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The relationships between metamorphism and deformation: report of the Tectonic Studies Group discussion meeting held at the Geological Society, Burlington House, London, 12 November 1980

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RECENT developments in structural geology which have followed the greater use of experimental methods and the transmission electron microscope have led to a far more mechanistic view of rock deformation (Rutter 1976, Poirier & Guillope 1979, Schmid *et al.* 1977). The result of these studies has been to demonstrate that under those conditions when rocks would alter to a metamorphic mineral assemblage, deformation will proceed by some combination of dislocation controlled deformation mechanisms, diffusion controlled deformation mechanisms and recrystallisation. Similarly a metamorphic phase change will be accompanied by diffusion and, depending on the concentrations of the old and new phases in the rock, some degree of recrystallisation. Because of this similarity, the time seemed right to bring together metamorphic and structural geologists who were considering both phase change and deformation to see if any common themes existed in their work, and if the continued separation of ideas in the experimental and theoretical aspects of these fields is justified.

As might be expected a large proportion of the papers submitted were to some extent describing field observations where phase change and deformation are so often related and two major themes emerged from these. Firstly that strain and mineral chemistry are often closely related in shear zones and secondly that in metamorphic nappes and associated with metamorphosed ophiolites, the isograds are often inverted. This inversion was discussed most fully by Platt but was also an important theme in a number of the papers which offered alternative explanations for specific field examples, notably Mason's discussion of the Sulitjelma Ophiolite in Norway.

Perhaps the two most important questions which this meeting set out to answer were: (1) is there any evidence for the extent of a deformation being controlled by the metamorphism, and more specifically do metamorphic phase changes facilitate or discourage deformation and (2) is there any evidence to indicate whether the rate or equilibria of a metamorphic reaction have been controlled or altered by contemporaneous deformation of the rock. Clearly these questions could be answered by either field observations or by an experimental study but it is the latter which would be the more use. Unfortunately this immediately highlights one of the major differences between the two fields, for whereas the majority of experiments performed on rocks by structural geologists are done under triaxial stress conditions with externally controlled pore water pressures, generally using monomineralic materials, metamorphic petrologists have invariably used hydrostatic conditions for their experiments in evaluating metamorphic equilibria. The starting materials in this latter case are normally more complex being either mixtures of oxides or powdered minerals. The deformation of minerals has been shown to be sensitive to their chemistry; this was first demonstrated for quartz by Griggs & Blacic (1964) and Griggs (1967) who showed the importance of trace quantities of water in the crystal (hydrolytic weakening). This process is still widely studied in rock deformation laboratories and recent work has tended to show the mechanism to be far more complex than considered by the earlier workers, e.g. the contribution by Dennis to this meeting, also Knipe (1980) and Paterson (1979). In his contribution, Murrell demonstrated that the mechanical effects of dehydration reactions during prograde metamorphism can be reproduced experimentally. During a dehydration reaction large pore water pressures may be generated in the rock which in Murrell's experiments led to fracturing and cataclasis. Some discussion on the relevance of this in nature occurred, with it being pointed out that the observed deformation in most metamorphic rocks is plastic rather than brittle. It is possible that the enhanced fracturing recorded by Murrell would be over-printed by subsequent recrystallisation phenomena in nature or simply that the strain rates employed in his experiments were too fast to permit plastic behaviour to occur.

It would seem therefore that deformation behaviour will be influenced by a metamorphic change; this was also discussed by White in the opening talk of the day. He speculated that strain rates might increase during a metamorphic phase change because of greater ease of diffusion. Thus during the prograde history of the rock the occurrence of a metamorphic phase change would also lead to a peak in the deformation behaviour. This is perhaps seen in nature where it is known that new micas (for example) will grow orientated to the stress system operative at the time of metamorphism. This possibility was widely discussed but no distinct conclusions were drawn. Unfortunately the experimental petrologists did not muster a speaker for this meeting so it was not possible to ascertain their views on whether deformation would significantly effect experimentally determined P/T equilibrium data or whether any effects would be purely kinetic.

The one area where chemistry and deformation do come together and are clearly related is pressure solution. Alastair Beach gave a paper considering chemical potential gradients, and the factors which contribute to them, in pressure solution. He concluded that considerations of the chemistry of the dissolving and precipitating phases, their mineralogy, their grain size and their dislocation density, will lead to a model in which pressure solution will proceed at much lower stresses than those predicted by existing models which are only stress dependent.

The contribution by Knipe described a detailed study of the development of slaty cleavage in which both mechanical and chemical processes were important. He refers to ten possible reactions which may be involved in cleavage development, all of which are influenced by deformation. It must therefore be concluded that at least in the case of a slate, deformation and metamorphism proceed hand in hand and thus the metamorphic history should not be considered in isolation from the deformation or vice versa.

