angle faults will crosscut the rotated fold-fault packets.

The model predicts different sequences of deformational structures in different parts of the complex; these can be tested against observational data.

The Helvetic nappes as shear zones. J. G. Ramsay, M. Casey and R. Kligfield, Geologisches Institut, ETH-Zentrum, CH-8092 Zürich, Switzerland.

The Mesozoic and Tertiary rocks making up the classic Helvetic nappes of the Alps show a variety of tectonic structures: major folds of different types with differing orientations, major thrust-, normal-, and strike-slip faults and a spectrum of small scale tectonic features (shear and extension fissures, slaty and crenulation cleavage). As a result of regional studies over the last three years we put forward a general synopsis of nappe development enabling these structures to be integrated into an overall movement plan.

The nappe units are today bounded by stratigraphically upward cutting thrusts with ramp-flat geometry and contain alternating competent and incompetent layers orientated obliquely to their boundaries. The initiation of the thrusts was preceded by the development of shear zones. The shear zones were initially broad but subsequently narrowed down to zones of intense shear and ultimately thrust faults. This history resulted in nappe units with differing amounts of shear in different parts of the units. The stratigraphic obliquity of the layering led to the development of different types of buckle folds during shearing. Variations in the shear gradient gave rise to variations of axial surface orientation, of fold shape and to different types of fabric associated with the folds. Rotation of fold limbs during buckling resulted in competent layers changing from a contractional to an extensional environment and the formation of normal fault systems.

The structure of the Maydan syncline in the Oman ophiolite. A. D. Rothery, Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, England.

The Oman ophiolite is a well exposed igneous complex thought to have been formed by sea-floor spreading and subsequent arc volcanism during late Cretaceous time (Glennie *et al.* 1973, 1974, Smewing in press, Pearce *et al.* in press). It was emplaced shortly afterwards from the north-east onto the Arabian platform and subjected to Tertiary folding, but has survived intact and relatively undeformed when compared with many other ophiolites. This paper presents the results of mapping at a scale of 1:50,000 in the Maydan syncline, a complex structure occupying an area of 1000 km^2 on the southwest-side of the Oman mountains. Here the crustal sequence of cumulate rocks, sheeted dykes and lavas, is surrounded on three sides by the tectonised harzburgite of the mantle sequence, and there are many structures which may have considerable bearing on the formation, emplacement and subsequent history of this ophiolite.

The south-easterly (130°) trend of the syncline and the parasitic folds within it is paralleled by the axis of a major anticline which exposes the sub-ophiolite succession in the heart of the mountains to the north-east and by fold axes in the early Tertiary sediments to the south-west of the area. The harzburgite–cumulate boundary (the petrological Moho) is near vertical on the limbs of the Maydan syncline, whereas the sheeted dykes, trending 165°, which must have been injected in a near vertical plane, remain effectively vertical throughout most of the structure. The Maydan syncline is therefore interpreted as a steep limbed but flat bottomed fold of mid to late Tertiary age.

The harzburgites, representing the depleted upper mantle, have a spreading related fabric shown by foliation of orthopyroxene grains. Measurements of this tectonite fabric show foliation usually parallel to the Moho, and steep throughout. Some traverses, however, show the foliation to be more randomly disposed or else at right angles to the overall structure of the area. There is clearly much to be learned about the deformational history of the lower part of this ophiolite from the study of folds in the harzburgites, but as yet field data is sparse.

Normal faults trending 130° cut all levels of the ophiolite in the Maydan syncline, and several are seen to control the distribution of intrusive bodies of ultramafic to acidic composition thought to represent an off-axis phase of island arc related activity. Similar faults occur throughout the ophiolite and possibly reflect an oblique transform fault trend (Smewing 1980, Pearce *et al.* in press). These faults were reactivated subsequently, and are parallel to mainly south-westward directed thrusts which cause major imbrications within the ophiolite. Some of the thrusting is likely to be a response to Tertiary folding, but most of the thrusts are regarded as late stage emplacement structures.

High pressure deformation and metamorphism in the Sesia-Lanzo Zone, Western Alps. D. C. Rubie, R. Danthine, P. Koons, J. G. Ramsay and A. B. Thompson, Departement für Erdwissenschaften, ETH-Zentrum, CH-8092 Zürich, Switzerland.

