

HARKERITE AND ASSOCIATED MINERALS IN MARBLE AND SKARN FROM
CRESTMORE QUARRY, RIVERSIDE COUNTY, CALIFORNIA AND CASCADE SLIDE,
ADIRONDACK MOUNTAINS, NEW YORK

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ABSTRACT

Of two newly described North American localities for harkerite, $\sim \text{Ca}_{48} \text{Mg}_{16} [\text{AlSi}_4\text{O}_{15}(\text{OH})_4 (\text{BO}_3)_{16} (\text{CO}_3)_{16} (\text{H}_2\text{O}, \text{HCl})_2]$, the high-temperature, low-pressure contact aureole in the Crestmore Quarry is typical for this mineral, whereas the deep-seated Cascade Slide xenolith in anorthosite is unique. Critical assemblages are harkerite + forsterite + clintonite \pm spinel (Crestmore marble), harkerite + monticellite \pm forsterite + spinel and harkerite + clinopyroxene + monticellite (Cascade Slide marble), and harkerite + vesuvianite + monticellite + clintonite (Crestmore skarn). The sequence of crystallization at both localities is first monticellite, then forsterite, and lastly, harkerite; at Crestmore, clintonite formed after forsterite and spinel. Variations in SiO_2 , Al_2O_3 and B_2O_3 in harkerite approximately fit the substitution $(\text{BO}_3)_4 \leftrightarrow \text{Al}_{0.75}\text{Si}_{4.25}\text{O}_{15.25}(\text{OH})_{0.75}$. The distribution of Fe^{2+} and Mg among the minerals is regular, and the ratio Fe^{2+}/Mg increases in the sequence forsterite < harkerite < spinel < monticellite \ll magnetite. This regularity is consistent with most Fe being Fe^{2+} in harkerite and with approach to chemical equilibrium between harkerite and associated minerals. At Crestmore, the harkerite formed at close to peak temperature, when

fluid introduced Al into the aureole. The boron was presumably introduced by this fluid at Crestmore, whereas it could have been present in the precursors to the harkerite-bearing rocks at Cascade Slide. The Cascade Slide harkerite probably formed at high temperature and low pressure in a marble xenolith entrapped in anorthosite at a high level in the crust, and re-equilibrated during granulite-facies metamorphism. Harkerite was stable at the 7–8 kbar pressure estimated for this metamorphism, but only because of the near-absence of a fluid phase.

Keywords: harkerite, monticellite, forsterite, spinel, contact aureole, ion microprobe, Adirondack Mountains, New York, Crestmore quarry, California.

EXPERIMENTAL EVIDENCE FOR THE EFFECT OF DEFECTS ON THE LUMINESCENCE OF SYNTHETIC CALCITE

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ABSTRACT

Synthetic calcite has been precipitated from CaCl₂ solution using four different reagents: (1) ammonium carbonate vapor, (2) ammonium carbonate solution, (3) sodium carbonate solution, and (4) sodium hydrogen carbonate. Crystals grew at room temperature over a period of 7 to 10 days using the first method and within 10 to 30 minutes at 6°C or below using methods (2) to (4). The calcite samples were heated hydrothermally and in CO₂ at 75° to 400°C and examined by SEM and powder X-ray diffraction to characterize the changes that take place during heating. Calcite synthesized by different methods has different initial sizes of crystals, widths of XRD reflections and intensity of cathodoluminescence (CL). On hydrothermal heating, crystal size increases and width of XRD reflections decreases. The magnitude of the changes in these parameters is greater at higher temperature and in longer experiments, and differs among the different types of calcite. Heating in CO₂ is relatively ineffective in changing grain size and width of XRD reflections. Differences in width and intensity of XRD reflections among different types of starting calcite are attributed to differing densities of defects acquired during crystal growth. The responses in width of XRD reflections and intensity of CL emission to heating are ascribed to the annihilation of defects.

Keywords: calcite, synthesis, recrystallization, luminescence, defects.

