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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, 7 March 1984. The meeting was organized by Dr M. Brown.

A Metamorphic Studies Group Meeting on 'Metamorphic studies: research in progress' and the third Annual General Meeting of the Group were held on 7 March 1984 and more than 80 members participated. Nineteen papers were presented which covered a wide range of interests in metamorphic geology, including for the first time three papers on isotope geology. Six papers were given by research students. Overall, the large number of contributions to the meeting, the lively discussion of these contributions and the substantial attendance at the meeting suggest that the "current research" style of meeting is very worthwhile.

The morning session, chaired by B. Harte, was opened by R. P. Hall who presented an account of the inter-relationships between metamorphism and magmatic and tectonic episodes in two contrasted areas within the Archaean craton of southern W Greenland. In Ivisârtoq the rocks are at amphibolite facies and have never been to granulite facies. In contrast, in the eastern Sukkertoppen region the rocks are partly retrogressed from granulite facies. In such retrogressed granulites, the presence of 'blebby' hornblende and biotite after pyroxene is characteristic. Hall presented data on various reactions by which hypersthene has been replaced and concluded that enclosing acid gneisses in which no evidence of granulite facies is preserved must have provided a metasomatic influx of elements such as potassium which are required to balance the postulated reactions. This paper provoked lively discussion. The second paper, brought forward from the afternoon session, was presented by A. M. McCaig on retrogressive metamorphism in shear zones. McCaig presented evidence from the central Axial Zone of the Pyrenees which had led him to the following conclusions: that fluid infiltration processes were dominant over lattice and grain boundary diffusion and that the retrogressive metamorphism was dominated by fluid buffering; that reaction sites are controlled by the deformation processes, and particularly microcracking events; that there was no pervasive grain boundary fluid but that fluid pressures must have been high to promote microcracking; and that fluid rock reaction was limited to a changeable network of cracks and occasional grain boundaries.

The Group was pleased to welcome P. Tuisku, a research assistant from the University of Oulu in Finland, to give the next paper, which presented an interesting account of the tectono-metamorphic history of the Puolankajärvi Formation, from the northern part of the Kainuu schist belt in N Finland. The pelitic part of the formation carries the following temporal sequence of minerals: garnet; biotite + staurolite + sillimanite; muscovite (after staurolite) + cordierite; and, andalusite. These data define an evolutionary path in P–T space within the amphibolite facies. M. J. Bickle presented a stimulating paper on the underlying reasons for a significant difference in T between two localities in the greenstone terrain forming part of the Yilgarn Block of Western Australia. At the first locality, towards the centre of the terrain, the metamorphic grade is lower and so is the amount of strain; P–T conditions here are 530–560°C and 4.2 kbar. However, the occurrence of quartz + staurolite + andalusite in equilibrium is difficult to reconcile with the Holdaway (1971) triple point in the Al_2SiO_5 system. The second locality is towards the margin of the greenstone terrain and is characterized by both higher strains and a higher grade of metamorphism. Although P was similar to the first locality, T was raised into the sillimanite stability field but remained below the breakdown of quartz + muscovite, i.e. 600–650°C. The cause of this increase in T is thought to have been heating during the emplacement of igneous material.

In the first contribution from a research student, L. H. Kanat considered conditions of metamorphism and some of the metamorphic processes of high pressure blocks within the Vestgötabreen Formation of Spitsbergen. The metamorphism has been dated at 425 Ma and P–T conditions determined from psammitic horizons in blueschists are 10 kbar at 300°C. Kanat examined in some detail the non-equilibrium breakdown of jadeitic pyroxene to albite, hematite and a mixture of white mica and chlorite and the subsequent growth of magnesio-riebeckite. R. Nicholson's talk was concerned with the metamorphic evolution of an eclogite occurring in marbles of the Upper Seve-Köli Unit from the N central Scandinavian Caledonides. Using the garnet–pyroxene geothermometer and the jadeite content of clinopyroxene as a geobarometer, Nicholson estimated peak metamorphic conditions to have been T = 500°C and P = kbar (minimum). The subsequent development of barroisitic amphibole and then calcic hornblende was documented in some detail. In the final paper before lunch, L. Hoke, a research student, presented some interesting new data on metamorphism and retrogression of pelites from the lowermost 4 km of the Altkristallin basement thrust sheet in the Eastern Alps. Within pelites, kyanite and staurolite grew post-D_2 but pre-D_3 by continuous reaction between garnet and muscovite at pressures around 6 kbar, determined using the ilmenite + Al-silicate + quartz → almandine + rutile geobarometer, and close to the kyanite to sillimanite inversion, within a zone in which the geothermal gradient was inverted as established from garnet-biotite geothermometry. Extensive retrogression was caused by fluid migration along the S_3 foliation and is, therefore, concentrated in the F_3 fold cores, although such retrogression is patchily developed on the regional scale.

The Annual General Meeting of the Group was held immediately after the lunch break. B. Harte, the Chairman of the Group, reported a proposal from the Committee that the Constitution of the Group be amended so that only Fellows of the Geological Society or Associate or Ordinary Members of the Mineralogical Society may serve on the Committee. After some discussion, this was agreed. The Chairman then announced that M. Brown retires as Honorary Secretary of the Group and that K. H. Brodie, C. M. Graham and R. Powell retire as members of the Committee of the Group at the AGM and, since the list of nominees for the Honorary Secretary of the Group and the Committee of the Group was equal to the number of vacancies, B. Harte declared that K. H. Brodie was elected Honorary Secretary for three years and R. A. Cliff, G. T. R. Droop and B. F. Windley were elected to the Committee for three years. After a brief discussion, a show of hands suggested that there is sufficient interest within the Group in a field trip to the Eastern Alps so that G. T. R. Droop will start planning such a trip for summer 1985.