Four episodes of deformation (D1–D4) have previously been recognized (Gosso 1977) in the rocks of the Sesia-Lanzo Zone, Western (Italian) Alps. Compagnoni *et al.* (1977) have suggested that the regional scale blueschist/eclogite facies assemblages in a wide range of rock types were generated through early Alpine subduction of continental crust. On the internal side of the Sesia body (to the SE), there is evidence for deformation prior to the growth of some high pressure minerals (e.g. glaucophone or omphacite), which then continued to grow during and after intense Alpine deformation (D1 and D2).

The preservation of high-pressure assemblages may be dependent upon rock type (i.e. the ability to withstand penetrative schistosity as with magmatic eclogites) and the physical conditions within the Sesia body. In this regard it is not yet demonstrated whether the greenschist assemblages in the external part of the Sesia body (to the NW) are contemporaneous with the eclogite metamorphism in the SE or are the products of a later 'retrogressive overprint'.

Most rocks are characterized by an elongate quartz fabric (D2) which may be related to quartz generated with a jadeite component through plagioclase breakdown at high pressures.

Shear zones are developed during high pressure metamorphism (including growth of jadeite and quartz at Mt. Mucrone) in rocks lacking penetrative schistosity. These felsic eclogites also preserve a magmatic texture.

Several sets of tectonic veins have been recognized. The earliest consist of non-fibrous, finely crystalline sugary quartz, quite unlike vein systems associated with deformation elsewhere in the Western Alps. Idiomorphic rutile, omphacite and glaucophane are commonly present in these veins.

Low-stress hydro-fracture dilatancy in thrust, wrench and normal fault terrains. R. H. Sibson, Department of Geology, Imperial College, London SW7 2BP, England.

Arrays of parallel extension fractures and veins are sometimes associated with exhumed faults and appear to be the product of repeated hydraulic fracturing under a shared stress regime. Theoretical considerations suggest that this type of hydro-fracture dilatancy is essentially a low differential stress phenomenon. It may develop under hydrostatic fluid pressures around normal faults at shallow depths, but can only occur around thrusts when fluid pressure exceeds the lithostatic load. This is in contrast to most existing models for dilatancy, where the effects only become pronounced at high (kbar) stress levels and are best developed around thrust faults.

The role of ductile shear zones in the structural evolution of the Maggia Nappe, Swiss Alps. Carol Simpson, Geologisches Institut, ETH Zentrum, Zürich, Switzerland.

The late Hercynian crystalline basement and Mesozoic cover rocks of the Maggia Nappe in the Lower Pennine zone of the Swiss Alps, were deformed predominantly by simple shear during the Alpine Orogeny. The first Alpine deformation phase gave rise to a strong penetrative linear fabric AL_1 which was locally modified into a planar fabric within ductile shear zones. This deformation event was most probably associated with the northwards movement and emplacement of the Maggia Nappe, with the main displacements occurring along zones of high shear strain near the basement and cover rock boundary.

Accommodation of the strain and bulk shape change of the basement between the large deformation zones was accomplished by stretching parallel to the movement direction, concomitant with the development of new, curviplanar ductile shear zones at low angles to the main deformation zones. Anastamosing shear zones of the same displacement sense now surround remnant pods of linear gneiss.

Continued deformation along zones of ductile shear occurred during a major AF_2 phase of isoclinal folding which formed the main synform of the Maggia structure. Minor AF_2 fold hinges are everywhere parallel to the AL_1 stretching lineation.

On the west side of the Maggia structure, the AF_2 foliation planes were deformed by AF_3 crenulation folds with fold hinges parallel to the earlier AF_2 hinges. The AF_3 folds were refolded by the regional backfolding event (AF_4), resulting in interference fold patterns in the northern nappe boundary region. The entire Maggia structure was finally rotated into an approximately north–south trending, steeply dipping zone which extends southwards to the Insubric Line.

Thermal metamorphism of Lower Amphibolite facies reached a maximum towards the end of the AF_4 deformation event. A little movement along some very small ductile shear zones continued after the thermal peak.

Evidence for slip on r and f in the positive sense in deformed calcite single crystals. C. J. Spiers, Department of Geology and Geophysics, University of California, Berkeley, USA.