THE CLASSIC HIGH-*T* – LOW-*P* METAMORPHISM OF WEST-CENTRAL MAINE: IS IT POST-TECTONIC OR SYNTECTONIC? EVIDENCE FROM PORPHYROBLAST–MATRIX RELATIONS

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ABSTRACT

Devonian polymetamorphism of the Central Maine belt of sedimentary rocks has been regarded as “static”, the result of advective heat due to sequential emplacement of “post-tectonic” granite plutons. The following evidence is cited in support of pluton-driven static metamorphism: (1) a spatial relationship between higher-grade metamorphic zones and pluton margins, and (2) a reported random orientation of euhedral porphyroblasts within matrix fabrics. In contrast, our observations of porphyroblast–matrix relations show that regional metamorphism was synchronous with progressive accumulation of plastic strain. Metasedimentary rocks have penetrative grain-shape fabrics defined by mica and quartz. Spatial variations in the style of matrix fabrics reflect contrasts in rheology as a function of lithology, stratigraphy and metamorphic grade. Strain partitioned into zones characterized by a high degree of parallelism between steeply oriented compositional layering and foliation (higher- strain zones) that surround zones in which variably oriented, moderately dipping foliation is not as strongly developed (lower-strain zones). A well-developed moderately to steeply northeast-plunging mineral-elongation lineation is pervasive in both types of structure, and is defined by the same mineral assemblage at the same grade of metamorphism. Thus, we interpret mineral growth to record the accumulation of plastic strain. Biotite “fish” and quartz-dominated polycrystalline aggregates in asymmetrical pressure-shadows around porphyroblasts, which are elongate in the direction of mineral elongation, show consistent dextral-reverse displacement along the mineral-elongation lineation in the plane of the foliation. Andalusite and staurolite porphyroblasts have preferred orientations, statistically parallel to matrix fabrics, and garnet and staurolite porphyroblasts include a foliation (S_i) that is discontinuous with matrix foliation (S_e). In staurolite, the obliquity of S_i with respect to S_e decreases through up to three textural zones from core to rim, to record episodic interkinematic growth of porphyroblasts and progressive modification of the matrix. In lower-strain zones, granite plutons are associated with retrogressive replacement of andalusite and staurolite, which reflects preferential contact metamorphism in these structures.

Keywords: Appalachian orogen, grain-shape fabrics, high-*T* – low-*P* metamorphism,

microstructures, strain partitioning, syntectonic growth, porphyroblast, Maine.

HIGH-PRESSURE AND HIGH-TEMPERATURE METAMORPHISM OF THE MAFIC AND ULTRAMAFIC LAC ESPADON SUITE, MANICOUAGAN IMBRICATE ZONE, EASTERN GRENVILLE PROVINCE

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ABSTRACT

The Lac Espadon suite (LES) of the Manicouagan Imbricate Zone (Quebec) is comprised of layered mafic and ultramafic rocks, Labradorian in age (*ca.* 1650–1630 Ma) that were variably deformed and metamorphosed under high-pressure and high-temperature (high-PT) conditions during the Grenvillian Orogeny. Maximum P–T conditions of 780–930°C at 16–19 kbar (high-T eclogite facies) are recorded in massive coronitic troctolite and hornblendite from the western part of the LES. In these rocks, metamorphic coronas of orthopyroxene, clinopyroxene and garnet have grown at the expense of igneous olivine and plagioclase. Relict plagioclase contains inclusions of kyanite and corundum, and garnet coronas locally preserve growth zoning. Deformed margins of the mafic rocks have granoblastic hydrous assemblages that are interpreted to have equilibrated during exhumation at *ca.* 700°C at 10–12 kbar and then down to *ca.* 600°C at 5 kbar (amphibolite-facies conditions), suggesting a steep retrograde P–T path. Olivine gabbro from the eastern part of the LES records peak conditions of 775–870°C at 14.5–16.25 kbar. Granoblastic areas in the rock are partially hydrated and give conditions of 760–820°C at 12–14 kbar, suggesting a near-isothermal P–T trajectory. The P–T paths are compatible with structural evidence suggesting tectonic exhumation of these rocks by northwesterly thrusting, with extension on top of the pile. The high-PT conditions and steep decompression paths recorded by the LES are similar to those in several adjacent and nearby terranes, suggesting widespread exhumation of the lower crust in this area of the Grenville Province.

Keywords: Grenville Province, mafic rocks, coronas, eclogite facies, amphibolite facies, Manicouagan, Quebec.

