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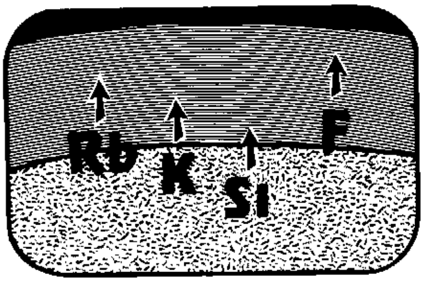

Fluid Movements, Element Transport and the Composition of the Deep Crust

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Fluids have long been known to be an important component in metamorphic and metasomatic reactions. In this NATO Advanced Research Workshop, held 18024 May 1987, attempts were made to quantify their composition, assess their origin and path, and understand their behaviour and effect — an ambitious undertaking for the 60-odd participants at this week-long session in rural Lindas, Norway, the site of Caledonian-aged, fluid-induced, eclogite-facies reworked granulite-facies anorthosite.

The technical sessions built from the bottom up, beginning with J.B. Dawson's presentation of evidence of mantle metasomatism affecting eclogite xenoliths brought up in the Lashaine east-African rift volcano. CO_2-rich fluids added Ti and K while removing Ca and Na and resetting U and Pb systematics some 2 Ga ago. Moving up into the crust, many speakers considered the agents of metamorphism at granulite facies and the amphibolite-granulite boundary. C.R.L. Friend compared the anatomy of the amphibolite-granulite transition in the well-known Kabbaldurga quarry in southern India with that in western Greenland. The former area shows a late, partly transgressive transformation whereas in the latter, gradational, layer-by-layer dehydration, melting and retrogression are inferred.

M. Raith and S. Hoernes reported on charnockite formation at two south Indian localities. At Kabbaldurga, structurally controlled infiltration of late CO_2-rich fluids derived from lower-crustal granulites caused dehydration and metasomatism at 700-750°C, 5-7 kbars, in the late Archean; whereas at Kottavattam, similar dehydration occurred during uplift degassing about 550 Ma ago.

J.B.H. Jansen and C. Maijer reported on high-temperature granulite-facies contact metamorphism around anorthosite bodies in Rogaland, SW Norway. Although water and other volatiles decrease with increasing grade, LIL (light-ion lithophile-element) depletion is not apparent, suggesting magmatic heat-induced metamorphism rather than fluid flushing.

D. Bridgwater, the conference convenor, in conjunction with H. Austrheim, S. Pedersen and J. Winter, discussed element mobility and isotopic resetting during Nagssugtogidian (1500-1900 Ma) metamorphism in SE Greenland. Retrogression of Archean granulites was accomplished through addition of Cl-rich aqueous fluids, which added K, Rb, Pb, Sr, Ba and the REE, and corroded zircons. All known isotopic systems are upset accordingly. Fluid inclusion studies of units associated with a 1.9 Ga "charnockite" complex in this terrain were discussed by T. Andersen, H. Austrheim and D. Bridgwater. The inclusions chart an isobaric cooling path where magmatic CO_2-rich fluids mixed with country rock fluids containing CH_4 and N_2. B.R. Frost, C.D. Frost and J. Touret suggested that synmetamorphic magmas are the source of heat and CO_2-rich volatiles in granulite terrains and heat and H_2O-rich fluids at high structural levels. Cumulate intrusions, crystallized under granulite-facies conditions, commonly show geochemical depletions like those of restites.

Theoretical aspects of transport of heat and matter during metamorphism were discussed by M.J. Bickle. Because heat is conducted at a rate several orders of magnitude greater than solutes can diffuse, evidence for the operation of one process does not necessarily imply the same mechanism for other effects. The character of, and processes at, the Conrad discontinuity beneath the Superior Province were illustrated by J.A. Pervical and D.M. Fountain. A layered reflectophile sequence in the lower crust partially melted under dehydrating conditions to provide undersaturated tonalitic magmas emplaced in seismically transparent upper crust. The interface is a complex prograde-retrograde amphibolite-granulite facies boundary.

J. Winter and K. Sorensen reported on a geochemical study of granulite-to-amphibolite retrogression in the Nordre Stromfjord shear zone of W Greenland. Accompanying mineralogical transformation are additions of K, Si, Rb and water, and depletion of Al, Ti, Fe, Ca, Sr and Na. Some changes can be related to intrusion of syn-kinematic pegmatites.