K. Brodie described a shear zone from an amphibolite facies metagabbro in which the compositions of the plagioclase and amphibole varied with deformation. The shear zone itself was shown to behave as an isochemical system. Iain Allison in his poster contribution described a similar situation for a granitic mylonite from the Aiguilles-Rouge massif. In this shear zone feldspars are seen to increase in Na and decrease in Ca and K relative to the original grains.

Variations in plagioclase composition were also reported by Powell *et al.* for Moine rocks in Scotland, where plagioclase compositions show a 'downgrading' at ductile shear zones. They attribute changes in grade, in both calc-silicate and pelitic rocks adjacent to the shear zones, to a model involving the interplay of displaced early isograds, thermal relaxation of syn-shearing isograds, and the dependence of mineralogical changes on the level of shear stress. Taking things a stage further, M. D. Max reports that the differential metamorphism of basic dykes in Co. Mayo is completely controlled by the deformation. In this example the metamorphism only proceeded in the more highly strained parts of these heterogeneously strained rocks.

In contrast to these and the other reported examples where a relationship between metamorphism and deformation can be demonstrated to exist, J. Ridley reported that at Syros, Greece, a blueschist terrain which is generally deformed, does show localised masses of undeformed rocks in which primary textures are overprinted by blueschist mineralogies. Thus here no direct relationship can be demonstrated to exist between the prograde deformation event and the concurrent metamorphism.

No hard and fast conclusions were drawn from the meeting, as might have been expected. However, the number of instances where a detailed field study revealed a direct relationship between metamorphism and deformation were such that it should encourage further research in this area. In particular the general failure to acknowledge the possible roles of deviatoric stress in experiments on metamorphic phase changes and equally the adherence to mineralogically simple rocks in rock deformation experiments should now give way to at least some experiments where deformation and metamorphic change are permitted to proceed simultaneously. Should these experiments show that P/T equilibria are unaltered then the facies concept as presented in most standard texts on metamorphic petrology will be corroborated; if on the other hand markedly different P/T data are obtained depending on deviatoric stress then perhaps it is time to look again at the old concept of Harker (1932) of stress and anti-stress minerals. Such experiments should also resolve the arguments concerned with the influence of phase change on strain rate. It is perhaps pertinent to note that similar suggestions were made at the Controls of Metamorphism meeting some sixteen years ago (Pitcher & Flinn 1965) and have apparently not been followed up by the experimentalists.

ABSTRACTS OF PAPERS PRESENTED

Microstructural and chemical transformation accompanying deformation of granite in a shear zone at Miéville, Switzerland. Iain Allison, University of Strathclyde, Glasgow, Scotland.

At Miéville, in the Aiguilles-Rouge massif, granite rocks of the basement are deformed into mylonite in a major shear zone. Deformation has involved reduction in grain size of quartz from ~ 3 mm to $\sim 20\,\mu m$ by dynamic recrystallisation, accompanied by development of a preferred crystallographic orientation. Porphyroclasts of oligoclase and orthoclase decrease from initial diameters of up to 20 mm, and assume elliptical shapes during progressive deformation, as they have recrystallised around their margins to form mantles of ultra-fine polygonal grains which extend out from the porphyroclasts in thin trails. The mylonitic foliation is defined by these tracts and by elongate areas of polycrystalline quartz. The recrystallised grains have a composition of Ab_{95} requiring gains of Na and losses of Ca and K relative to the precursors, implying short range redistribution of elements during deformation.

Transformation of granite to mylonite was essentially isochemical involving average additions of $< 1\%$ H_2O and CO_2 at approximately constant specific gravity. Limited access of fluids to the shear zone may have controlled the extent to which feldspars reacted to hydrated phases. Constraints imposed by abundances of major elements imply that volume changes in the shear zone were less than $\pm 10\%$.

The long albite trails imply relatively high ductility which, coupled with microstructural criteria, is interpreted as superplastic flow. Estimated temperatures of 200°C ($T/T_m \simeq 0.2$) for albite deformation are lower by a factor of 2, than previously recorded for superplastic behaviour of silicates.

Chemical potential gradients and deformation of rocks by pressure solution. Alastair Beach, Department of Geology, University of Liverpool, L69 3BX, England.