KYANITE IN THE WESTERN SUPERIOR PROVINCE OF ONTARIO: IMPLICATIONS FOR ARCHEAN ACCRETIONARY TECTONICS

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ABSTRACT

Thirteen occurrences of kyanite in Archean supracrustal rocks of the western Superior Province of Ontario are grouped into three distinct lithotectonic associations: I) metapelites close to subprovince and terrane boundaries, II) metapelites near faults within greenstone belts, and III) metamorphosed Al–Si-rich alteration assemblages associated with volcanogenic massive sulfide (VMS) mineralization in greenstone belts. Kyanite of groups I and II is commonly associated with staurolite and texturally predates the main assemblage of metamorphic minerals (Sil + Grt + Bt + Pl + Qtz), indicating that a medium-P, low-T Barrovian metamorphism occurred before the main, regional low-P, low-T metamorphism that characterizes the western Superior Province. This earlier Barrovian metamorphism (670–730 MPa, 500–560°C) was followed by significant unloading (up to 12 km at the Quetico–Wabigoon boundary) before the development of the main penetrative deformation and the regional low-P, low-T metamorphism. The results of geothermobarometry and the restricted locations of group-I and group-II kyanite are interpreted to reflect crustal thickening as part of accretionary tectonic processes for the collage of individual greenstone belts and subprovinces for the formation of the western Superior Province. In particular, the three occurrences of kyanite along the Quetico–Wabigoon boundary support the origin of the Quetico Subprovince as an accretionary wedge during northward subduction. Group-III kyanite, on the other hand, reflects unusual whole-rock compositions and hydrothermal fluids, and may be a potentially useful exploration tool for VMS deposits.

Keywords: kyanite, occurrences, Barrovian metamorphism, Archean, accretionary tectonics, western Superior Province, Ontario.

CORDIERITE – ANTHOPHYLLITE – CUMMINGTONITE ROCKS FROM THE LAR
DEPOSIT, LAURIE LAKE, MANITOBA

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ABSTRACT

The assemblage cordierite–anthophyllite characterizes the alteration zone of the Lar Cu–Zn deposit in the Lynn Lake volcanic belt, in Manitoba; in some altered rocks, cummingtonite is present as well. Under appropriate pressure–temperature conditions (approximately 3–4 kbar and 550°–700°C), colinearity in the composition of cordierite, anthophyllite and cummingtonite, in the presence of quartz, results in the degenerate univariant reaction anthophyllite = cordierite + cummingtonite. We contend that the assemblage cordierite–anthophyllite crystallized below the temperature of this reaction, and the assemblage cordierite – anthophyllite – cummingtonite, slightly above. Mantling of cummingtonite by anthophyllite probably was the result of cooling from peak conditions of metamorphism.

Keywords: cordierite–cummingtonite, metamorphism, Lar deposit, Lynn Lake belt, Manitoba.

SUBTLE OSCILLATORY ZONING IN GARNET FROM REGIONAL METAMORPHIC
PHYLLITES AND MICA SCHISTS, WESTERN ERZGEBIRGE, GERMANY

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ABSTRACT

Growth zoning patterns of garnet grains in phyllite and mica schist from the Garnet–Phyllite Unit and the Mica–Schist/Eclogite Unit of the western Erzgebirge, in Saxony, Germany, have been studied in detail by electron microprobe and are characterized with X-ray-intensity mapping images (MAPS) and quantitative chemical analyses. Zoned grains of garnet in the phyllite show a continuous decrease in spessartine component from core (28 mole %) to rim (19%), and, over about 100 μm at the rim, a discontinuous, oscillatory increase, decrease and further increase to 30%. These changes are correlated with an antithetic, oscillatory zoning of comparable amplitude in the almandine component (47% in the core, 56% toward the rim, 49% at the extreme rim). Available data for diffusion rates in garnet suggest that no significant modification of growth zoning attributable to later intracrystalline diffusion has occurred. In two samples of mica schist, oscillatory zoning with respect to the grossular component is correlated with an antithetic pattern of the almandine component (*e.g.*, sample E 514: 17.0 mole % grossular component in the core, decreasing to 4.7 mole %, then increasing to 6.8 mole % and decreasing again to 4.3 mole % at the extreme rim). Although the patterns of zoning in themselves do not yield any evidence of modification after growth, available data on diffusion do not entirely rule out this possibility. In agreement with the observed textural relationships, we attribute the oscillatory changes in garnet composition to specific continuous reactions during regional metamorphism, indicating a complex

growth-and-resorption history of the garnet resulting from small-scale variations in the rate of decompression of the rocks. No evidence in support of an open-system behavior of the fluid phase, such as highly variable and irregular patterns of oscillatory zoning, could be found. Where oscillatory zoning occurs, the number of oscillations and their relative changes in composition are the same throughout that sample, and may even be correlated between samples collected many kilometers apart.

