Conference Report

Metamorphic studies: research in progress

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Report of a meeting of the Metamorphic Studies Group held at Burlington House, 6 March 1985. The meeting was organized by Dr K. H. Brodie.

A Metamorphic Studies Group Meeting on 'Metamorphic studies: research in progress' and the fourth Annual General Meeting of the Group were held on 6 March 1985. Fifteen papers were presented, on a wide range of metamorphic subjects, ranging from very low-grade metamorphism to high-grade granulites and migmatites. Half the papers were presented by research students, and each contribution was followed by lively discussion.

The morning session was chaired by Ben Harte, the retiring Chairman of the Group, and concentrated on high-grade metamorphic rocks, and regional deformation and metamorphism. I. Cartwright presented a joint paper with A. C. Barnicoat which considered reactions within partially melted corundum-bearing metapelites from the Lewisian Complex. They demonstrated that silica-undersaturated restites can co-exist with silica-saturated partial melts under appropriate conditions. This was followed by a contribution from T. F. Emmett on the magmatic and metamorphic evolution of high-grade rocks from the Jotun Nappe in Norway. The Group was then pleased to welcome J. C. Schumacher from the Mineralogisches Institut in Kiel, F.R. Germany, who presented a paper describing microstructural evidence for reactions producing a range of Al-rich assemblages and discussing the relative roles of diffusion versus reaction in controlling the reactions. P. J. Treloar then gave a paper describing some unusual and colourful mineral assemblages from a Cu-Zn massive sulphide body in Finland, where high concentrations of Cr in the rocks has allowed extremely high levels of Cr substitution into the silicate phases.

N. B. W. Harris discussed the metamorphism and evolution of pelitic and interlayered mafic rocks from the Limpopo mobile belt, using detailed analysis of the mineral assemblages to constrain the conditions of metamorphism and uplift history of the area. This was followed by a contribution from D. Prior, jointly with R. Broughton, which emphasized the role of deformation in influencing metamorphic evolution in orogenic belts, with an example from the Karakorum Range, N Pakistan.

The afternoon session, which was chaired by Michael Brown, the newly elected Chairman of the Group, was opened by D. Robinson and R. E. Bevins with a paper considering the transition from diagenesis to low-grade metamorphism in rocks of the 'zone of non-metamorphics' from the Welsh Back-Arc Basin. They presented details of the four zones of alteration that can be established across this transition, based on mineral assemblages and illite crystallinity. In the south of the area metamorphism is largely related to burial, whereas deformation plays an important role in catalysing the metamorphism in the north. This contribution was followed by a series of papers considering more detailed aspects of the processes which influence the microstructures of metamorphic rocks, particularly the role of deformation in metamorphism. J. G. Spray presented details and results of some unusual experiments utilizing frictional welding apparatus to generate frictional melts of basaltic composition from natural dolerite. The strain rates generated in these experiments are quite likely for seismic movements on natural fault zones. S. J. Covey-Crump then presented a joint contribution with E. H. Rutter discussing a detailed analysis of grain size and grain-size distribution from marbles surrounding a migmatite dome on the island of Naxos. The observed correlation between grain size and peak metamorphic temperature was used as a basis for the discussion of competing grain growth models. This was followed by a paper presented by J. Wheeler which considered the application of thermodynamic theories to metamorphic rocks under non-hydrostatic pressure conditions, emphasizing the local nature of equilibrium in such rocks, and arguing for the discontinuation of the term PHZO in view of the different ways in which it is used. F. Wigley then presented a paper describing shear zones developed in granulite facies gabbroic rocks from the Outer Hebrides. He presented geochemical and microstructural evidence for the interaction of deformation and hydration in the development of these high strain zones.
The latter half of the afternoon was chaired by Stephen Daly, a new member of the Groups' Committee. C. R. Neal and M. Crewe both presented papers on metamorphosed ultrabasic rocks. Neal described garnet-forming reactions in poorly exposed lherzolite nodules from one of the highly vegetated Solomon Islands, and Crewe considered metasomatic processes affecting well-exposed ultrabasic pods in gneisses from Greenland. The last two papers of the meeting considered high-pressure metamorphic rocks from North Wales and the Alps. W. Gibbons presented a contribution, with M. Gyopari and J. Horak, which described new outcrops of blueschists on Anglesey recently exposed by excavation in connection with a new highway construction. A. C. Barnicoat brought the meeting to a close with an account of the new highway construction. A. C. Barnicoat brought the meeting to a close with an account of the new highway construction.