In a spectacular example of ancient and current fluid pathways from the German deep drilling program, H.J. Behr showed geophysical evidence for high electrical conductivity and low seismic velocity and incontravertible textural evidence for multiple fluid pathways. The combination of cathodoluminescence microscopy to image different mineral generations and fluid inclusion microthermometry to derive temperatures and compositions is a powerful approach to understanding fluid evolution and migration. In combination with future K-Ar and Rb-Sr isotopic dating of material in inclusions, this work will constitute a thorough characterization of fluid behaviour.

A.A. Garde presented evidence of retrograde metamorphism in the vicinity of a prograde amphibolite-granulite boundary of 3 Ga age in W Greenland. On a large scale, closed-system behaviour could relate the H_2O-rich retrogressing fluids at moderate depths to granulite dehydration reactions below. Some tectonic controls on fluid motion were outlined by F.J.A.S. Barriga, W.S. Fyfe and A. Ribeiro using examples from the high-level Carrapateira fold and thrust belt of S. Portugal and pyrope-coesite rocks of the Italian Dora Maira Massif. Some 50 m of hanging wall carbonate is missing and presumably dissolved by thrust-transported acidic fluids according to palinspastic reconstruction of the Portugese belt. The 30 kb coesite-bearing rocks were emplaced syntectonically by fluidized injection.

High-temperature ductile deformation in the Mt. Helen mylonites of the Wind River Range occurred in the presence of highly saline aqueous fluids according to T.P. Hulsebosch. Neither mineralogaical nor chemical changes accompanied grain size reduction.

P. Blattner and J.G. Williams measured oxygen isotopes and chlorine in the Darran complex of New Zealand. Mineralogical transformations such as apatite and garnet growth can be related to fluid fluxes. A sobering examination of the geochemical effects of 350-450°C Proterozoic retrogression on Archean gneisses from W Greenland was presented by A.P. Nutman, T. Rivers, F. Longstaffe and F.J.W. Park. Large volumes of probable meteoric water disturbed major- and minor-element composition as well as isotopic systems.

R. Kerrich and W.S. Fyfe discussed auriferous, quartz-carbonate bearing shear zones of the Abitibi belt. Based on stable isotope signatures, huge quantities of 500°C metamorphic or magmatic saline waters circulated through the faults; possibly sea water driven down and back up by seismic pumping in a transtensional tectonic regime. Fluid inclusions in skarns studied by J. Touret provide direct evidence of metasomatic fluids. In both the 30 Ma Serifos (Greece) skarn and the highly metamorphosed 1500 Ma Arendal (Norway) deposits, saline fluids, derived from intrusions, mixed with externally derived CO_2-rich fluids. Multiple generations of inclusions and quartz record pulses of fluid injection.

D.H. Jackson, D.P. Mattey, N.B.W. Harris and M. Santosh applied a step-heating technique to the study of carbon isotopes in CO_2-rich fluid inclusions from south Indian granulites and charnockites. Incipient charnockites have distinctly heavier, more abundant and possibly later, carbon than massive charnockite and khondalite. I. Cartwright modelled closed-system behaviour of mineral-fluid-melt systems at the amphibolite-granulite boundary, using the Lewisian complex as an example. Partial melting is the main dehydrating process, followed by retrogression upon melt crystallization.

A much-needed break was provided by a day in the field, looking at spectacular examples of eclogitized anorthosites under the guidance of the H. Austrheim, H. Fossen and B. Jamtveit. Aqueous fluids permeating along Caledonian shear zones converted granulite to eclogite assemblages at 15 kbar, 700°C.

I. Ermanovics reported on brines from drillholes in Canada, Sweden and the USSR. The fluids are in isotopic equilibrium with the rock, implying extended residence time. Structural control of fluid migration was discussed by J.M. Caron, using shear zones in Corsica as an example. Free fluids were not necessarily present during eclogite to blueschist-facies retrogression along shear zones, veins, cracks or cleavage. J.L. Potdevin, J.M. Lardeaux and G Trolliard compared fluid motion and mass transfer in fold hinges and shear zones. Processes of dissolution, diffusion and recrystallization have variable effects in different environments. The processes of diffusion and dissolution-recrystallization were compared in a study of synthetic fluid inclusions in quartz by A.M. Boullier, G. Michot and A. Pecher. Such changes take place at a scale discernible by TEM.

An interpretation of lower crustal conductivity by measuring physical properties such as porosity and permeability, was made by E. Huenges, G. Nover and G. Will. The model calls for open pores and cracks at 12 km depth. Electrical properties of the Falkenburg granite were studied by G. Nover and G. Will. Complex resistivity measurements allow models of crack geometry and fluid movement to be developed.