Chemical potential gradients provide the driving force for diffusion in metamorphic rocks and when such gradients exist within the grain boundary aqueous phase of a rock undergoing deformation then pressure solution may occur. Classically, the driving force for pressure solution has been analysed in terms of variations in solubility of a mineral between differently stressed solid–fluid interfaces. However, other factors may make important contributions to the chemical potential gradient and pressure solution may proceed to an appreciable extent at much lower stress differences than those predicted by the simple stress-dependent model. The factors considered to enhance the chemical potential gradient are: (1) a difference in composition between the dissolved and precipitated parts of a phase, as commonly observed in carbonates; (2) a metamorphic reaction is involved where the precipitated phase is different from the dissolved phase and the free energy of the reaction becomes an important factor, for example, the dissolution of feldspar and precipitation of mica is commonly seen in deformed rocks; (3) when a rock is deforming by a combination of mechanisms, then the dislocation density of old grains will be greater than newly precipitated material, and the energy of the dislocations will lead to increased solubility and (4) to the extent that a small difference in free energy exists between fine and coarse grains of the same phase, solubility in the vicinity of the fine grains will be enhanced. These factors were illustrated with examples of phase relations from a variety of deformed rocks, and their role in the process of pressure solution was assessed.

Variation in amphibole and plagioclase composition with deformation. K. H. Brodie, Department of Geology, Imperial College, London SW7 2BP, England.

Investigation of the mineral chemistry of a shear zone in an amphibolite facies metagabbro has shown that the composition of the amphibole and plagioclase varies with deformation. Chemical analyses of the rocks indicate that the shear zone approximates to an isochemical system. The amphibole varies progressively from an initial magnesio–hornblende to a ferroan pargasitic hornblende in the shear zone with alkalies, Ti and $Fe^{2+}/Fe^{2+} + Mg$ increasing, while the plagioclase becomes more anorthitic, varying from labradorite to bytownite. These changes in composition of amphibole and plagioclase from metabasic rocks are normally associated with increasing temperature in prograde regional metamorphic terrains; such chemical variations observed in localized shear zones would suggest that shearing stress in regional metamorphism may play an important role in producing the documented discrepancies in amphibole chemistry between different metamorphic belts.

Structural study of the Almklovdalen Massif, Southern Norway. F. Cordellier and F. Boudier, Laboratoire de Tectonophysique, Université de Nantes, 2 chemin de la Houssinière, 44072 Nantes Cedex, France and A. M. Boullier, C.R.P.G., Case officielle n° 1 54500 Vandoeuvre les Nancy, France.

The basal gneiss complex in Western Norway contains a series of ultrabasic intrusions which are considered to have been emplaced at an early stage of the gneiss history, starting 1400–1700 Ma. Using petrographic, structural, microstructural, mineral preferred orientations (MPOs) and gravity data, we have attempted to reconstruct the kinematic and metamorphic history of the Almklovdalen Massif.

The progressive evolution of the deformation markers and the lack of overprinted structures indicate that the successive deformations must be included in a deformation continuum. This slow structural evolution is related to a slow retrograde evolution. Two main episodes are recognised:

Intrusion episode

A garnet bearing peridotite slice is intruded from the mantle into the crust. Garnet flattening S_1 and elongation L_1 are respectively parallel to the axial planes and to the fold axes of the parallel folds affecting S_0.

Chloritization of garnet due to water penetration is assigned to the first crustal event. During this stage, the foliation S_2 marked by chlorite nodule flattening, remained unchanged, but lineation L_2, marked by chlorite nodule elongation, plunges steeply and may be vertical. Development of vertical shear zones is related to this stage.

Traces of this episode are now observed only in some residual masses in the core zone.

Sinking and shearing episode

The main part of the ultramafic mass is made up of harzburgite and dunite, with chlorite developed homogeneously in relation to a strong deformation continuous with the previous one. The S_3 foliation, defined by chlorite lamellae, is parallel to the gneiss/peridotite contact and folded with it, the fold axis is parallel to the L_3 lineation marked by chlorite lamellae elongation and spinel strings.

The gravity data and the geometry of the structures suggest an imperfect cone shape with a downward pointing apex. Such a shape can be interpreted as due to gravity tectonics resulting from density and ductility contrasts between the peridotite and the enclosing gneiss. This deformation occurred in the almandine amphibolite facies.

The gravity sinking stage is followed by N–S compression with a SE–NW shear component, responsible for the present nestled fold shape of the peridotite body and for the development of the S_4 foliation and L_4 lineation in the retrograde gneiss.

Microstructures show a progressive change from porphyroclastic to mosaic equigranular and to tabular equigranular during retrograde events as the MPOs indicate a transition from high temperature intracrystalline gliding following $[010]_{ol}$ $[100]_{ol}$ to low temperature intracrystalline gliding with $[001]_{ol}$ as the slip direction.

Chlorite–mica stacks in low-grade rocks from Mid-Wales. J. Craig, W. R. Fitches and A. J. Maltman, University College of Wales, Aberystwyth, Wales.

