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Conference Report

Metamorphic studies: research in progress

Michael Brown

Report of a meeting of the Metamorphic Studies Group held at Burlington House, 4 November 1981. *The meeting was organized by Dr M. Brown.*

A Metamorphic Studies Group meeting on 'Metamorphic studies: research in progress' was held on 4 November 1981. The meeting comprised 14 papers covering a wide range of interests in metamorphic geology and was attended by over 90 participants.

The morning session, chaired by John Winchester, began with a stimulating contribution from Rutter, Peach, White & Johnson who presented results of experimental work in progress on the syntectonic hydration of basalt under simulated amphibolite facies conditions. Their innovative approach to an assessment of the role of diffusive mass transfer during metamorphism as a deformation mechanism is already yielding interesting and important results. The Group looks forward to a further report. Primmer, in the first of a welcome number of papers presented by research students, gave an interesting account of his work so far on the polyphase low-grade metamorphism in the Tintagel Volcanic Formation of SW England. He presented a preliminary interpretation of detailed data on the metamorphic mineral assemblages and mineral chemistry of epidote, chlorite, biotite, actinolite phengite and spessartine garnet (the only mineral to show appreciable zoning). It was clear from the discussion of this paper that the Group awaits with interest the further development of this work. Isaac gave an excellent account of his work as part of the Exeter University team working with the IGS to remap sheet 337 between Bodmin Moor and Dartmoor. The identification of a nappe pile comprised of fo̊ur thrust units over an autochthon within this area and the establishment of metamorphic conditions before, during and after nappe emplacement, from which it may be inferred that erosion of the nappe pile accompanied its emplacement, are major advances in our understanding of the geology of this neglected part of SW England.

Tessa McRae, in the first of two papers concerned with establishing conditions of metamorphism using geothermometers and geobarometers based upon mineral assemblages and mineral chemistries in pelites and considering the implications of the results obtained, presented an account of the contact metamorphism associated with the Adamello plutonic complex in the southern Alps of northern Italy. She generated lively debate through the unexpected variation in calculated P_{total} at different localities around the aureole and her model to explain these apparently contradictory data. Harris completed the morning session with a well-rounded contribution on the metamorphism of pelites associated with the substantial, linear Closepet granite which occurs within the Archaean craton of southern India. T and P_{total} both increase and P_{H_2O} decreases from N to S along the length of the granite, based upon data from cordierite-garnet bearing assemblages, which correlates well with the change from amphibolite facies to granulite facies mineralogies on a regional scale.

The afternoon session, chaired by Bruce Yardley, was opened by Treloar with a fascinating and detailed account of the chemistry and microstructure of orthoamphiboles from cordierite-orthoamphibole rocks from Finland. Hudson presented a stimulating paper on the K-deficient mineral assemblages of the Dalradian of NE Scotland which culminated in the presentation of a petrogenetic grid for the system FeO-MgO-Al_2O_3-SiO_2-H_2O, an approach characteristic of Ben Harte's school at Edinburgh. Eileen McLellan, in the fourth of six contributions from current research students, considered a modern interpretation of Barrow's 'oligoclase biotite gneiss'. Of particular interest are the post-D_3 coarse trondhjemitic migmatites produced by solid-state differentiation (stromatic structure) and, possibly, partial melting (schlieren and nebulitic structures). This migmatization overprints the pre-D_3 Barrovian metamorphism. Eileen McLellan's talk highlighted the difficult task of distinguishing between the processes of differentiation in the solid state and differentiation by partial melting, a task which has been debated in the literature since the work of Sederholm and Holmquist (references in Brown 1973) through to the recent past (e.g. Brown 1973; Ashworth 1976; Yardley 1977; Ashworth 1977; Yardley 1978; Ashworth 1979; Yardley 1979).

In two linked papers Carswell & Harvey and Cuthbert, Harvey & Carswell considered the problem of the origin of the basal gneiss complex within part of the Scandinavian Caledonides and then attempted to bring together a variety of evidence to establish a plate tectonic model for the high pressure metamorphism of the region. The first problem is the common one of a

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possible origin by migmatization of a metavolcanic-metasedimentary sequence versus a possible origin by intense deformation of plutonic igneous rocks. Carswell & Harvey prefer the latter origin in their particular case. The problem of the attainment of extremely high pressures during metamorphism and also of subsequent exhumation of rocks containing high pressure mineral assemblages, considered here by Cuthbert, Harvey & Carswell, generated a lively discussion which continued during the discussion period at the end of the meeting.