The afternoon session, chaired by M. Brown, started with a paper by S. Robertson, a research student member of the team from the University of Exeter working on the Ivisârtoq map sheet in southern West Greenland. He presented isotopic evidence for Archaean crustal reworking in the Ivisârtoq area. Amîtsoq and Nûk gneisses and a variety of younger granitic rocks culminating in members of the Qôrqut granite complex have been investigated by Robertson. The gneisses are richer in K, Rb and Pb than equivalent gneisses in the Outer Godthåbsfjord area, a feature which may have resulted from a metasomatic influx of material driven off from those parts of the crust which underwent granulite facies metamorphism at about 2800 Ma ago. Partial melting associated with or triggered by this metasomatic infiltration gave rise to a suite of granitic rocks dated at 2750 Ma and subsequently up to three further suites of granitic rocks have been derived by crustal melting in the zone of LIL-enriched gneisses, culminating in granites assigned to the Qôrqut granite complex at 2550 Ma. Thus there is a complex inter-relationship between high-grade metamorphism, metasomatic infiltration and crustal fusion. This theme was continued by M. B. Fowler in his talk on the Scourian gneisses of Gruinard Bay in Scotland. Here rare samples of quartzo-feldspathic gneiss contain the assemblage orthopyroxene + clinopyroxene + Ti-rich hornblende + Ti-rich biotite and overall the major element chemistry of the gneisses is typical of granulite facies terrains elsewhere. However, aspects of the trace element chemistry are transitional between granulite facies patterns and those more typical of amphibolite facies rocks. The partially depleted geochemistry of the rocks of Gruinard Bay is regarded as a result of loss of material, in particular the radioelements, in a fluid phase rather than by partial melting. In a rather different approach to a similar problem, H. Downes presented some interesting data on granulite xenoliths from Cantal, Massif Central in France, assumed to represent samples of the lower crust in this area. The xenoliths comprise both basaltic, assemblage clinopyroxene + orthopyroxene + plagioclase + ilmenite, and metasedimentary, assemblage quartz + K-feldspar + plagioclase + garnet + ilmenite + rutile ± sillimanite, protoliths. On the basis of Sr and Nd isotopic work Downes concludes that external differentiation of the lower continental crust in this area occurred 1600–1200 Ma ago, that Rb was removed from the system during a granulite facies event 380–360 Ma ago and that unmetamorphosed granitoids in the area dated at about 375 Ma old could have been derived by partial melting of a source similar to the undepleted xenoliths and resulting in residues similar to the depleted xenoliths.

In another contribution by a research student, J. E. Pillar considered reactions and the activity of fluids in Tertiary granulite facies rocks from British Columbia. The granulite facies rocks represent an accretionary wedge sequence of greywackes with subordinate meta-basic and calc-silicate rocks into which a number of large calc-alkaline plutons have been emplaced, such as the Ecstall Pluton (Rb/Sr age of 89 Ma) and the Quottoon Pluton (Rb/Sr age of 50 Ma). It is well documented that the Central Gneiss Complex has undergone rapid near isothermal uplift involving a drop in P of 2.5–3 kbar during the time interval 50 Ma to 43 Ma (see Hollister 1982). Pillar established the conditions of metamorphism as T around 725°C (using garnet–biotite Fe-Mg exchange geothermometry and the Ferry & Spear (1978) calibration gives T = 675–730°C and using hornblende–plagioclase geothermometry (Spear 1981) gives T = 725 ± 50°C) and P around 6 kbar (using the plagioclase–orthopyroxene–garnet–quartz geobarometer of Newton & Perkins (1982) at 700°C gives P = 5.5 – 6.4 ± 1 kbar and using the Ca–Tschermakite–clinopyroxene–plagioclase geobarometer of Wood (1977) at 700°C gives P = 5.9 ± 1 kbar). He then presented an interesting analysis of melting reactions in the meta-basic lithologies. Biotite dehydration melting to produce orthopyroxene or cummingtonite is followed by a hydration reaction in which orthopyroxene is replaced by cummingtonite as the activity of water is raised by introduction of water through convective circulation induced by cooling plutons emplaced during the metamorphism. Dehydration melting was also the theme of the contribution from D. J. Waters, who examined a local, layer by layer, scale transition from amphibolite facies to granulite facies assemblages in metapelites from southern Namaqualand in South Africa. In general, the transition from amphibolite facies to granulite facies assemblages is characterized by a lowering of the activity of water in the fluid phase. This can be caused either by metasomatic infiltration of e.g. CO_2, in which case the activity of water is externally buffered, or by melting in a vapour-deficient or vapour-absent environment, in which case the activity of water is internally buffered. In the example presented by Waters, it is clear that biotite + sillimanite + quartz reacts to garnet + cordierite + K-feldspar + water on a regional scale, but that locally this reaction becomes one involving melt generation and occurring first in Fe-richer horizons which results in lower activity of water in those horizons. More Mg-rich horizons are unaffected and retain the amphibolite facies assemblage. Finally, in this session, S. Harley considered mineral assemblages and chemistries from orthopyroxene + sillimanite-bearing granulites occurring in the Napier Mountains, the Tula Mountains and the Scott Mountains in western Enderby Land. The metamorphic peak conditions coincident with the D_1-D_2 deformations were T approximately 950°C and P around 8 kbar, whilst the post-D_2 metamorphic conditions were T approximately 800°C and P around 7.4 kbar. Thus the initial cooling path followed by the Enderby Land granulite facies terrain was close to isobaric. Harley analysed assemblages and reactions in these rocks using a projection from sillimanite in the system Al_2O_3–SiO_2–FeO–MgO. All three of these papers led to lively discussion of the ideas presented.