Attempts to establish the tectonic and metamorphic evolution of the Lower Palaeozoic rocks of Mid-Wales have involved detailed petrographic and statistical analysis of 'chlorite–mica stacks'. These are intergrown megacrysts of chlorite (showing good [001] cleavage and characteristic blue birefringence) and higher birefringent stubby and wispy white micas. The stacks average 0.04 mm in length, and comprise 25–30% of the bulk composition of the argillaceous rocks in the region. Wet-chemical and microprobe analyses show the chlorites to be Fe rich and of ripidolite–brunsvigite composition. They show marked similarity to stacks described from elsewhere e.g. Central Appalachians, U.S.A., Rhein Massif, West Germany.

Several theories for the origin of the stacks have been proposed. These include: a detrital origin (Beutner 1978, Bjø rlykke (1971); strain-controlled growth of chlorite on a detrital mica nucleus (Voll 1960, Roy 1978); and strain controlled intergrowth during metamorphism (Weber 1980). None of these are compatible with the observations of the present work. For example, presence of relatively large stacks in Bouma E units and their delicate shape preclude a detrital origin, whilst their bedding–parallel orientation, petrographic form, occurrences in undeformed rocks and pre-cleavage age, militate against strain-controlled growth. It is proposed that the chlorite–mica stacks originated through pre-tectonic, mimetic growth on a primary bedding fabric, probably of clay minerals. This theory is consistent with the above observations.

Subsequent effects on the stacks include kinking and removal of their ends by pressure solution during cleavage formation. There is a progressive decrease in stack axial-ratios as the cleavage-bedding angle increases. With increasing metamorphic grade the stacks are lost, although relicts do persist, e.g. in the Penrhyn Slate, N. Wales and Easdale Slates, W. Scotland.

Effect of variations in oxygen and water fugacity on the point defect chemistry of quartz. P. F. Dennis, Geology Department, Imperial College, London SW7 2BP, England.

Formal thermodynamic arguments (Kröger 1964) have been used to determine variations in the point defect chemistry of quartz with changes in oxygen and water fugacity. The oxygen frenkel defect (interstitials and vacancies) appear to be the dominant intrinsic disorder with a formation enthalpy of approximately 620 KJ mol^{-1}. Under dry conditions, $f_{H_2O} = 0$, non stoichiometry in the oxygen excess region, $f_{O_2} > 10^{-2}$ bars, is likely to be accommodated by the creation of silicon vacancies ($[V_{Si}''''] \propto f_{O_2}^{1/3}$) and in the oxygen deficient region, $f_{O_2} < 10^{-4}$ bars, by oxygen vacancies ($[V_O''] \propto f_{O_2}^{-1/3}$).

Incorporation of hydrogen as a cation impurity under hydrous conditions severely modifies the defect state of quartz. Hydrogen is incorporated in the lattice at interstitial sites and oxygen at 'new' oxygen sites. Charge neutrality is maintained via the creation of silicon vacancies according to the defect reaction (Weeks 1963, Dennis & Atkinson 1980).

$$2H_2O \rightleftharpoons 2O_o^x + 4H_i' + V_{Si}''''$$

with

$$[V_{Si}''''] \propto f_{H_2O}^{2/3}.$$

Oxygen diffusion experiments tentatively bear these predictions out, with D_0 inversely proportional to both f_{H_2O} and f_{O_2}. Experimental activation enthalpies lie in the range 140–200 kJ mol^{-1} and suggest that extrinsic defects dominate at temperatures less than 1300°C. Oxygen and silicon diffusion studies are continuing in order to refine these models.

Fugacity variations in metamorphic environments consequently play an important role in determining modes and kinetics of natural solid state deformation, and the models shed new light on the controversy of hydrolytic weakening.

Structure and metamorphism in the Phyllite–Quartzite Nappe of western Crete (Greece). Reinhard Greiling, Institut für Geowissenschaften, Johannes Gutenberg-Universität, Saarstrasse 21, D-6500 Mainz 1, F.R. Germany.

The Phyllite–Quartzite (PQ) Nappe, constituting an external allochthonous complex of the Hellenides on Crete shows a polyphase structural evolution.

(1) A first phase of recumbent isoclinal folds, penetrative schistosity, and boudinage (*F* 1–2; Greiling 1979) which occurred under high P/low T metamorphic conditions (Seidel 1977) during subduction.
(2) Late metamorphic thrusting and nappe transport which led to mylonite formation, best observed at the top of the PQ Nappe with further boudinage and flattening.
(3) Postmetamorphic small folds, lineations, and a crenulation cleavage (*F* 3) were probably formed synchronously with the spreading of the PQ Nappe.