The final session, chaired by Michael Brown, began with two papers on Alpine metamorphic events. In the first paper Droop established the metamorphic conditions close to the Penninic basement-cover interface at the metamorphic peak as $T = 560 \pm 20°C$ and $P_{total} = 6.5 \pm 1$ kbar, which are compatible with a model of thermal relaxation following tectonic burial. Vearncombe's paper compared and contrasted the high pressure metamorphism of the basement with that in the overlying nappe pile in the Western Alps and came to the conclusion that the latter pre-dates the former, the basement metamorphism being the result of tectonic burial during nappe emplacement.

In a welcome contribution from mainland Europe Westra contrasted the tectonic and metamorphic styles of different domains within the Kemiö-Orijärvi region of SW Finland. He presented detailed data on the metamorphic geology of Kemiö, one of the amphibolite facies terrains within the region. Finally, Sanders, Daly & Davies presented an interesting paper on high-grade metamorphic rocks from the Ox Mountains inlier. Extreme metamorphic conditions of $T = 850 \pm 50°C$ and $P_{total} = 11 \pm 2$ kbar were followed by movement from the sillimanite field to the kyanite field and there is a later reworking under epidote-amphibolite facies conditions. This represents another example of the very complex metamorphic histories preserved within many metamorphosed orogenic rock sequences which are now becoming better understood.

A period of lively discussion brought the second meeting of the Metamorphic Studies Group to a close. I would like to thank the other two chairmen for a job well done (J. A. Winchester and B. W. D. Yardley) and the projectionist (Mr W. T. Perkins) for splendid service.

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On the inter-relationships between deformation and metamorphism, an experimental study of the syntectonic hydration of basalt E. H. Rutter, C. J. Peach, S. H. White & D. Johnson

The problem of devising experimental approaches to the study of inter-relationships between deformation and metamorphism were discussed. Samples of a high calcium, low alkali olivine tholeiite from Skye have been deformed, in experiments up to 2 months' duration, at 600°C, 1.5 kbar effective confining pressure and 200 bars pore water pressure, and strain rates as low as 10^{-9} to 10^{-10} sec^{-1}. At low strain rates the rock strength falls off rapidly with strain rate and optically discernible chemical transformations occur. Fibrous overgrowths elongate in the finite extension orientation form on all pre-existing phases. From microchemical analyses, it is inferred that anthophyllite grows on plagioclase and olivine, and cummingtonite on pyroxenes. There is some possibility of calcium loss via the pore fluid plumbing, or alternatively only olivines are being consumed.

Several strain rate determining processes are possible, and a principal aim is to determine whether the chemical transformations seen are part of the rate determining mechanism or are passive reactions merely accompanying deformation whose rate is controlled by other, less obvious processes.

Low-grade metamorphism of the Tintagel Volcanic Formation, SW England T. J. Primmer

Low-grade regional greenschist metamorphic assemblages have been recognized in the Tintagel Volcanic Formation of North Cornwall. Its mineral paragenesis is albite-epidote-chlorite ± biotite ± actinolite ± calcite; seen in two main phases of growth, one syn-kinematic, the second post-kinematic with porphyroblastic minerals oblique to the first formed fabric.

Mineral chemistry reveals whole-rock control on Mg/Fe^{2+} ratios in chlorite and biotite. Their low Al content and small range in $Al/(Fe^{2+} + Mg)$ consistent with an origin under low grade conditions; any muscovite is typically phengitic. Actinolite is rare and when found shows whole-rock Mg/Fe^{2+} control throughout single samples, but with extensive $Si \rightleftharpoons Al$ substitution. It appears that the availability of SiO_2 is the important factor in actinolite formation, this being controlled by the diluting effect of the fluid phase (possibly a primary igneous feature).

Epidote contains up to 33% Fe^{3+} substitution for Al, indicating high pO_2. No $Al \rightleftharpoons Fe^{3+}$ zoning was seen, implying a relatively constant pO_2 persisted through growth. The epidote appears to follow sphene in many cases. Garnets from associated graphitic slates are rich in MnO (cores up to 28% MnO). There is a sympathetic zoning relationship with FeO, although the FeO content never exceeds 12%.

Distribution coefficients calculated for coexisting biotite and chlorite, and actinolite and chlorite indicate conditions approached equilibrium between the two generations of mineral growth with maintenance of high pO_2. Under such conditions, MgO and FeO are found to act as independent components. With the deficiency in SiO_2 in the rocks ascribed to a dilution effect by the fluid phase, the diagnostic minerals of low-grade conditions are not always formed, even if such conditions are reached.