The final session, chaired by K. Brodie in the absence of C. Graham through illness, commenced with a well-rounded paper presented by T. J. B. Holland which considered the implications of jadeitic pyroxene relics in lawsonite–pseudomorph-bearing greenschists from the central-southern Tauern region of Austria. Reactions preserved in these rocks include jadeitic pyroxene to albite + hematite + actinolite, sodic amphibole to actinolite + albite + hematite + chlorite and epidote to paragonite + hematite with some loss of sodium to the bulk rock system. P–T conditions determined from the greenschist assemblages are P = 5–6 kbar at T = 400°C. It is clear that these rocks must have passed through an earlier higher pressure metamorphism and Holland suggested that a similar early history has probably happened to other Barrovian terrain rocks but evidence for it has been completely wiped out. N. J. Ray contributed a detailed account of the likely mechanism by which orthozoizite is transformed to clinozoizite. The mechanism proposed involves the movement of dislocations by shear and some shuffling around of Ca^{2+} and Al^{3+} cations.

R. A. Cliff presented some interesting data on the mechanism of isotopic equilibration from so-called 'tillites' from the Ogcheon Belt in South Korea. The rocks were metamorphosed about 200 Ma ago and based upon biotite ages must have cooled slowly, having achieved peak conditions of T approximately 500°C (using calcite–dolomite and biotite–garnet geothermometry) and P approximately 6 kbar (using the celadonite geobarometer of Powell & Evans 1983). The data suggest that a fair degree of equilibration has been reached in those samples in which either dolomite-consuming reactions have occurred or in which high integrated fluid/rock ratios can be inferred. Such cases are amenable to dating the metamorphism using the Rb–Sr method. In a stimulating contribution, B. Yardley examined the temperature profile across the Connemara Schists and considered that it could be produced by a 'sideways heating' model analogous to high-temperature contact metamorphism. Modelling the temperature profile associated with a heat source represented by a 5 km thick vertical slab of quartz diorite and assuming no fluid circulation during metamorphism, which is consistent with the mineral assemblages in calc-silicate horizons interlayered with pelites which require high XCO_2 in the fluid phase in these horizons during recrystallization, gives a result similar to the observed temperature profile. As usual, Yardley provoked lively discussion.

There are two approaches in the determination of P and T by calculation. The first is to use individually calibrated reactions such as the garnet–biotite Fe-Mg exchange geothermometer (e.g. Ferry & Spear 1978) and the garnet–plagioclase geobarometer (e.g. Newton & Haselton 1981). The second is to develop a thermodynamic data set in a model system which is consistent with available experimental work on the position of P–T lines for reactions and colorimetric work and to calculate P and T for specific assemblages using reactions in the model system and the appropriate thermodynamic data from the set. Most of the values in the set are dependent on other values via the position of P–T lines for reactions. This means that updating the thermodynamic data set with new experimental work or colorimetric data usually involves adjusting many values in the data set. R. Powell outlined the requirements in developing this second approach and explained the methodology underlying the development with T. J. B. Holland of a new internally consistent set of thermodynamic data. This will be based upon experimentally determined mineral equilibria to avoid the difficulties encountered with the large uncertainties on the calorimetrically determined enthalpies of reaction for end-member phases. It is encouraging that enthalpies calculated in this manner were largely consistent with the calorimetrically determined values. The revised data set should become available later in the year.

Finally, B. Harte speculated on the relative importance of depth in metamorphism in comparison with tectonic effects such as large-scale folding and magmatic effects such as major plutonism. He drew on examples from the British Caledonides, in particular the classic Barrovian terrain of Angus in Scotland, and from the Acadian of New England in the U.S.A., in particular the Bronson Hill gneiss dome belt and the Merrimack synclinorium belt of central Massachusetts. Naturally, this contribution provoked some discussion.

My thanks go to all the speakers for their stimulating contributions and for keeping to time in a very crowded programme, to those members of the Group who made contributions to the lively discussion which followed many of the presentations, and to Ben Harte and Kate Brodie for acting as chairmen.

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Relationship of metamorphism to magmatic and tectonic episodes in the Archaean craton of southern W Greenland R. P. Hall

The Archaean craton of southern W Greenland comprises areas of amphibolite facies and granulite facies rocks consisting of metasedimentary and basic-to-acid meta-igneous units.

The Malene paragneisses of Ivisârtoq include assemblages bearing quartz + muscovite, garnet + biotite, cordierite + sillimanite, kyanite + sillimanite, garnet + staurolite + cordierite + biotite and garnet + diopside + carbonate. These indicate amphibolite facies metamorphic conditions (500–700°C, 3–7 kbar). The predominantly metavolcanic basic rocks are hornblende + plagioclase amphibolites. Iron-formation enclaves within the *c.* 3800 Ma gneisses comprise quartz + magnetite + actinolite ± cummingtonite ± hornblende.