A last event (*F* 4) developed small folds, crenulation/fracture cleavage, and the regional folds after nappe movement.

Nappe transport obviously took place in two stages:

(1) The transport of the higher, nonmetamorphic units, which were thrust over the PQ Nappe, deformation being essentially confined to a few m wide shear zones (mylonite) and flattening elsewhere.
(2) Subsequent spreading (and further transport) of the PQ Nappe itself with a major strain rate in the central parts of the nappe, decreasing towards the upper thrust.

Hercynian regional and thrust related metamorphism and deformation in central South West England. K. P. Isaac, Department of Geology, University of Exeter, North Park Road, Exeter, EX4 4QE, England.

Detailed geological mapping and qualitative and semi-quantitative X-ray diffraction analysis of metapelites sampled in vertical traverses across thrusts in the Lydford area, NW Dartmoor, have been carried out. The results show significant relationships between Hercynian regional and thrust related metamorphism and deformation. Three major nappe forming deformations have been identified (*D*1, *D*2 and *D*3): *D*1 is associated with medium grades of regional metamorphism observed in calc–silicate and metabasite pods in the lowest tectonic units seen. The main *D*1 structure observed, the Whitelady Thrust, is characterized by up to 50 m of mylonitic and phyllonitic lithologies, and represents a major tectonic discontinuity.

Prolonged burial of the deepest observed tectonic units beneath the nappe pile, but at decreasing depths, caused retrogression to low and very low grades. Clay mineralogical metamorphic indicators record this retrogression and the inferred temperature and pressure conditions represent a complex syn-*D*2 and *D*3 metamorphic configuration. The fine sensitivity of some clay mineralogical indicators to temperature (crystallinity and mixed layer type) has enabled thermal profiles to be constructed across thick tectonic successions and the relationship of the late metamorphic imprint to *D*2 and *D*3 thrusting to be examined. Large scale inversion of the thermal gradient is identified and this is used to delineate the approximate boundaries of the major nappe units. It is suggested that in the study area the base of the main nappe development migrated upwards with each successive deformation.

Deformation and metamorphism in slates. R. J. Knipe, Department of Earth Science, University of Leeds, England.

The distribution, microchemistry and internal structures of phases present in a slate are used as a basis for a discussion of the interaction between deformation and metamorphism in slates. The phases present, especially the phyllosilicates show a range in composition and internal structure which can be related to their location in the deformation induced microstructure.

The study reveals that slaty cleavage development is via a complex interaction of both mechanical and chemical processes which vary in importance during the cleavage evolution. The processes include simple mechanical rotation, solution and crystallization and a complex set of deformation processes in metamorphic reaction zones. There are approximately ten potential reactions which may be involved in the cleavage development and deformation influences them all. Evidence is presented for reactions ranging from ionic exchange with solutions, to crystallization from solution and solid-state reordering of elements. The details of these reactions were presented and the influence of the distribution of strain accommodation in the aggregate on these reactions were discussed. Evidence for a change from a simple mechanical alignment process during the early stages of cleavage development to a more complex reaction — grain growth process during the later stages was presented.

Caledonian metamorphism and deformation in Western Svalbard. G. M. Manby, Geology Department, Goldsmiths' College, New Cross, London, SE14 6NW, England and A. P. Morris, Wayne State University, Detroit, Michigan, U.S.A.

Central Western Svalbard contains 12.5 km of late Precambrian to early Palaeozoic rocks exposed over the areas of Prins Karl Foreland (PKF) and Oscar II Land (OIIL). The whole sequence (known as the Hecla Hoek Complex) has been subjected to Caledonian metamorphism and deformation (D_1) and Mid-Cenozoic high level folding and thrusting (D_2). Here, as elsewhere in Svalbard, successively older rocks record progressively higher grades of metamorphism, ranging from lower greenschist facies in younger rocks to lower-mid amphibolite facies in older rocks. Pre-kinematic (D_1) crystal growth is indicated by the occurrence of randomly oriented and rosette bundles of chloritoid which deflect S_1 and have well developed pressure shadows. 'S' trail garnets and albites and nematoblastic hornblendes show crystallization was also synkinematic. Phyllosilicates overgrowing S_1, but which are themselves truncated by a late D_1 pressure solution fabric, suggest late kinematic crystallization. Mineral assemblages suggest an ambient geothermal gradient of 17°C/km during metamorphism. Assuming the gradient was constant to the surface, then the occurrence of biotite in the youngest rocks requires a further 20 km of overburden at peak metamorphism. P_L values for the exposed sequence would have been in 5–8 kb range. D_1 deformation was dominated by the emplacement of a large scale fold nappe which was subsequently imbricated. Successive thrusts up-sequence carry progressively older inverted rocks over younger rocks. The lowest exposed sheet is largely uninverted and cleavage development here is co-axial with thrust related folds not the earlier nappe fold. However, structurally higher, inverted (lower limb) sheets show S_0–S_1 parallelism. These and other fabric variations reflect the different strain histories in the lower and upper limbs of the nappe. Thermal relaxation within the nappe proceeded with deformation, and once thrusting occured, metamorphism virtually ceased. Despite thickening of the sequence by folding and thrusting, blanketting has not occurred and isograds are not redistributed but remain parallel to the stratigraphic surfaces. Although locally modified by granite plutonism and migmatisation, a similar pattern of events can be recognised in all Hecla Hoek Complex rocks across Svalbard. This combined with the conclusion that Svalbard developed as an ensialic orogen has led to the suggestion that gravity inversion and spreading tectonics were responsible for Caledonian orogenesis.