In recent discussions of texture development in calcite rocks, there has been concern whether slip on the $r\{10\bar{1}4\}\ \langle 2\bar{2}01\rangle$ and $f\{01\bar{1}2\}\langle 2\bar{2}01\rangle$ systems can occur in the positive sense in addition to the well-documented negative sense, and if so, what the critical resolved shear stresses (or CRSS) might be. To answer these questions, cleaved prisms of optical quality calcite have been compressed in the $[40\bar{4}1]$ direction at temperatures of 350–650°C, at a strain rate of $2.5 \times 10^{-5}\ s^{-1}$, and at atmospheric pressure in an Instron testing machine. Slip-line analysis was used to identify the activated glide systems. Samples increase in strength in the range 350–475°C and decrease in strength above ~500°C. At 350–400°C, deformation occurs by $e\{01\bar{1}8\}\langle 40\bar{4}1\rangle$ twinning activated at stress concentrations near the sample ends. Above 475°C, slip on $r(10\bar{1}4)\ [\bar{2}021]$ in the *positive sense* becomes dominant. This is accompanied above 575°C by slip on the two $f(\bar{1}012)\langle 2\bar{2}01\rangle$ systems, again in the *positive sense*. It is inferred that at low temperature slip is difficult, and stress concentrations nucleate twins which propagate at low loads via stress enhancement at the twin tips. Towards higher temperatures, however, slip becomes easier and can relax stress concentrations, so that twinning becomes effectively harder and the samples increase in strength. This occurs until r slip becomes dominant at ~500°C. The samples then weaken as r slip becomes even easier and is eventually joined towards 600°C by the initially stronger but more rapidly weakening f systems. The CRSS for positive r slip at 600°C was measured as ~16 MPa, i.e. about twice the value for negative r slip. The CRSS for positive f slip at 600°C was measured as ~18 MPa. Because of the stress concentration effect, it is suggested that previous CRSS determinations for e twinning represent a minimum value reflecting the stress intensification characteristics of the sample. A minimum value of 12 MPa at 500°C was obtained here.

N.B. Crystallographic indices based on a hexagonal cell with a = 49.9 nm and c = 170.6 nm.

Total strain within a major mylonite zone, southern Canadian Shield. Denver Stone and W. M. Schwerdtner, Department of Geology, University of Toronto, Canada.

The Sydney Lake fault zone (SLFZ) is several hundred kilometers long and marks the interface between two structural subprovinces in northwestern Ontario. The fault zone coincides with a zone of mylonitic rocks which are derived from a variety of metasedimentary, metavolcanic and undeformed plutonic rocks with isotropic fabrics. The mylonitized plutonic rocks of the SLFZ, like those of several other fault zones studied previously in the Canadian Shield, are characterized by markedly oblate ellipsoids of magnetic susceptibility anisotropy. Prolate ellipsoids seem to be absent from the SLFZ and the other fault zones. This suggests that the mylonitic granitoids, at least on the scale of large hand specimens, were subjected to significant amounts of simple flattening.

For a suite of mylonitic granitoids with feldspar megacrysts, ratios of principal strain were determined using Fry's method. The associated strain ellipsoids are invariably oblate. Total volume decrease along a traverse across the middle segment of the SLFZ are as large as 38% if the mylonite zone is a genuine band structure. Because the SLFZ has a finite length, it is impossible to account for the observed states of total strain by pure distortion unless the overall deformation was markedly discontinuous. There is no conspicuous evidence of large amounts of discontinuous dilation such as closely spaced discordant veins or tension gashes in the rocks of the SLFZ and the other fault zones. Have the associated mylonite zones experienced large amounts of simple flattening together with the simple shearing, or is the band model inapplicable to mylonite zones?

Examples and explanations of axial directions of folds anomalous to regional trends. A. J. Watkinson and Craig N. Schriber, Department of Geology, Washington State University, Pullman, Wa. 99164, U.S.A., and P. R. Cobbold, C.A.E.S.S. Université de Rennes, Campus de Beaulieu, 35042 Rennes-Cedex, France.

We believe that there are potential mechanical constraints on the orientation of axes of folds in deformed rocks with linear/planar fabrics. This follows from the theoretical and experimental investigation of the rheological properties of orthotropic materials (Cobbold & Watkinson in press). The control of the orientation of folds may be a result of both the rheological and structural anisotropic properties of the rocks. We define structural anisotropy as an anisotropy induced by shape, such as corrugation or pinch and swell, which gives a directional strength to the material leading to a different flexural resistance in different directions (Troitsky 1976). The structural anisotropy may contribute to the overall rheological properties of the material or, indeed, if pervasive throughout the material, constitute the bulk rheological anisotropy.

Examples of structural anisotropic elements in rock could include early folds, boudins and pinch and swell structures, which would mechanically control the orientation of later formed structures. In the Kootenay Arc, in N.E. Washington, U.S.A., there is clear evidence that early boudinage and pinch and swell structures control the complex fold and refold geometries and axial directions anomalous to the regional Kootenay trend. Further examples of structural anisotropic control on fold axial directions exist in other orogenic belts.

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