Various two-pyroxene granulite facies gneisses in the eastern Sukkertoppen region (including rare two-pyroxene iron-formation enclaves) indicate temperatures of 770–940°C.

Large scale nappe structures defined by the supracrustal rocks have been 'exploded' by the syntectonometamorphic emplacement of successive diorite and granitic (*s.l.*) plutons. Abundant relict intrusive relationships suggest that while the acid gneisses have been deformed, their common domal form is strongly influenced by the diapiric emplacement of their trondhjemitic/granitic precursors.

The presence of 'blebby' hornblende and biotite replacing pyroxene is a characteristic feature of the retrogressed granulite facies rocks. Hornblende and biotite with this texture provide evidence of retrogression in rocks which preserve no pyroxene. Acid gneisses without such textures may have been emplaced during the retrograde amphibolite facies metamorphism. This hypothesis is supported by K/Rb/Sr ratios. Younger grey gneiss dykes commonly carry epidote. In the retrogressed rocks, variable mafic phase transformations:

hypersthene → cummingtonite → actinolite
→ hornblende → biotite
hypersthene → hornblende
hypersthene → biotite

are not simply balanced by the commonly invoked reactions with plagioclase and K-feldspar. If the system was open, then the acid gneisses provide an obvious source of metasomatic fluids.

Reaction pathways and scale of equilibrium during retrograde metamorphism A. M. McCaig

Dioritic mylonites from the Pyrenees contain the stable greenschist facies matrix assemblage bi–An_{22}–chl–qz–ep–sph with feldspar porphyroclasts relict from an amphibolite facies *hb*–An_{30-35}–*bi*–*qz* assemblage. Recrystallization involved removal of CaO and addition of K_2O as well as H_2O. The porphyroclasts contain abundant veins of An_{18-25} and in some cases a 'tartan' pattern of alteration is developed. The margins of porphyroclasts are not necessarily altered even when in contact with matrix epidote. It is inferred: (1) that lattice and grain boundary diffusion (in the absence of a fluid phase) were unimportant during neocrystallization; (2) that porphyroclasts were broken down mainly by reaction with infiltrating fluid during microcracking events, and probably by pressure solution on some grain boundaries; (3) that fluid was not pervasively present on all grain boundaries.

In a banded mylonite of mixed granitic, dioritic and pelitic protolith from the same area tschermakitic hornblende, plagioclase and epidote grew as porphyroblasts up to 400μ in size during mylonitization. New plagioclases range from An_{13} to An_{45} and show lengthwise zoning by up to 8 mol.% An with both normal and reverse zoning present in adjacent grains. These patterns suggest constantly changing local fluid chemistry, with deformation allowing fluid access to different plagioclase growth sites at different times.

Activity diagrams show that in each example local variations in fluid chemistry can be explained by fluid interaction with and movement between domains of different mineralogy. Fluid rock reaction was confined to a limited but variable network of cracks and some grain boundaries.

Main metamorphic and structural development of the Early Proterozoic Puolankajärvi Formation, Puolanka, N Finland K. Laajoki & P. Tuisku

The Puolankajärvi Formation is composed mainly of turbiditic mica schists with metasandstone interbeds. These rocks have been through at least three main stages of metamorphic mineral growth and three deformation phases during the Svecokarelidic orogeny (1900–1800 Ma ago). The pelitic part of the formation is characterized by abundant garnet (M_1, syn-D_1), porphyroblastic biotite (post-D_1, M_2), staurolite (post-D_1, M_2), sillimanite knots (M_2), muscovite pseudomorphs after staurolite (post-D_2), cordierite knots (post-D_2) and andalusite (post-D_3, M_3).

The D_1/M_1 structures are S_1 schistosity, local metamorphic banding and garnet veins, and tight to isoclinal F_1 folds; those of D_2 are S_2 schistosity and associated faults, asymmetrical sinistral F_2 folds and L_2 lineation defined by biotite; while D_3 produced crenulation cleavage.

The mineral assemblages indicate T = 510–560°C, P = 3.5 ± 1 kbar for M_2, while the presence of andalusite suggests that the M_3 pressure was lower.

Chloritoid and staurolite stability: implications for metamorphism in the Archaean Yilgarn Block, Western Australia M. J. Bickle

The stability of quartz–chloritoid–staurolite–almandine–cordierite and aluminium silicates is used to constrain both metamorphic conditions and P–T trajectories for two localities within the 2700 Ma Archaean Yilgarn Block in Western Australia. Available experimental data are used to calculate thermodynamic data for a self-consistent set of equilibria between these minerals. A lower amphibolite grade locality from the margin of a lower strain area contains assemblages including quartz–chloritoid–staurolite–garnet–biotite with altered cordierite replacing chloritoid, quartz–staurolite–andalusite, and quartz–cordierite–andalusite–biotite. This locality was heated to 530°C to 560°C in the andalusite field, at 4.2 kbar. A sample from a mid- to upper-amphibolite facies, highly strained locality contains relict staurolite enclosed by andalusite, in turn replaced by cordierite and muscovite with biotite and sillimanite in the matrix. The assemblage was heated isobarically from conditions near the maximum experienced by the lower grade locality of 560°C at 4.2 kbar to temperatures in excess of the andalusite–sillimanite transition but within the quartz plus muscovite stability field (600°C–650°C). The higher grade locality is close to a granitoid dome and sections based on gravity profiles reveal that this locality is underlain by granitoid at shallow depths. The higher grade metamorphism apparently reflects superposition of the thermal aureole on regional metamorphic conditions similar to those in the lower grade areas.