Inverted metamorphic isograds beneath the Sulitjelma Ophiolite, Norway. Roger Mason, Department of Geology, University College, Gower Street, London WC1E 6BT, England.

Recent research has confirmed the presence of inverted isograds in the copper mining district of Sulitjelma, Norway. On the other hand, the identification of the thrust surface generally regarded as present in the area (Nicholson & Rutland 1969, Bryhni & Brastad 1980) has proved very difficult. The demonstration by Boyle (1979) that the Sulitjelma Gabbro is a member of the Sulitjelma Ophiolite suite casts doubt on the statement that the gabbro was intruded across the thrust-plane after nappe emplacement (Mason 1971). The thickness of the region of inverted geothermal gradient, more than 800 m, makes explanation by the thermal relaxation model of Oxburgh & Turcotte (1976) or the 'freight train' model for dynamothermal aureoles beneath ophiolite nappes unlikely. Two models, one involving progressive simple shear of the Furulund Schist beneath the ophiolite, the other markedly different thermal diffusivity in different layers, are presented. Both require as a starting condition that horizontal as well as vertical thermal gradients be present before thrusting. The known deformation history of the Furulund Schist makes the simple shear model attractive.

The interdependence of strain and metamorphic recrystallization in basic dykes in N.W. County Mayo, Ireland. M. D. Max, Geological Survey of Ireland, Dublin 2, Eire.

Pre-metamorphic metadolerite dykes in Co. Mayo display the complete tectono-thermal history of the local Caledonian amphibolite facies metamorphism. These dykes are differentially metamorphosed with irregular, blocky volumes of largely unmetamorphosed (olivine) dolerite grading into marginal amphibole schists with no relic igneous textures. Recrystallization begins by uralitization and polygonization on grain boundaries, suggesting development of activated sites for nucleation by a process of inter-grain distortion and movement of reactants. Penetration growth of the new metamorphic minerals into the respective amphibole and plagioclase commonly results in a totally new, amphibole–plagioclase–quartz + accessories, metamorphic assemblage which exhibits little foliation. The imposition of planar fabrics is largely confined to dyke margins but central areas also contain irregular 'hot shear' zones. Deformation appears to have controlled the extent of metamorphism. As heat can have varied little over such a small area, the manner in which the dykes adapted by recrystallization during the Caledonian metamorphism must have been controlled by heterogeneous strain.

Metasomatic and isochemical metamorphic changes in the basal peridotite of the Bay of Islands Complex during ophiolite emplacement. A. M. McCaig, Department of Earth Sciences, Downing Street, Cambridge, England.

Metamorphic conditions of $T = 780$–$850°C$ and $P > 7$ kbar are estimated for the contact between the basal lherzolite of the Bay of Islands ophiolite complex and the underlying, predominantly metabasic, dynamothermal aureole (cf. Malpas 1979), on the basis of gt–cpx geothermometry and corona textures in metagabbro. A fabric subparallel to this contact is developed in the basal 500 m of the peridotite, with intense mylonization in the 10–20 m closest to the contact. These basal mylonites contain three distinct hydrated assemblages: (1) pargasite–lherzolites which are locally interbanded with mafic aureole rocks; (2) Ti–pargasite–phlogopite–ilmenite–lherzolites which show enrichment in Fe, incompatible elements and LREE compared with normal lherzolite, and preserve steep chemical gradients on a mm-scale; (3) garnet–amphibole–websterites which are also strongly Fe-enriched. High alumina (6–8%) pyroxenes in relatively undeformed primary lherzolite show marginal re-crystallization to lower-alumina pyroxenes and spinel. In fully recrystallized pargasite–lherzolite (assemblage 1) all pyroxenes contain 3–4% Al_2O_3. This change indicates isochemical recrystallization during deformation at 800–900°C. In contrast, rocks of assemblage 2 are thought to result from intense metasomatism, perhaps due to interaction with a hydrothermal circulation system at a ridge crest during emplacement. Assemblage 3 is more problematical, and may represent tectonic inclusions of mafic aureole rocks.