Keywords: garnet, oscillatory zoning, regional metamorphism, elemental X-ray-intensity mapping (MAPS analysis), Erzgebirge, Germany.

THE CASE AGAINST OSTWALD RIPENING OF PORPHYROBLASTS

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ABSTRACT

Recently published numerical models of Ostwald ripening greatly overestimate rates of coarsening for garnet porphyroblasts, because of inappropriate choices for values of the input parameters that control diffusional fluxes of Al. More appropriate values compel the conclusion that diffusional fluxes are much too small for this process to modify garnet size-distributions appreciably, because driving forces are negligible for crystals larger than a fraction of a micrometer. Measured crystal-size distributions for garnet porphyroblasts differ in important details from those predicted for Ostwald ripening, but match those predicted by models of thermally activated primary nucleation and growth. Self-similar pseudonormal porphyroblast size-distributions that coarsen with metamorphic grade, previously offered as the principal evidence in favor of Ostwald ripening, are instead the combined consequence of nucleation rates dependent upon the amount of thermal overstepping of reaction and growth rates that are exponential functions of absolute temperature.

Keywords: Ostwald ripening, crystallization, porphyroblast, kinetics.

FORWARD MODELING OF METAMORPHIC TEXTURES

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ABSTRACT

A technique of quantitative forward modeling that combines differential and irreversible thermodynamic techniques is used to gain insight into the types of textures that develop in regional metamorphic terranes. Two different P–T paths are examined that produce sillimanite–garnet schist from staurolite–garnet schist of the same bulk composition. One is an isobaric heating path from 600°C to 630°C at 4 kbar, and the other is an isothermal decompression path from 8 kbar to 4 kbar at 630°C. The final temperature, pressure, mineral compositions, and whole-rock mineral modes are the same in the two cases. However, the mineral textures are different, allowing the two paths to be distinguished. The critical information that permits the paths to be discriminated is the recognition of textures that show that the higher-pressure rock originally had more garnet and less staurolite than the lower-pressure rock. There also is a difference in the reactions that produced sillimanite: in the isobaric heating case, most sillimanite is produced by staurolite breakdown, whereas in the isothermal decompression case, most sillimanite is produced by garnet breakdown. The different mechanisms of sillimanite formation cause the rock that decompressed to have much less biotite in the matrix than the rock that was heated. The textures produced for each path are distinct, easily recognizable, and should persist over a wide range temperature and pressure, making it possible to identify them even if the rock undergoes multiple prograde or retrograde events. The simulations show that considerable information about the P–T history of metamorphism is recorded in textures produced by mechanisms of reaction in metapelites. Integration of this technique with regional studies of metamorphic textures has the potential to provide significant constraints on the detailed 3-D thermal history of mountain belts and valuable insight into the tectonic processes that produce them.

Keywords: metamorphic textures, reaction mechanisms, P–T–t path, irreversible thermodynamics, differential thermodynamics.

GEOCHEMISTRY AND TEXTURES OF METASOMATIC COMBS AND ORBICULES IN ULTRAMAFIC ROCKS, NAMEW LAKE, MANITOBA

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ABSTRACT

Metasomatic alteration of ultramafic rocks with igneous orbicular textures from the Namew Lake Ni–Cu mine 60 km south of Flin Flon, Manitoba, has produced metamorphic comb and orbicular textures. These textures occur in a 3-m-thick concordant layer of ultramafic rock that occurs within polymetamorphic Early Proterozoic gneisses. The ultramafic rocks were fractured into blocks and altered during amphibolite-facies metamorphism, producing talc + dolomite in the cores of blocks, a 2-cm-thick layer of tremolite displaying comb textures perpendicular to boundaries of the blocks, and a rind of phlogopite. Trends of gain or loss of elements vary from zone to zone and were controlled in part by the minerals in the zone. For example, the *REE* were removed during the alteration of igneous minerals to talc + carbonate, whereas heavy *REE* were preferentially enriched in the tremolite zone and subsequently depleted in the phlogopite zone. The original igneous orbicules are elliptical, 2–4 cm in size, and have rinds with thin, concentric shells of fine-grained chromian magnetite. The orbicules originally had a core of olivine and pyroxene and a rim of olivine, now partially replaced by metamorphic tremolite, phlogopite, and serpentine. The matrix between these orbicules now contains metamorphic tremolite and phlogopite, and minor serpentine, magnetite, and sulfide. In the centers of some blocks, orbicules and their matrix have been replaced by talc + dolomite. Near the edges of these blocks, however, the cores of orbicules contain talc + dolomite, the rims have radiating tremolite, and the matrix is phlogopite. Thus, the orbicules were apparently a barrier to fluid flow, possibly the consequence of textural differences between the orbicules and the matrix.