Metamorphic studies in the Vestgötabreen Formation, Spitsbergen, Svalbard L. H. Kanat

The Vestgötabreen Formation of central western Spitsbergen occurs within a fold nappe and is characterized by a suite of very high pressure rocks of Caledonian age. Blocks of blueschists, eclogites, metabasalts, garnet amphibolites and serpentinites are contained within a pelitic schistose matrix. Trace and rare earth element concentrations suggest that the metabasalts have ocean floor affinities, and field relations indicate that the related blocks have undergone similar metamorphic conditions. One aspect of the Caledonian metamorphism of the Vestgötabreen Formation is examined by analysis of jadeite mineral chemistry data and textural relationships.

Psammitic horizons, 10–20 cm thick, are intercalated with the blueschists and contain sodic clinopyroxene, phengite, quartz, hematite, often albite and occasionally magnesio-riebeckite. The large jadeitic component of clinopyroxene within this horizon ($Jd_{91}Acm_4Aug_5$) coexisting with albite and quartz indicates pressures of 10 kbar at 300°C.

Jadeite is commonly seen breaking down to albite and hematite and a fine admixture of phengite and chlorite within the psammitic horizons. A wide range of clinopyroxene alteration is recognized on the centimetre scale. Textural evidence shows that magnesio-riebeckite has grown in areas where jadeite has broken down. The following reaction utilizes the cations associated with the breakdown of jadeite and could explain the later growth of magnesio-riebeckite:

$$0.8\mathrm{Acm} + 0.9\mathrm{Di} + 0.7\mathrm{Hed} + 0.2\mathrm{Jd} + 1\mathrm{H_2O} \rightarrow 1\mathrm{Qz} + 0.5\mathrm{Mg\text{-}Rbk} + 1.5\mathrm{Ca^{++}}$$

Equilibrium has not been reached, although the reaction pathways have allowed for the development of magnesio-riebeckite following the breakdown of jadeite.

The composition and mineralogy of an amphibolitic eclogite from the Upper Seve-Köli of central S Norrbotten, Sweden R. Nicholson

The basaltic composition and dominant garnet–pyroxene minerals of a quartz-bearing metabasite from Råvvejaure in central South Norrbotten define it as an eclogite of the type associated with high-pressure metamorphism (Group C, Coleman *et al.* 1965). No trace of the minerals or textures of the probable parent igneous rock remains. The oldest phases are crystals of paragonite, quartz, epidote and sodic-calcic amphibole included in the cores of garnet crystals. Garnets have almandine-rich cores and rims significantly enriched in pyrope (from 10% up to 27%). Grossular content remains about constant at about 25% from core to rim. Clinopyroxene has an average content of jadeiite 43%, diopside + hedenbergite 50%, and acmite 7%. Clinopyroxene crystals are unzoned. The distribution of Fe^{2+} relative to Mg^{2+} in garnet rims, compared with that in clinopyroxene, defines a distribution coefficient K_D of 24. Together with a jadeiite content of the clinopyroxene (Holland 1979), a peak temperature of 500°C for metamorphism, and a minimum pressure of 10 kbar may be estimated (Ellis & Green 1979). The apparently secondary epidote of the ground mass may have been produced at the same time as the barroisite, through reaction of garnet rims with omphacitic clinopyroxene, quartz and water. In the final stages of alteration calcic hornblende crystallized with albite to form symplectite sheaths to both garnet and clinopyroxene. The host marble of the Råvvejaure eclogite forms part of the Upper Seve-Köli complex of the N central

Scandinavian Caledonides. Pelitic schists of the host rock appear to belong to the greenschist facies. If the marble correlates with the possibly Lower Palaeozoic Pieske Marble, as it may do, then eclogite formation was a Late Caledonian event.

Metamorphism and retrogression in metapelites in the bottom part of the Altkristallin thrust sheet L. Hoke

The Altkristallin basement thrust sheet is comprised of Palaeozoic and older sedimentary and igneous rocks which have undergone a polyphase tectono-metamorphic history, Micas within the bottom 4 km or so of the Altkristallin are characterized by 80 Ma cooling ages. Metapelites are restricted to the top 600 m of the 80 Ma sub-unit and are characterized by the AFM phase assemblage kyanite + staurolite + garnet + biotite + quartz + muscovite. Garnet–biotite geothermometry indicates an inverse geothermal gradient. Temperatures of 650–680°C are reached at the highest structural level, decreasing downwards to 480°C. The reaction 3 ilmenite + Al_2SiO_5 + 2 quartz = almandine + 3 rutile has been used to determine a pressure of 6 kbar at an equilibrium temperature of 588°C, still in the kyanite stability field but very close to the univariant kyanite/sillimanite line.

Textural evidence shows that kyanite and staurolite formed by the continuous reaction garnet + muscovite = staurolite + kyanite + biotite + quartz + water, and they grew across a pre-existing mica fabric. The mica fabric is in places axial planar to F_2 chevron folds, but it is also crenulated within open F_3 buckle folds. Kyanite and staurolite post-date F_2 but are deformed by D_3. F_3 related crenulations are asymmetric on F_3 fold limbs and symmetric in the core regions, where they can be intense enough to form a new S_3 schistosity. Extensive retrogressive metamorphism occurred in F_3 fold cores, where fluid migration was enhanced along S_3. Here, kyanite and staurolite are pseudomorphed by fine-grained sericite, with small amounts of chlorite and margarite. This pseudomorphous retrogression has a patchy distribution on a regional scale.