Reaction and water loss rate effects on deformation styles in rocks undergoing metamorphism. S. A. F. Murrell, Department of Geology, University College, Gower Street, London WC1E 6BT, England.

A number of experimental studies have been carried out concerned with the effects of decomposition of hydrous minerals in rocks undergoing deformations at elevated temperatures. The water released into the rock can produce high pore pressures, depending on the reaction rate and the rate at which water can be lost from the rock, and these can have very marked effects on the strength and deformation style. These effects are discussed in the context of their implications for crustal deformation processes.

Patterns of apparent lineation in deformed rocks and their relationship to spiral inclusion trails in porphyroblasts. Declan G. De Paor, Geology Department, University College, Galway, Ireland.

The apparent lineation fabric in an arbitrary section through a deformed rock is controlled by the shape and orientation of the local strain ellipsoid. By substituting the strain ellipsoid for the optical indicatrix, figures analogous to the biaxial skiodrome and index surface (Wahlstrom 1951, p. 172) may be constructed. The 'structural skiodrome' serves as a contoured plot of sectional strain semi-axes in the directions of the poles to the section planes. By superimposing on the skiodrome a great circle of poles to section planes, the shape of an apparently folded lineation on a cylindrically folded surface may be analysed. It is seen that the most intense development of apparent lineation need not coincide with the most intense development of stretching lineation.

By examining the apparent lineation in a section of constant orientation on a series of skiodromes representing successive stages in a deformation history, it is concluded that some low amplitude spiral inclusion trails in porphyroblasts may develop during coaxial progressive strain. Thus the fabric included need not predate the porphyroblast, but may develop synchronously.

Metamorphic evolution of nappe complexes: a constraint on orogenic mechanisms. J. P. Platt, Department of Geology and Mineralogy, University of Oxford, Oxford, England.

Patterns of metamorphism in nappe complexes place constraints on emplacement mechanisms. Significant features are:

(1) The structurally highest nappes in high P/T complexes tend to carry the highest pressure assemblages. Nappe contacts cut isograds and high and low pressure nappes are interleaved. High P/T metamorphism generally predates nappe emplacement and major ductile deformation.
(2) The tectonic cover above high P/T complexes is inadequate to provide the required lithostatic load.

Points (1) and (2) are demonstrable in Pacific type subduction complexes (Franciscan Complex; Sanbagawa Belt) and in collisional orogens (Penninic Alps; Nevado–Filabride Complex in the Betic Cordilleras).

(3) Inverted metamorphic zonations beneath ultramafic nappes have been steepened by sub-horizontal faults that excise parts of the aureole (Bay of Islands; Catalina Schist Terrain in the Franciscan Complex).
(4) Normal metamorphic zonation developed in some belts has been similarly steepened during subsequent nappe formation. This is well illustrated by the Alpujarride Complex in the Betic Cordilleras, where grade increases abruptly downwards across nappe contacts, and individual nappes show histories of decreasing pressure and constant or increasing temperature.

All these features suggest that although crustal thickening is an essential process during orogenesis (causing high P/T metamorphism), substantial thinning plays an important role in nappe emplacement. The structure of orogenic belts does not therefore simply reflect lithospheric convergence. A reconciling concept is that of gravitational collapse and spreading of an orogenic welt, initially thickened by convergence. The pile thins and spreads laterally, thinning and steepening metamorphic zonations, and emplacing high-pressure rocks with a reduced tectonic cover onto less metamorphosed adjacent terrains. If spreading occurs while isotherms are rising in the pile, individual nappes may show negative P/T histories.

Metamorphic patterns in ductile shear zones. Derek Powell, A. W. Baird, N. R. Charnley and P. J. Jordan, Department of Geology, Bedford College, Regent's Park, London NW1 4NS, England.

Study of changes in the mineralogy of calc–silicate ribs in Moine rocks of the south-western part of the Northern Highlands of Scotland reveals a relationship between mafic mineralogy, plagioclase composition, and metamorphic grade; in particular the anorthite content of plagioclase increases with grade. A general rise in grade across an 18 km section is reflected not only in the calc–silicate ribs but also in pelite mineralogy. This rise is interrupted at syn-metamorphic, ductile, slide (shear) zones where 'downgrading' of plagioclase composition is apparent but obvious retrogressive mineralogical changes are not seen in psammite or pelitic metasediments. In one case, regionally developed, sillimanite bearing, migmatitic pelites are brought against rocks of lower metamorphic grade.