Keywords: metasomatism, comb, orbicule, compositional alteration, fluid flow, ultramafic, metapyroxenite, Namew Lake Ni–Cu deposit, Manitoba.

CRYSTAL-CHEMICAL AND THERMAL CONTROLS ON TRACE-ELEMENT
PARTITIONING BETWEEN COEXISTING GARNET AND BIOTITE IN METAMORPHIC
ROCKS FROM WESTERN LABRADOR

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ABSTRACT

Trace-element concentrations of coexisting garnet and biotite in thirteen metamorphic rocks from western Labrador, ranging from lower-greenschist to upper-amphibolite facies, were determined by laser-ablation microprobe – inductively coupled plasma – mass spectrometry (LAM-ICP-MS). Systematic trace-element distributions across wide compositional and thermal ranges suggest that equilibrium was approached during metamorphic crystallization. Zn depletion in garnet and biotite from staurolite-bearing assemblages demonstrates the control of mineral assemblage on the concentrations of trace elements. Mean molar distribution coefficients [$(D_i^*$ (garnet/biotite))] from greenschist-facies assemblages have the following values: Sc 5.03 ± 1.27 (1σ), Eu 1.99 ± 1.69 , Cr 0.83 ± 0.53 , V 0.39 ± 0.13 , Co 0.27 ± 0.07 and Zn 0.12 ± 0.02 . For upper-amphibolite-facies assemblages, the D_i^* values are: Sc 8.98 ± 7.08 , Eu 64.77 ± 41.66 , Cr 0.88 ± 0.56 , V 0.17 ± 0.06 , Co 0.46 ± 0.08 and Zn 0.15 ± 0.03 . Other trace elements have concentrations near or below detection limits in either garnet or biotite. The partition of Sc and Ti between garnet and biotite is controlled by the contents of ^{IV}Al in biotite and Ca in garnet, respectively, indicating that crystal chemistry exerts an influence on trace-element partitioning. In contrast, the partition of Co and Zn shows a thermal dependence and is less sensitive to compositional changes in the host minerals. Distribution coefficients for Zr, Sm, Eu and Gd between garnet and biotite vary systematically with both the Mg/(Mg + Fe) values of garnet and biotite as well as with metamorphic temperature; it was not possible to isolate these two competing factors. The partition of elements between coexisting garnet and biotite is strongly controlled by crystal structure, so that the distribution of elements occupying each cation site in the garnet structure is characterized by a parabola-shaped peak in a diagram where distribution coefficients are plotted against ionic radius. Our study indicates that some instances of irregular partitioning of trace elements between garnet and biotite, found in previous work utilizing bulk analyses of mineral separates, may have been due to inclusions, impurities, and zoning involving trace elements.

Keywords: trace elements, garnet, biotite, laser-ablation microprobe, ICP–MS, distribution coefficients, crystal chemistry, thermal dependence, crystal structure, Labrador.

DOCUMENTATION OF VARIABLE TRACE- AND RARE-EARTH-ELEMENT
ABUNDANCES IN CARBONATES FROM AURIFEROUS QUARTZ VEINS IN MEGUMA
LODE-GOLD DEPOSITS, NOVA SCOTIA