The generation of corundum-bearing restites in metapelitic rocks I. Cartwright & A. C. Barnicoat

Within the Lewesian gneiss at Stoer, Sutherland, several units of paragneiss exist, including an aluminium 'metapelitic' unit which occurs as metre-thick layers. This metapelite comprises a white mica—corundum-staurolite—kyanite—feldspar assemblage with veins or layers of quartz—feldspar(s) ± white mica interpreted as in situ partial melts. Modelling of the parageneses in the systems KASH and KNASH (following work by Thompson & Algor and by Luth) shows that silica—undersaturated restites can coexist with silica-saturated partial melts under certain conditions of P, T and aH₂O in both fluid-present (internally and externally buffered) and fluid-absent environments.

K-rich basic granulites and associated high-grade rocks from the Jotun Nappe, central S Norway T. F. Emmett

The central part of the Jotun Nappe is composed of ultrabasic to intermediate gneisses of mid-Proterozoic age metamorphosed to spinel-lherzolite (intermediate pressure granulate) facies. There is abundant petrographic evidence for the plag + ol + spinel + Al-cpx reaction.

The rocks are of calc-alkaline geochemistry, and appear to be the products of magmatic fractionation or differentiation. There is a clear distinction between cumulate rocks and rocks produced by liquid descent, with the latter much more potash-rich than other intermediate pressure granulites of comparable silica contents. This is thought to reflect their original magmatic composition. Metasomatic effects of the high-grade metamorphism seem to be confined to Sr and, possibly, Ba enrichments.

Petrology and metasomatic growth of aluminous enclaves in gedrite-cordierite gneiss, SW New Hampshire, USA John C. Schumacher

Gedrite (GED)—cordierite (CRD) ± minor hornblende (HBL) gneisses in the sillimanite-staurolite zone of Acadian metamorphism contain enclaves in CRD of kyanite, sillimanite (SILL), corundum, staurolite, zincian spinel, sapphireine, and calcic plagioclase (PLA). In enclaves containing PLA, CRD surrounds PL (An90) in which the other phases are set. Textures suggest SILL reacted with GED/HBL to form mineral assemblages via diffusion-controlled reactions. Assemblages limit the choice of path through model Fe-Mg-Al-Si reactions in P–μH₂O space (P–T analog). This enables construction of a P–μH₂O path v. μFeMg₁⁻ diagram that demonstrates bulk compositional effects and contrasts reaction-v. diffusion-controlled growth paths.

The chrome minerals of Outokumpu—their chemistry and significance Peter J. Treloar

The Cu-Zn massive sulphide body at Outokumpu in Finnish Kätilä is unique among such stratiform deposits by virtue of the high Cr content exhibited by both the sulphide body and the host metasediments. These high Cr contents stabilize an unusually high degree of Cr substitution in most of the metamorphic silicate and oxide phases present in the region. Analysed Cr contents include up to 3.74% Cr₂O₃ in tremolite, 3.15% in diopside, 27.5% in uvarovitic garnet, 15.4% in epidote, 24.6% in muscovite, 8.6% in biotite, 5.2% in chlorite, 2.8% in staurolite and 9.6% in tourmaline. Cr content within these minerals can be extremely variable even on the thin-section scale. Throughout the metasediments the bulk rock Cr content averages 0.2% Cr₂O₃. This high Cr level is always associated with high Ni, regardless of whether Zn and Cu are high or low, and suggests that Cr and Ni were added to the sequence as part of the sedimentary process rather than through the intervention of the hydrothermal system that generated the volcanogenic sulfides. However, excessively high levels of both Cr and Ni in the stockworks indicate that both elements may have been partly reworked by the hydrothermal ore-forming fluids. The Cr-rich metamorphic phases represent metamorphism of a Cr-rich precursor in which the variable Cr contents of the metamorphic phases result from a rapid overgrowth of localized skarn-forming diffusion between marble and quartzite horizons, rather than through the intervention of the hydrothermal system that generated the volcanogenic sulfides. However, excessively high levels of both Cr and Ni in the stockworks indicate that both elements may have been partly reworked by the hydrothermal ore-forming fluids.