Hercynian metamorphism in the Launceston–Tavistock area of SW England K. P. Isaac

Recent mapping by the Geology Department at the University of Exeter has shown that the region between Dartmoor and Bodmin Moor can be divided into four allochthonous tectonic units and an autochthon. A study has been undertaken to examine the Hercynian regional metamorphism in these units and to identify the relationships between metamorphism and the regional deformation. To date 164 samples have been analysed by X-ray diffraction methods and 75 thin sections have been examined and the following preliminary conclusions can be presented.

The allochthon has undergone a very low grade regional metamorphism representing temperatures of between 200 and 300°C and pressures in the range 0.3 to 1.0 kbar. The allochthon is highly deformed and textural observations indicate that considerable strain has been taken up within tectonic units as well as by thrusts. The metamorphism was largely syn-deformational but some evidence indicates that an advanced stage of burial metamorphism had been attained prior to tectonism.

The metamorphic grade increases rapidly across the allochthon/autochthon boundary zone and greenschist facies conditions, temperatures ranging up to 480–500°C and pressures of about 1.5 kbar maximum, prevail in the autochthon. The bulk of the deformation in the autochthon was confined to relatively narrow ductile shear zones associated with internal thrusts, with the rocks outside these zones remaining relatively undeformed. Consequently, the metamorphism is similar in style to a contact metamorphism.

The lower part of the tectonic succession shows evidence of retrogression and the tectonometamorphic history in fault rocks along thrusts indicates declining P and T conditions with time. The main features of the metamorphism and the relationships with deformation are thought to represent two things: (i) the erosion of a 4–5 km thick allochthon to *c.* 1 km during emplacement of the nappe pile, and (ii) the possibility that the SW England batholith was already in place at some depth early in the deformation history which, from stratigraphical relationships revealed by mapping, began in the late Viséan/early Namurian.

Contact metamorphism of the Adamello Complex T. A. McRae

The Adamello tonalites and quartzdiorites were intruded, in mid-Tertiary time, into low grade Hercynian quartz phyllites of the Southern Alps and their Permo-Mesozoic cover. They have an outcrop area of about 1000 km^2, bounded on the N and E by two major faults, the Insubric and Giudicarian lines. The present level of erosion approximates that of their original roofs.

Assemblages containing quartz, andalusite, sillimanite, cordierite, orthoclase, biotite and muscovite were found in the metapelites of the aureole. An internally consistent dataset, in agreement with experimental results, was used to calculate temperatures and pressures of intrusion from reactions involving these minerals. Reaction textures showing the breakdown of almandine and sillimanite to hercynite-cordierite symplectites were also used for pressure determinations.

Temperatures of 650–700°C were obtained with pressures of 5 ± 1 kbar in the NW aureole and 3 ± 1 kbar at the eastern contact. A pressure of 1 kbar was determined by Frisch & Helgeson (*Am. J. Sci.*, in press) from the southern margin.

The difference in stratigraphic cover between the northwestern and southern contacts (25 km apart) is only 3 km of schist and sediment. In order to reconcile these incompatible results, a southward moving thrust sheet has been invoked which slid backwards off the African plate as it over-rode the European plate about 70 Ma ago. The two plutons which give the pressures of 1 and 5 kbar are 41 and 35 Ma old, respectively. Therefore, either the thrust sheet did not extend to the southerly part of the area, or it was emplaced after the cooling of the more southerly pluton.

The present outcrop pattern required 4 km of post-intrusion uplift on the S side of the Insubric line.

Metamorphism of pelites associated with the Closepet granite, S India N. B. W. Harris

The Closepet granite is a 300 km long, N-trending line of granitoids intruding tonalitic gneiss from the Archaean terrain of S India. Pelitic assemblages from metasedimentary enclaves along the contacts of the Closepet granite in the Bangalore region indicate pressures of 4.5–5.0 kbar (from garnet-cordierite-sillimanite-quartz and garnet-plagioclase-sillimanite-quartz assemblages) and temperatures of 690–730°C (from garnet-cordierite pairs). The restriction of the six phase assemblage cordierite-garnet-sillimanite-biotite-microcline-quartz to outcrops S of the charnockite line indicates a decreasing P_{H_2O} to the S. Pelitic assemblages from the northern margin of the Closepet granite contain andalusite and the indicated field of peak metamorphism is 2.6–3.8 kbar, 520–620°C, which suggests an overall southwards increase in P_{total}. The inferred piezothermic array is strongly convex towards the temperature axis and may represent a transient geotherm in the upper crust related to the emplacement of the Closepet granite, or to volatile activity along the margins of the granite.