The changes in grade in both calc–silicate and pelitic rocks adjacent to the shear zones cannot be explained by ductile shear during a single metamorphic event. Rather a model involving the interplay of displaced early isograds, 'thermal relaxation' of syn-shearing isograds and the dependence of mineralogical changes on the level of shear stresses, is required. This modifies the model given by Grocott (1979) for a Precambrian shear zone in Greenland.

The interpretation of the metamorphic pattern associated with the Moinian shear zones (constituting the Sgurr Beag Slide of Tanner 1971) may have application to other terrains where older metamorphic complexes suffer reworking during subsequent tectono-thermal events. In the Moinian context a Caledonian syn-metamorphic shear zone appears to have partially reworked an older (Grenvillian? Brewer, *et al.* 1979) metamorphic complex.

Strain history and microfabrics in a blueschist terrain, Syros, Greece. J. Ridley, Grant Institute of Geology, University of Edinburgh, Scotland.

The island of Syros consists almost entirely of high grade blueschist facies rocks. These have not been affected by any later pro-grade events and display well the evolution of a blueschist 'event'.

The dominant fabric is a flat-lying schistosity predating the earliest recognisable isoclinal folds which themselves fold the glaucophane–mica fabric without any axial planar recrystallization.

Although local superimposition sequences of subsequent asymmetric folds and associated fabrics exist, the parallel hinge directions and consistent vergence of these folds suggest they represent a single rotational deformation phase. This deformation and all the penetrative deformation of these rocks took place under blueschist facies conditions.

Localised masses on the island show undeformed primary textures overprinted by blueschist mineralogies consistent with those in neighbouring deformed rock. Marginal to these areas the first strain took place on an already developed blueschist mineralogy. In all rocks there is close synchroneity in the cessation of recrystallization and deformation.

This information and pertinent phase relationships are used to constrain a possible PTt trajectory. The result is a concurrent prograde and deformational event, ended by an abrupt turn in the curve and passive isothermal uplift. This resulting sharp turn round contrasts with broader curves suggested for other metamorphic terrains, and suggests a different mechanism of uplift for these rocks.

Relationships between deformation and metamorphism in the Nevado–Lubrin unit, Betic Zone, S. Spain. R. L. M. Vissers, Institute of Earth Sciences, Utrecht, Netherlands.

The Nevado–Lubrin unit, the lowest tectonic unit of the Betic Zone in S. Spain, is made up mainly of Palaeozoic and Early Mesozoic sediments, affected by Alpine multiple folding and plurifacial metamorphism.

Five generations of deformational structures have been recognized (D_1–D_5). D_1 structures include a penetrative layer-parallel schistosity and strongly attenuated isoclinal folds. These structures postdate an early stage of HP–LT metamorphism, and formed prior to an interkinematic stage of up to amphibolite facies conditions. D_2 and D_3 structures comprise tight to open folds and associated axial-plane crenulation foliations. Adjacent to higher Betic nappes D_3 structures include mylonites. Both D_2 and D_3 structures were formed under broadly retrogressive metamorphic conditions. The two younger generations of structures (D_4 and D_5) include largely post-metamorphic folds and kink bands.

Activity of particular deformation mechanisms appears to be primarily related to factors such as rock type and structural position in the pile rather than solely to the metamorphic conditions. Both crystal–plastic and diffusive mass transfer processes appear to be involved in the syn-metamorphic deformations. The younger post-metamorphic folding, however, appears to have largely been accommodated by brittle processes.

The microstructural study of the rocks fails to yield conclusive evidence for reaction-enhanced deformation (White & Knipe 1978). Some microstructures showing mineral transformations linked to sites of both brittle and ductile (D_2–D_3) deformation suggest that deformation of mineral grains may have facilitated retrogressive chemical changes.

Metamorphism associated with the Alpine Fault N.Z.S. White, D. Johnston and J. White, Department of Geology, Imperial College, London SW3 2BP, England.

The Alpine Fault, N.Z. has progressively uplifted deeper levels of its associated fault rock zone. The lateral across-strike sequence of cataclasite–mylonite–curly schist also reflects a depth profile. A study of the metamorphic assemblages in the fault rocks gives an indication of the depth at which each was formed. This in turn permits the estimation of stress variations with depth. The study also revealed that there was little retrogression between the early schist and adjacent parent Alpine schist (garnet–oligoclase grade). There are two possible reasons for this — (1) the lack of water during the development of the curly schists or (2) shear heating. The composition of garnet–biotite pairs and of the plagioclase suggests the latter.

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