J. Dubessy and C. Ramboz discussed devolatilization reactions in the system C-O-H-N-S. The amount and composition of fluid, controlled by complex variables such as P, T, fO_2 and rock composition, in turn affect metal transport. The mobility of trace elements in aqueous fluid inclusions in granites was studied by micro-analysis by D. Norman, P. Kyle, T. Segalstad and I. Walder. Significant variations in mobility were detected among elements, although all are susceptible to transport by hydrothermal fluids.

W. Glassley studied chemical changes at well-defined amphibolite-granulite "fronts" in Sri Lanka, finding both enrichment and depletion trends in different examples. Detailed mineralogical study suggests a model whereby fluxing CO_2 mixes with ambient H_2O and precipitates LIL-bearing phases which are subsequently dissolved as $^aCO_2$ increases.

A.P. Nutman and A.A. Garde presented a model for intrusion of hot tonalites into wet metavolcanic rocks to produce xenolithic intrusions like those in SW Greenland. Hydraulic fracturing leads to "blowing up" of the volcanic sequence. A gabbro-amphibolite transition was studied by H.P. Zeck to determine changes in bulk-rock composition. Significant changes included increases in Cl, H_2O, Th, K. Rb, Pb, Na and Zn and decreases in S and Ca.

J.B.H. Jansen discussed the origin and effect of CO_2-rich fluids on a zoned 20-Ma-old greenschist- to amphibolite-facies transition from Naxos, Greece. Although there is little evidence of carbonate-pelite reaction, C isotopes suggest exchange with fluids which have passed through a C-rich sedimentary source, obviating the need for an externally derived fluid.

Redistribution of U and Pb by fluids was suggested by L. Schiotte as the cause of a geologically meaningless but statistically significant Pb-Pb isochron from early Archean gneisses near Saglek, Labrador. A protolith of 3.8 Ga age was enriched during metamorphism at 3.6 Ga and depleted by another event at 2.8, resulting in a 3.44 Ga isochron.

S.M.F. Sheppard demonstrated the utility of D/H *versus* $^{18}O/^{16}O$ plots in characterizing water as meteoritic, sea, metamorphic, magmatic, etc. The source of water in a Himalayan peraluminous granite was H_2O-rich sediments underthrust during collision. U deposits in the Alps resulted when metamorphic and meteoric waters mixed. Hydrothermal graphite deposits of Acadian age in New Hampshire were studied by D. Rumble, C.P. Chamberlain and P. Zeitle using C-O isotopic, petrologic and U-Pb geochronologic constraints. Carbon was mobilized as CO_2 and CH_4 by metamorphic devolatilization, transported in aqueous fluids, and deposited in fractures in fluid-heated metamorphic "hot-spots".

Sr isotopes were used by H.J. Chapman, M.J. Bickle and S.M. Wickhama to monitor the timing and direction of fluid flow in metamorphic rocks from the Pyrenées. In an interlayered pelite/carbonate sequence, there is evidence of more extensive Sr diffusion above carbonate units than below, suggesting structurally upward fluid flow some 300 Ma ago. B.W. Evans discussed a Cretaceous prograde blueschist to granulite-facies transition from the Seward Peninsula, Alaska. A thermal dome was superimposed on a high-P subduction complex, leading to a closely spaced sequence of isograds.

A theoretical treatment of fluid transport, stable isotope fronts and crustal buffering was given by P. Blattner, R. McKibbin and A. Absar. It is possible to determine the kinetics of replacement processes knowing water/rock ratios and isotopic values of both water and rock. D. Norman reported that Nd/Sm isotopes in water from fluid inclusions in the Drammen granite, Norway, can be fitted to a 265 Ma isochron and are more primitive than that of the whole rock. The water was probably trapped during caldera formation.

An overview of granulites in China was provided by Sun Dazhong. The Archean granulites of Inner Mongolia are mainly metasedimentary garnet-sillimanite-plagioclase-quartz rocks with economic deposits of graphite. In the East Hebei Province, mixed acid, basic and metasedimentary rocks were metamorphosed to 8-10 kbar, 800-1000°C, probably about 2725 Ma ago.

An exposition of isotopic problems in old rocks was given by D. Bridgwater, using the Uivak/Amitsoq gneisses of the North Atlantic craton as an example. Using zircon geochronology for control on events, whole-rock isotopic systems may be understood in terms of a series of additions and depletions.

On the whole, the conference provided a useful summary of approaches to the problem of fluid composition and movements on different scales. The importance of fluids in influencing a variety of processes cannot be overestimated. However, quantifying fluid volumes and compositions is a task requiring all the tools at our disposal. Bill Fyfe put the problem into a global perspective in a plate-tectonics framework but also emphasized the need for geologists to apply the lessons learned from fluid behaviour in rocks to contemporary problems such as preservation of the planet's environment.

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