Chemistry and microstructure of orthoamphiboles from amphibole-cordierite rocks, Outokumpu, Finland P. J. Treloar

Orthoamphiboles from the cordierite-amphibole bearing rocks at Outokumpu span a large part of the gedrite-anthophyllite solid-solution series. The orthoamphiboles, which form part of low variance equilibrium assemblages, grew at temperatures near to or above that of the solvus crest. Post-metamorphic cooling resulted in sub-solvus exsolution, the distribution of which is compatible with an asymmetric solvus in which the anthophyllite limb is the steeper. Metamorphic conditions in the area imply that the crest of the solvus is unlikely to be at a temperature in excess of about 600°C. Electron microprobe traverses and Al Kα scans indicate that amphibole compositions vary rapidly both along and across grains. These variations may be explained by varying availability of Na controlling the edenitic substitution in the solid solution series. Variation in Na availability may be due to external control of μ_{Na} through the fluid phase.

Potassium deficient mineral assemblages in the Dalradian of NE Scotland N. F. C. Hudson

A suite of muscovite-free, staurolite- and cordierite-bearing assemblages has developed in metasiltstones and metagreywackes of the Buchan staurolite zone by continuous reactions which consume muscovite.

Rare orthoamphibole-bearing rocks are associated with this suite. They are thought to have developed by isochemical metamorphism and suitable precursor compositions are shown to exist elsewhere in the Dalradian.

A petrogenetic grid for the system FeO-MgO-Al_2O_3-SiO_2-H_2O is advanced and is used to model the P–T relationships of K-deficient rocks in the Buchan Dalradian.

A reappraisal of Barrow's 'oligoclase-biotite gneiss' E. McLellan

The "oligoclase-biotite gneiss" described by Barrow as a single intrusive unit has been remapped as a trondhjemitic migmatite complex developed in metatuffs and metagreywackes. It contains three units of diverse origins:
(i) The earliest formed unit, predating the last major deformational event, consists of variably developed segregation of feldspar (± hornblende) from biotite (± quartz). Such segregation may have developed by the action of shear stress upon minerals of differing ductility.
(ii) Post-dating D3, the last major deformational event, is the development of coarse trondhjemitic masses. Modal analyses and plagioclase composition correlations suggest an origin by internal differentiation of palaeosome. Stromatic leucosomes in metagreywackes appear to result from solid-state differentiation. Migmatization of metatuffs has produced both nebulitic and schlieren types. Sodic shifts in plagioclase composition from melanosome to leucosome suggest the involvement of a melt, and geothermometric data indicate that metamorphic conditions were adequate for anatexis. However, modal analyses of metatuff leucosomes do not correlate well with predicted cotectic compositions.
(iii) Contemporaneous with the formation of (ii), but not spatially associated with it, and chemically distinguishable from it, is the development of discordant veins of very high plagioclase to quartz ratio. Feldspars identical to those in the veins occur sporadically as isolated porphyroblasts in otherwise unmigmatized rocks. Such porphyroblasts can develop in the absence of discordant veins. Where such porphyroblasts occur in the metasediments, associated metabasite intrusives may show isochemical recrystallization veins.

The development of migmatite units (ii) and (iii), and the growth of sillimanite, represents a post-D3 overprint on pre-D3 Barrovian metamorphism of chlorite to kyanite grades. These migmatites are not magmatic intrusives, and therefore do not support the concept of convective heating of the area suggested by earlier authors.

The instrusive history and tectono-metamorphic evolution of the basal gneiss complex in the Moldefjord region, W Norway D. A. Carswell & M. A. Harvey

Field, petrographic and geochemical data were presented to demonstrate that large volumes of granitic-granodioritic gneisses in this region were not of migmatitic origin but developed through extensive attenuation and shearing of instrusive rocks emplaced during a major igneous event with a Rb-Sr isochron age of 1510±20 Ma. The igneous precursors of these orthogneisses intruded and partly migmatized an older metavolcanic-metasedimentary rock sequence. Both lithological units were then cut by an extensive swarm of basic sheets or dykes. The timing and effects of the ensuing pervasive prograde (eclogite facies) and retrograde (amphibolite facies) tectono-metamorphic events affecting the complex were discussed.