Metamorphism and evolution of the Central Zone, Limpopo Mobile Belt N. B. W. Harris

The Central Zone of the Limpopo mobile belt is noted for extremely ancient rocks (>3.7 Ga) and high pressure assemblages (>10 kbar). However, the older ages are somewhat controversial and have been located only in a restricted area. Published Sr isotopic data suggest that many, if not all, Central Zone formations are derived from a crust <3.0 Ga, and the oldest unit with widespread distribution is the Beithbridge Group of supracrustals.

Petrographic studies from the Diti Formation of the Beithbridge Group provide evidence of decomposition reac
tions. An internally consistent thermodynamic data set in the MAS system has been derived for constituent phases from pelites from this formation, and conditions of $P = 4.5$ kbar $T > 670^\circ$ are implied, assuming $a_{\text{H}_2O} = 0$. Thermobarometry from interlayered mafic granulites indicate conditions of $P = 3.0-5.5$ kbar, $T = 750 \pm 50^\circ$C, and the consistency between the $P-T$ fields derived from pelitic and mafic samples confirms that metamorphism was virtually dry. No quantitative estimate of the $P-T$ field of the high-pressure event has been possible. A period of essentially isothermal uplift prior to 2600 Ma is implied, and various tectonic models can be erected to accommodate this.

The important role of large-scale deformation as a major control upon metamorphism in orogenic belts: an example from the Karakorum Range

David J. Prior, Dave C. Rex & Roger D. Broughton

Orogenic contraction and associated large-scale overthrusting is accepted as a major cause of regional metamorphism, via the processes of thermal relaxation and uplift. Rates of thrusting in orogenic belts suggest that the cumulative effect of uplift by deformation can be much more important than uplift by isostatic readjustment. In such cases the down $P-T$ part of the $P-T$-time path is likely to be controlled by the deformation path; metamorphic assemblages developed and their interrelationships will be modified according to the geometry of the orogenic thrust system.

Structural analysis, petrological studies and K/Ar isotope data for metasediments from the Hunza Valley, N Pakistan, have been used to elucidate the tectono-metamorphic history of the area. The evolution of this area is envisaged as a continuum but may be summarized in four stages:

1. Regional metamorphism is caused by early collision overthrusting, deep intrusion of the Karakorum batholith or a combination of these.
2. The area undergoes a bulk rock deformation, and a regional schistosity is developed. During the deformation, and partly in response to it, porphyroblasts growth is initiated in rocks at greenschist grade. Porphyroblast development in higher grade rocks may have been initiated prior to deformation.
3. Growth of porphyroblasts changes the rheology such that bulk rock deformation ceases and strain is transferred to discrete fault planes in a southward propagating thrust system.
4. The thrust fault system juxtaposes higher grade assemblages, from deeper levels, in the north against lower grade assemblages in the south. Uplift by thrusting, and erosion of emergent thrusts brings the rocks rapidly down pressure and down temperature, ‘freezing in’ assemblages with no retrogression.

Burial metamorphism in the Welsh Back-Arc Basin

D. Robinson & R. E. Bevins

The clay fractions of over 30 pelitic rocks have been examined for variations in mineralogy and crystallinity values from the Lower Palaeozoic suite of the Welsh Back-Arc Basin. Four zones of alteration have been recognized: diagenesis, lower anchizone, upper anchizone, and epizone. Estimated temperature ranges are from 150–200°C for the diagenetic zone to near 400°C for the greenschist zone. Measurement of $b_T$ values indicate a low-pressure metamorphic facies series. In the main part of the basin the metamorphic zones show a simple relationship to the shelf/basin form of the belt, and no regional correlation between metamorphism and deformation can be discerned. It is concluded that the main control on metamorphism is that of burial. In North Wales the pattern is more complicated because of increasing deformation, and it is probable that in this region there is an overlap of the burial effect with deformation-related metamorphism.

Shear heating effects investigated using friction welding apparatus

John G. Spray

As part of a recently initiated research programme to investigate shear heat phenomena in rock, a number of experiments have been performed using continuous drive ‘friction welding’ machines. Such apparatus is conventionally used in the engineering industries to join metal rods and tubes by rotating the ends of these components against each other under loads of several tonnes, at velocities of several thousand r/min and for several seconds until the interface becomes plastic and the two parts ‘stick’ together. Following a final forging event at the end of the rotation cycle, the result is a high-quality welded interface. In the case of the experiments performed on geological materials, machined core samples of various rock types, saw-cut at right angles to their length, were sleeved in mild steel cylinders and loaded into an orbital friction welding rig.