It is concluded that D_3 deformation deforms the micas which give 80 Ma cooling ages. Hydration reactions causing retrogression are syn- or post-D_3 and must have occurred at temperatures below the blocking temperature of micas, *c.* 300°C. Later brittle shearing, syn- or post-D_3, caused distinct retrogressive shear zones to develop.

Late Archaean crustal reworking in the Ivasârtoq region, southern W Greenland S. Robertson

Two major crustal accretion events have been recognized in the Godthåbsfjord region of southern W Greenland; the Amîtsoq gneisses (*c.* 3700 Ma) formed during the first and the Nûk gneisses (*c.* 3000 Ma) during the second event. Both these suites of quartzo-feldspathic rocks were derived from a source with mantle-type isotope ratios. Amîtsoq and Nûk gneisses in the Ivisârtoq region are enriched in K, Rb and Pb compared with their equivalents elsewhere in the Godthåbsfjord region. Sr and Pb isotopes indicate that this enrichment occurred not more than 200 Ma before 2800 Ma. The enrichment may have resulted from metasomatic addition of these elements which were derived from rocks undergoing granulite facies metamorphism below the present level of erosion. Mineral parageneses in enclaves of metasedimentary gneiss are typical of upper amphibolite facies metamorphic conditions. Granulite facies rocks dated at 2800 Ma outcrop 30 km to the S of this region. Granite *s.s.* gneisses, which were derived by partial melting of Amîtsoq gneisses, have yielded an Rb-Sr age of 2750 Ma indicating that partial melting was associated with and/or caused by the metasomatic event. The Rb/Sr ratio of the granite source region between 3700 Ma and 2800 Ma was *c.* 0.05 as evidenced by the initial Sr isotope ratio of 0.703. Many outcrops show that extensive reworking of Amîtsoq and Nûk gneisses gave rise to granites which have yielded ages between 2650 Ma and 2550 Ma. Pb isotope compositions show that the Qôrqut granite (*c.* 2550 Ma) in Ivisârtoq was derived from a source similar to that of the 2750 Ma granite gneisses. The initial Sr ratio of 0.706 suggests that the Rb/Sr of this source between 2800 Ma and 2550 Ma was *c.* 0.35 indicating that partial melting occurred within the zone enriched in LIL elements. Other late Archaean granites in the region have also been generated within this zone.

These various lines of evidence show that the late Archaean crustal history (*c.* 3000 Ma to *c.* 2500 Ma) of the Ivisârtoq region included a complex interaction of high grade metamorphism, metasomatism and partial melting of crustal rocks.

Large-ion lithophile element mobility in the Lower Continental Crust: mineralogy and geochemistry of the hornblende-granulite subfacies at Gruinard Bay and its relationships with amphibolite-facies and granulite-facies end members M. B. Fowler

The Scourian gneisses of Gruinard Bay preserve mineralogical and geochemical features which are transitional between amphibolite- and granulite-facies end members. The data are discussed in the light of LILE depletion in granulitic terrains and implications for the LILE-removal mechamism (fluid or partial melt?) are explored. Briefly, depletion is shown to be *progressive* (there is a continuum between non-depleted and depleted lithologies), *selective* (it operates differently according to rock type), and *differential* (elements are lost at different rates and at different times).

REE modelling does not permit Gruinard Bay lithologies to represent residua after the removal of a 'typical granite' from 'typical upper crustal rocks', as has been suggested for granulites (*s.s.*). However, more elaborate partial melting mechanisms cannot be conclusively ruled out. Nevertheless, published mineral-melt partition coefficient data for U and Th preclude the development of the observed amphibolite-facies to granulite-facies fractionation by sensible degrees of melting, particularly when minor phases are taken into account. A medium with a much high affinity for the radioelements is required, which may represent a CO_2-H_2O fluid.

Depleted and undepleted granulite xenoliths, Cantal, France H. Downes

Ten lower crustal granulite xenoliths from Cantal, French Massif Central, have been analysed for REE, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. The xenoliths are both basic and intermediate-acid in composition. REE patterns fall into two types: a) those showing high overall REE concentrations, LREE enrichment and negative Eu anomalies, and b) those with lower REE concentrations, flatter patterns and zero or positive Eu anomalies.

Many of the basic granulites have low Rb/Sr ratios, but some differentiated granulites are much less depleted in Rb. Certain samples are depleted in Nd relative to Sm, which is interpreted as a result of partial melting during granulite facies metamorphism, with the production of LREE-enriched upper-crustal granites and residual granulites.

θNd values range from −0.5 to −11.1, with θSr values between +13 and +202. The basic samples are similar to granulite xenoliths from Australia and Southern Africa, but the intermediate-acid granulites are very different and may represent undepleted lower crust from which upper crustal granites were extracted during the Hercynian orogeny.

Tertiary granulite facies assemblages from British Columbia: fluid composition during metamorphism J. E. Pillar

Localized granulite facies assemblages occur in the Central Gneiss Complex of the Coast Range Batholith region of British Columbia. Plutonic activity both preceded and coincided with the attainment of the migmatitic metamorphic maximum, which was followed by rapid uplift and cooling.

The dominant country rock is a garnet–biotite gneiss, containing lensoid meta-basic and calc-silicate bodies, which together comprise approximately 7% of the whole.