A tectonic framework for the high pressure metamorphism in the Scandinavian Caledonides S. J. Cuthbert, M. A. Harvey & D. A. Carswell

Combining available geological, geochemical, geochronological and geophysical data, an evolutionary model for the Caledonides of the Basal Gneiss Complex of western South Norway was presented.

Closure of Iapetus and underthrusting of the Baltic margin beneath the Greenland plate to give a high pressure (eclogite) metamorphism was followed by uplift and erosion. A second suture developed within the Baltic plate, underthrusting a postulated intra-continental marginal basin beneath the eclogite bearing rocks. Exhumation and retrogression followed to give exposure in the Mid-Devonian.

The crustal thicknesses and time constraints of this model have been tested using isostasy equations.

P-T conditions of Alpine metamorphism in the SE Tauern Window, Austria G. T. R. Droop

The Penninic rocks exposed in the SE Tauern Window contain mineral assemblages which crystallized in the 35–40 Ma Alpine metamorphism. The pressure and temperature conditions at the thermal peak of this metamorphism have been calculated for a small area close to the Penninic basement cover interface using a variety of published and thermochemically derived geobarometers and thermometers. The estimated metamorphic conditions fall in the ranges 560±20°C and 6.5±1 kbar, and imply the existence of 23±3.5 km thickness of overburden at the time of equilibration.

The results are compared with published solutions of a 1-dimensional conductive thermal model, and are shown to be consistent with the hypothesis that the 35–40 Ma Alpine metamorphism was entirely the result of thermal relaxation following tectonic burial. However, the results are not precise enough to rule out models in which the metamorphism was accompanied by an enhanced mantle heat-flow.

The Alpine HP/LT metamorphism in the Palaeozoic basement of the Western Alps J. R. Vearncombe

Basic rocks within the Palaeozoic basement massif of Gran Paradiso (French and Italian Alps) are intruded by a late Hercynian granite. These basic rocks locally preserve glaucophane eclogite and more commonly a prasinitic assemblage. The early glaucophane eclogite assemblage occurs in the contact zones with the intrusive granite and cannot pre-date the granite in origin. Other evidence for a high pressure metamorphism in the basement includes kyanite and phengites with a high celadonite content in metasediments, aegirine and magnesioriebeckite in a quartzite and blue amphibole in basic and metasedimentary rocks.

This metamorphism differs from the HP/LT event in the overlying ophiolites and Sesia zone. Jadeite, garnet and quartz assemblages are not developed in the basement granites and textural evidence suggests that the metamorphism is synchronous or immediately post-dates an Alpine deformation event involving the emplacement of the already metamorphosed Schistes lustrés and Sesia nappes.

Field and petrographic evidence combined with preliminary finite difference modelling suggest that the basement HP/LT metamorphism is probably the consequence of the overlying nappe pile.

Amphibolite facies and granulite facies metamorphism in two different tectonic domains, SW Finland L. Westra

The Svecofennides in SW Finland show two main types of structural domains: (A) narrow E–W belts with large scale superposed fold structures with parallel axes, and (B) wide, diamond-shaped belts with dome-like structures. The metamorphic grade varies from amphibolite to granulite facies. Tectonics are controlled by shear-zones in three major directions: E–W, NE–SW, NW–SE. It is suggested that the type-A domain is dominated by E–W shear zones and amphibolite facies metamorphism and the type-B domain by crossing shear zones (NE–SW, NW–SE) associated with granulite facies metamorphism. The supracrustal belts originated by fragmentation of an Archaean craton along Archaean lineaments. Repeated remobilization of these lineaments is possibly responsible for the tectonics of the area.

Petrology and geochemistry of high-grade metamorphic rocks from the NE Ox Mountains inlier, NW Ireland I. S. Sanders, J. S. Daly & G. Davies

In the Lough Gill area of the NE Ox Mountains inlier, polyphase deformation was accompanied and followed by extreme metamorphism yielding clinopyroxene-garnet-plagioclase in meta-tholeiites, and quartz-K-feldspar-garnet-kyanite in metasediments. Decompression or heating brought the rocks, probably from the eclogite facies, to conditions of 850 ± 50°C and 11 ± 2 kbar. Evidence of kyanite replacing sillimanite may reflect later cooling. Preliminary Sm-Nd isotopic data suggest an age of about 1500 Ma for the tholeiites, assuming a chondritic mantle source, and the high-grade metamorphism occurred before 460 Ma.

Later reworking under epidote amphibolite facies conditions is widespread, particularly outside the Lough Gill area.

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