In one experiment, two dolerite cores, 3.15 cm in diameter, from the Skærgaard intrusion were rotated against each other for 11 sec at 3000-min and an orbital offset of 0.15 cm (equivalent to a mean surface velocity of 24 cm/sec$^{-1}$) and an axial loading of 330 kg (equivalent to an axial force of about 40 kg/cm$^2$). After an initial 3-sec ‘warm up’ period the rock interface was observed to glow cherry red for 8 sec. After the experiment, a matt black, 100-μm thick layer was seen to have been generated which partly covered both core sample faces. In addition, gouging and plucking of the surfaces and transfer and adhesion of dolerite fragments from one saw-cut face to the other had taken place. Adhesion occurred via the matt back intervening layer which appears to have acted as a ‘weld’ to the transferred rock fragments.

Scanning electron microscopy and electron microprobe analysis of the matt black layer reveal that it mainly comprises subangular to rounded clinopyroxene and feldspar clasts (<20 μm in diameter) set within a silicate glass matrix. Simple thermal calculations confirm the SEM observations that localized melting occurred at the rock-to-rock interface and that the melt layer represents an artificially generated pseudotachylite formed at a temperature of about 1000°C. The mean surface velocity attained by the dolerite and the duration of the experiment compare well with the proposed velocity and duration of a typical single jerk event occurring during stick-slip seismic faulting within brittle crust (i.e. slip rates of 10–50 cm/sec$^{-1}$ for, say, 5–10 sec). In these respects the experiment successfully simulated frictional fusion on a fault plane in the absence of an intergranular fluid.

Future experiments will aim to develop the use of friction welding apparatus as a method for investigating deformation, metamorphism and anatexis in rock.
Calcite grain growth in marbles from Naxos, Greece E. H. Rutter & S. J. Covery-Crump

The island of Naxos is dominated by a migmatite complex in the core of a domal structure. Rock types are dominantly calcite and dolomite marbles and metapelites in similar proportions which outcrop over almost the entire area of the island. Petrogenetic grid temperatures range between 350° and 400°C. The pure calcite marbles have suffered grain growth under hydrostatic conditions. Some 250 samples were collected and calcite grain size determined from optical thin sections using the linear intercept method and from the planar distribution of grain size. A remarkable linear relationship was obtained between root grain size and temperature, with different trends being observed on opposite sides of the migmatite complex.

The data can be used to compare predictions of grain size v. temperature from different theoretical models. A parallel experimental study of grain growth kinetics in calcite marble is also being carried out.

Thermodynamics of rocks under anisotropic stress: a discussion J. Wheeler

A state of anisotropic stress must exist in many rock systems, not only in those being subject to tectonic forces, but also in rocks undergoing passive burial or uplift, and in rocks where the pore fluid pressure differs from the 'rock pressure'. Any crystal, when subject to anisotropic stress, will deform (by dislocation creep etc.), and therefore true chemical and mechanical equilibrium can never be attained under anisotropic stress. However, idealized systems may be discussed in which solid phases behave elastically. In these models local chemical equilibrium can be described. Such models include equilibrium between (1) a single component, soluble elastic solid, and a fluid; (2) a multicomponent, elastic solid with one immobile component, and a fluid; and (3) two orientations of an elastic solid, with a coherent interface.

Some aspects of these model systems are discussed. The popular idea that chemical potential in these systems is a tensor is criticized. Application of the models to real processes has often involved the use of system 1. For instance, Bruton & Helgeson (1983) apply it to determine metamorphic equilibria in rocks where fluid pressure is less than 'rock pressure', whereas Rutter (1983) uses it to model pressure solution. In all applications it is important to have a thermodynamic model of the grain boundary with its included solvent components. It is shown that if the included solvent etc. can be modelled as a discrete phase (the 'grain boundary film'), then the state of stress in it, at equilibrium, must be anisotropic. This means that system 1 cannot be applied in this context, because it assumes the solvent-containing phase is under hydrostatic pressure. A different model can be proposed in which the grain boundary film consists of an elastic solid component with mobile solute components (this is analogous to system 2). The reality of the process of pressure solution shows that chemical potentials in grain boundaries can affect diffusion in a network of grain boundaries and pores. Models of metamorphic 'equilibrium' (in rocks where fluid pressure differs from rock pressure) must take this into account, or be restricted in their applicability.