The meta-basic lithologies host the assemblage qtz + plag + bi + gt + cumm + opx, and bear evidence of two stages of reaction involving biotite. The earlier caused the partial replacement of biotite by orthopyroxene, the latter by cummingtonite. Orthopyroxene grains show marginal retrogression to cummingtonite. The absence of orthoclase in these assemblages necessitates the removal of the potassic biotite reaction product from the system, presumably in a melt phase. Significant reactions in the history of the meta-basic assemblages are therefore:

(1) Plag + Bi + Qtz = melt + Opx

(2) Plag + Bi + Qtz = melt + Cumm

(3) Opx + H_2O + Qtz = Cumm

Graphical analysis of the assemblages by projection of the system $KAlO_2$–$NaAlO_2$–$CaAl_2O_4$–SiO_2–FeO–MgO–H_2O reveals that the progression from anhydrous to hydrous reaction products is due to a differing value of μH_2O, higher values favouring the hydrous product. It is considered likely that the low aH_2O of the early orthopyroxene assemblage is due to the production of a melt strongly undersaturated in H_2O by biotite dehydration melting. Initiation of melting at moderate aH_2O will result in the formation of cummingtonite by reaction 2, though the amount of product will be insignificant and will be lost during reaction at the (univariant) intersection. The degree of melting becomes significant only as the temperature maximum of reaction 1 is approached. Reaction 2 cannot follow reaction 1 during cooling unless H_2O is introduced into the system.

Adjacent calc–silicate assemblages indicate that mobile H_2O-rich fluids were present in the region during uplift, probably moving in convective systems initiated by nearby cooling plutons, and it is suggested that these fluids also caused the transition from reaction 1 to reaction 2.

Dehydration melting and the granulite transition in metapelites from southern Namaqualand, South Africa D. J. Waters

In a prograde amphibolite–granulite transition zone in the Namaqualand Metamorphic Complex, metapelites show an inter-banding of the amphibolite facies association biotite + sillimanite + quartz with the granulite facies association garnet + cordierite + K-feldspar. Relict graded bedding shows that compositional banding is of sedimentary origin. The garnet–cordierite–K-feldspar gneisses contain quartzo-feldspathic segregations surrounding garnets, and have more Fe-rich bulk compositions than the biotite–sillimanite schists.

The contrasting assemblages could have formed at the same pressure and temperature provided that aH_2O was systematically lower in the garnet–cordierite–K-feldspar layers. The aH_2O reduction resulted from the production of silicate melt by a vapour-absent continuous Fe-Mg reaction such as

biotite + sillimanite + quartz = garnet + K-feldspar + liquid

which affects Fe-rich compositions before vapour-absent melting occurs in more Mg-rich rocks. The segregations represent the solid and liquid products of the reaction.

Such processes imply local control of aH_2O, and indicate that this granulite transition did not result from a regional influx of metasomatizing fluids.

Orthopyroxene-sillimanite granulites from western Enderby Land, Antarctica: P–T conditions of formation and Archaean P–T-time paths S. Harley

Orthopyroxene and sillimanite coexist in a range of quartz-bearing and silica-undersaturated parageneses in aluminous pelites from Archaean (3100–2500 Ma) granulites in western Enderby Land, Antarctica. Orthopyroxenes zone rimwards from alumina contents of 11–12 wt% to only 6–8 wt%. Cores are less magnesian (82–75) than rims (84–77). Garnet, which coexists with orthopyroxene and sillimanite in some primary metamorphic assemblages, may also form as recrystallized grains on orthopyroxene. Garnet, which is very low in grossular component (<2 mol%), zones to more Fe-rich compositions rimwards (cores Mg 56–52, rims Mg 52–50).

In some quartz-bearing samples, two generations of orthopyroxene and sillimanite occur, the second generation consisting of aggregates of these phases with granular garnet. This feature reflects the expansion of the ga–opx–sill 3-phase field with decreasing T, caused by movement of orthopyroxene to more magnesian and less aluminous compositions. Samples containing sapphirine coexisting with orthopyroxene and sillimanite also occur, and often show the formation of garnet + sapphirine at the expense of orthopyroxene and sillimanite in secondary assemblages and coronas.

Application of published geobarometers, geothermometers, and experimentally constrained topologic relations to these rocks indicates that the primary orthopyroxene–sillimanite (± garnet) assemblages formed at 900–980°C and 7–9 kbar, while recrystallized grains and rims reequilibrated at 800–840°C and 5–6.5 kbar. The data support a near-isobaric Archaean cooling path for the western Enderby Land granulite province.

Jadeitic pyroxenes in greenschists: breakdown mechanisms and implications T. J. B. Holland & N. J. Ray

Amongst more or less typical lawsonite pseudomorph-bearing greenschists from the central-southern Tauern region of Austria occurs a thin band containing abundant sodic amphibole and jadeitic pyroxene (Jd50Acm50). A common assemblage is Na-amph + qz + cpx + ep + ab + chl + pheng + hem. Sodic pyroxene has broken down to a fine intergrowth of albite + hematite with some actinolite acicles; the amphibole is replaced by various breakdown products including albite + talc or by actinolite rims.

These rocks, occurring at a relatively high tectonic level, indicate evidence for early high pressure/low temperature metamorphism followed by thermal relaxation and uplift/erosion to yield the normal late alpine Barrovian type greenschist-amphibolite assemblages. It is thought likely that other Barrovian-type sequences may have undergone a similar history.