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ABSTRACT

Samples of vein carbonate from 16 Meguma lode-gold deposits in Nova Scotia have been analyzed by solution chemistry (ICP–MS) and laser ablation micro-analysis (LAM ICP–MS) for their trace- and rare-earth-element (*REE*) abundances in order to assess the potential use of such data to decipher the origin of the mineralization. The gold deposits, hosted by metasedimentary rocks of the Meguma Group, are well suited to such a study because carbonate is the second most abundant phase (after quartz) in these mesothermal lode-gold deposits. Trace-element abundances in the carbonates are low for all elements except Sr (100 to 15 000 ppm), which has larger intra- and inter-deposit variation and is zoned within individual grains (LAM analysis). The *REE* data on vein carbonates are variable, both in terms of abundance (*ca.* 5 to 100 times chondrite) and degree of fractionation, with patterns generally flat to slightly fractionated [(La/Sm)_N and (Gd/Yb)_N both generally ≤1–2] and Eu/Eu* of *ca.* 1 to 2; however, excursions to extreme enrichment in either light or heavy *REE* may occur. The fact that the large chemical variations obtained *via* solution chemistry (*i.e.*, bulk separates) are replicated by LAM ICP–MS analysis precludes putative contamination by micro-inclusions as a critical factor controlling the *REE* content of the carbonates. Instead, a crystal-chemical control is suggested. The data are interpreted to reflect modification of a primary *REE* signature inherited from a reservoir by secondary processes operating at the vein scale. These secondary processes may include one or all of the following: (1)

precipitation and dissolution of *REE*-bearing phases, including carbonate, (2) development of narrow wallrock-alteration zones marginal to veins, (3) changes in fluid composition [*i.e.*, pH, $f(\text{O}_2)$], (4) recharge of the vein fluid, and (5) rate of fluid flow. Given that the carbonate *REE* patterns deviate markedly from the *REE* signature of the host metasedimentary rocks, the data are in permissive agreement with vein fluids originating from a non-Meguma Group reservoir.

Keywords: carbonates, rare-earth elements, strontium, lode-gold deposits, Meguma Group, Nova Scotia.

DEFORMATION-INDUCED MASS TRANSFER IN FELSIC VOLCANIC ROCKS HOSTING
THE BRUNSWICK NO. 6 MASSIVE-SULFIDE DEPOSIT, NEW BRUNSWICK:
GEOCHEMICAL EFFECTS AND PETROGENETIC IMPLICATIONS

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ABSTRACT

Four samples of felsic volcanic rocks, footwall to the Brunswick No. 6 massive sulfide deposit, in the Bathurst area of New Brunswick, were analyzed to assess the chemical effects of solution transfer during the development of a fabric (composite S_1/S_2 , septa/fovia). Wide-beam electron-microprobe traverses across the domainal fabric show no obvious chemical change within the microlithons. Using Al as a conserved element, mass balance of the averaged contents principally show Si and Zn (\pm Na) removal from the septa relative to the microlithons, with some notable changes in Fe, Mg, Mn, Na, and K. Whole-rock compositions of separates of the microlithons and septa show major-element changes similar to the mass-balanced microprobe data, although there were no significant mass changes involving trace elements, except Zn. However, individual samples exhibit some trace-element mobility ($< 50\%$), in particular the light- rare-earth elements (< 50 to 150%). Values of $\delta^{18}\text{O}$ are lower in the septa than in the microlithons, on average -0.13% per 1 wt.% SiO_2 (depletion) within the septa. On the basis of an estimated solubility of silica (1 wt.%) and a small degree of silica unsaturation (80% saturated), a minimum fluid:rock ratio (F/R) of 50 is required to produce these septa *via* solution transfer, assuming the microlithons were unchanged. This situation requires the removal and transport (open system) of chemical constituents, mainly silica. Alternatively, if the microlithons were changed during deformation, the F/R would be proportionally lower, with constituents (mainly silica) locally redistributed owing to pressure differentials between the septa and microlithons (*i.e.*, closed system). The relative homogeneity of the microlithons and mobility of silica (among other constituents) to form regional quartz veins here and from numerous other localities documented in the literature indicate that the F/R were relatively high, favoring considerable open-system mass transport. The isotopically light, possibly cooler metamorphic fluids (-1 to 7%) were probably derived at depth in the accretionary wedge (Brunswick subduction complex).

Keywords: element mobility, mass transfer, pressure solution, fabric, foliation, cleavage, differentiated layering, massive sulfide, Brunswick, Bathurst, New Brunswick.