Geochemical changes related to metamorphism and deformation at Caisteal Odair, N Uist F. Wigley

The Laxfordian metamorphism and deformation of a Scourie dyke at Caisteal Odair, N Uist, has converted a gabbro to an amphibolite containing relatively anhydrous blocks of meta-gabbro.

Softening due to the fine-grained size of the hydration reaction products has localized some of the deformation into small shear zones, which have acted as pathways for the introduction of fluids.

A garnet-producing reaction preserved in the blocks of metagabbro suggests an initial anhydrous response to the metamorphism prior to the hydration to amphibolite. Amphibole and plagioclase compositions show systematic variations adjacent to the small shear zones. These and other geochemical changes are discussed.

Spinel-garnet relationships as deduced from ultrabasic mantle xenoliths from Malaita, Solomon Islands Clive R. Neal

In lherzolite xenoliths from Kwaikwai, Malaita, garnet replaces and mantles spinel. The spinels are zoned, becoming more aluminous and magnesian adjacent to garnet. In between garnet and spinel in two specimens clinopyroxene occurs as tiny slivers, and in four lherzolites amphibole occurs in the same mode. These relationships can be explained by a cooling and pressure increasing event in the sub-oceanic mantle promoting garnet growth by two reactions:

Spinels + clinopyroxene = garnet + olivine
Spinels + amphibole = garnet + olivine.

This was followed by a reheating event reversing these reactions.

The occurrence of amphibole as a primary phase in most of these rocks and in a spinel-free garnet lherzolite, along with experimental data and geothermobarometric calculations, help define the conditions under which these nodules equilibrated in the garnet stability field.

Metasomatic alteration of Archaean ultrabasic rocks, S West Greenland M. Crewe

Several large bodies of ultrabasic rock associated with amphibolites and metasedimentary gneisses have been intruded by granitic sheets and have suffered widespread metasomatic alteration associated with the late Archaean regional metamorphism which was of upper medium-grade in the area. Textural studies reveal a complex series of hydrous mineral replacements during retrogression, and the mineral chemistry of olivine, orthopyroxene and spinel indicates some re-equilibration. Chemical changes across a large spinel harzburgite body are consistent with significant interaction with the bordering granitic rocks.

New exposures of old blueschists in Anglesey, North Wales Wes Gibbons, Mark Gypoari & Jana Horák

Fresh exposures of Monian schists were revealed during the recent construction of the Llanfairpwllgwyngyllgogerych-
wyndrobwlllllantysiliogogogoch by-pass in SE Anglesey. Quartz-phengite and chlorite-epidote schists are underlain by amphibolite blueschists similar to those exposed beneath the nearby Marquis of Anglesey's Column. Typical blueschist is composed dominantly of amphibole and epidote, although locally the schists are rich in small Mn garnets. A strong N-S mineral lineation in the blueschist is parallel to the axes of sub-isoclinal, synmetamorphic folds and is folded by a late, steep crenulation. Sodic amphiboles (crossite-ferroglauco-
phane-glaucophane) often preserve green actinolitic or
barroisitic cores which record an earlier greenshist meta-
morphism. The tectono-metamorphic history of this 'Pen-
mynydd' blueschist belt is quite different from that of the
Pennmynydd schists in Central Anglesey.

High-pressure metamorphism in the Zermatt–Saas zone of
the Swiss Alps A. C. Barnicoat

Rocks of the Zermatt–Saas Fee ophiolite zone of the
Penninic Swiss Alps, caught up between the two basement
masses of the Dent Blanche klippe and the Monte Rosa-Gt
St Bernhard nappe complex, display a long history of
metamorphism at high pressures. The sequence of para-
genesis observed, together with an analysis of the assemb-
lages, suggests that a water-rich vapour phase was present for
much of the mineralogical evolution of the rocks. This
analysis also suggests a $P$–$T$ path involving a 'hairpin' at peak
conditions, and a recovery path that is always down
temperature which closely resembles both that of the Sesia
zone and that suggested on the basis of numerical thermal
modelling by a number of authors.