The roles of metamorphism and deformation in the transformation from orthozoisite to clinozoisite N. Ray

Large orthozoisite crystals occur as pod-like segregations in calcareous schists from the eclogite-bearing zone in the Tauern Region of the Eastern Alps. A specimen deformed in a kink-band has been studied by low and high resolution electron microscopy. The zoisite displays abundant stacking faults on (100) planes. A mechanism was proposed for the movement of partial dislocation through the orthozoisite structure to produce stacking faults with a clinozoisite structure. The high resolution images are consistent with the proposed mechanism and computer simulated images of the structure. The energetics of stacking fault formation were discussed in terms of recent experimental studies on the relative stabilities of the two polymorphs.

Mechanisms of isotopic equilibration during metamorphism of tillites from the Ogcheon Belt, South Korea R. A. Cliff & G. Jones and W. C. Choi & T. J. Lee

The NE–SW trending Ogcheon Belt formed during the Mesozoic by deformation and metamorphism of a sedimentary sequence which includes 'tillite' formations of Late Precambrian or Lower Palaeozoic age. In the central part of the belt pelitic assemblages record a Barrovian-style metamorphism up to kyanite grade, followed by local contact metamorphism associated with extensive granite plutonism.

Rb-Sr isotopic data are reported from cm-scale sampling of clasts and matrix in the "tillites" in a profile across the metamorphic zones. Sr-isotopic disequilibrium between clasts and matrix persists up to the highest grade but in four out of five rocks the matrix samples approximate to isochrons (MSWD's < 12). The mechanism for this selective isotopic equilibration is attributed to processes associated with metamorphic reactions in the matrix. Comparisons between samples suggest that dolomite-consuming reactions are essential to these processes. Samples from the biotite and garnet zones have low-variance assemblages in which internal buffering of the fluid phase is likely to have occurred. Consideration of the modal mineralogy and possible reaction paths will place limits on the integrated fluid/rock ratio and the importance of fluid migration for Sr-isotope equilibration.

The matrix 'isochrons' for three of the rocks, together with separated white micas from associated schists, suggest that metamorphism took place in the Trias, approximately 200 Ma. Metamorphism was followed by slow cooling and biotite closure temperatures were not reached until 190–150 Ma.

These results suggest that where high fluid/rock ratios can be demonstrated on independent petrological grounds, the analysis of small scale whole rock samples may allow effective Rb–Sr dating of metamorphism.

A temperature profile across the Connemara Schists—implications for heat transfer in metamorphism B. Yardley & J. Barber

During progressive burial, heating and metamorphism a significant part of the heat input to the metamorphic pile is absorbed in raising temperature and driving reactions. Hence if heat transfer is purely conductive, temperature gradients will decrease upwards, in contrast to steady-state gradients in stable crust. A temperature profile across the Connemara Schist belt shows a region of very shallow temperature gradient in the migmatite zone, with a marked steepening of the gradient at lower grades, around the upper sillimanite isograd. This is incompatible with purely conductive heating and requires convective heat transfer by melts or fluids in the migmatite zone (for which there is independent evidence) coupled with 'temperature-buffering' by melting reactions. Severe restrictions on the effectiveness of metamorphic fluids as agents of heat transfer at medium grades were pointed out.

A new method for the generation of internally consistent sets of thermodynamic data R. Powell & T. J. B. Holland

Minimum requirements for thermodynamic calculations on mineral assemblages using thermodynamic data for end-members are:

(1) a set of thermodynamic data which are consistent with experimentally determined mineral equilibria, and, if possible, calorimetric measurements; and

(2) the uncertainties on these data, and, in particular, correlations between these data.

While (1) is self-evident, (2) is essential for calculating the uncertainty on the Gibbs energy of any reaction and, consequently, the uncertainty on, for example, a calculated pressure.

The method involves finding the *region* of discretized thermodynamic data space which is consistent with the experimentally determined brackets on mineral equilibria by first locating an acceptable point on the grid, then examining all the adjacent points on the grid for acceptability. This region, a convex polyhedron, is approximated by an ellipsoid which is used to generate a covariance matrix for the calculated thermodynamic data.

The inapplicability of the depth concept to the interpretation of regional metamorphic zones B. Harte

Depth is obviously such a fundamental control on the distribution of pressure and temperature in the Earth that it has often dominated interpretation of regional metamorphic zones. Even in the recent dynamic models of orogenic belts in which thermal evolution is traced during erosion of thickened crust (as developed by Richardson, England and co-workers e.g. England & Richardson, 1977) the overall control of variations in mineral facies *within a single terrain* is related to depth, because of the one-dimensional nature of the models. Examining classic areas of regional metamorphic zones shows that in the case of andalusite–sillimanite sequences it is usually difficult to exclude lateral variations in temperature as a consequence of magmatic activity. The classic Barrovian terrains of Scotland, New England, Lepontine Alps and New Zealand show various combinations of: evidence of differential tectonic uplift and sometimes thickening during metamorphism, narrow zonal spacings, and proximity to major tectonic boundaries. Thus the existence of lateral heat transfer as a consequence of tectonic movements is indicated, and the metamorphic zones probably reflect temperature variation due to this control as well as to depth. This may cause metamorphic zones to be orientated (at their initiation) obliquely to the Earth's surface, and such zones may become inverted by later tectonic events without necessarily appealing to nappe formation.

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