QUARTZ AND FELDSPAR MICROSTRUCTURES IN METAMORPHIC ROCKS

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ABSTRACT

The shapes of quartz and feldspar grains in metamorphic rocks are among the most reliable criteria for determining parental rock-types. Rational faces and elongate crystals of feldspar, especially with oscillatory zoning, indicate an igneous precursor, and residual faces and embayments in quartz indicate a volcanic precursor. Simple twinning in K-feldspar indicates a magmatic origin, and aligned crystals of feldspar indicate magmatic flow. Quartz and plagioclase inclusions are useful for distinguishing between phenocrysts and porphyroblasts of K-feldspar in metamorphic terranes. K-feldspar phenocrysts are characterized by zonally arranged inclusions, whereas K-feldspar porphyroblasts are characterized by spherical inclusions of quartz and plagioclase, either at random or arranged in trails that reflect an overgrown foliation. Inclusions of quartz and feldspar tend to be spherical in metamorphic porphyroblasts (*e.g.*, staurolite), even where the boundary between the porphyroblast and quartz or feldspar in the matrix is a rational face, which may be due to absence of fluid along the host–inclusion boundary, compared with its accumulation along the advancing porphyroblast–matrix boundary. The following microstructural criteria, preserved best in less deformed migmatites, indicate anatectic leucosome. (1) Crystal faces of K-feldspar or plagioclase may occur against quartz. (2) Inclusion trails are absent, in contrast to grains of the same minerals in the mesosome. (3) Overgrowths free of inclusion trails may occur on minerals with inclusion trails (*e.g.*, K-feldspar, cordierite). (4) Simple twinning may occur in K-feldspar, which appears to be diagnostic of crystallization of K-feldspar in a melt, rather than in the solid state.

Keywords: crystal faces, feldspar, inclusions, leucosome, metamorphism, microstructures, migmatites, quartz.

DEFORMATION OF SILICATE GARNETS: BRITTLE–DUCTILE TRANSITION AND ITS GEOLOGICAL IMPLICATIONS*

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ABSTRACT

To understand the deformation behavior of silicate garnets, we performed experiments on six representative silicate garnets at temperatures (T) of 1173–1673 K, strain-rates ($\dot{\epsilon}$) of 10^{-7} – 10^{-4} /s and well-controlled thermodynamic conditions. On the basis of mechanical data, microstructures and the comparison between experimental results with deformation of natural garnets, this study yields three new insights into the deformation behavior of silicate garnets. (1) The critical temperature (T_c) for the brittle–ductile transition of garnet deformation, in terms of melting temperature (T_m) and strain-rate ($\dot{\epsilon}$), can be described by an empirical equation: $T_c = T_m [(1.043 \pm 0.032) + (0.030 \pm 0.001)\log(\dot{\epsilon})]$. In the ductile regime, where $T > T_c = T_m [1.075 + 0.029\log(\dot{\epsilon})]$, steady-state creep of garnets follows a power law:

$$\dot{\epsilon} = A(\sigma)^n,$$

where $n = 3.0 \pm 0.5$, $\ln A$ (/s) = 40.1 ± 5.6 , $g = 32 \pm 2$, σ is the flow stress at steady-state creep, and μ is shear modulus of garnet. (2) A microstructural investigation suggests that crystal plasticity, enhanced by the activation of dislocation glide (slip systems $\frac{1}{2}\langle 111 \rangle\{1\bar{1}0\}$), is responsible for the brittle–ductile transition. (3) Extrapolation of the experimental results to geological strain-rates (10^{-16} – 10^{-14} /s) suggests that the brittle–ductile transition of silicate garnets in nature occurs at $T > 0.65$ – $0.70 T_m$. This indicates that crustal garnets such as almandine, pyrope and grossular can be deformed in ductile fashion under extremely high temperature ($T > 1123$ K). The extrapolation also shows that in the crust, garnet (*e.g.*, “pyrope”) is much stronger than quartz and feldspar at temperature lower than 1123 K, but the rheological contrast of garnet with quartz and particularly with feldspar is minimal at temperature higher than 1123–1173 K. In the upper mantle, however, pyrope is invariably about two orders of magnitude stronger than olivine, and the rheological contrast between these two minerals is almost constant. We conclude that silicate garnets are mostly rigid and brittle in the crust, but ductile as long as the conditions of high temperature and low strain-rate are satisfied.

Keywords: silicate garnet, brittle–ductile transition, flow law, high-temperature deformation,

dislocation creep.