DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/6

Metamorphism in supracrustal and ultramafic rocks in southern West Greenland and South-West Greenland 64 – 61.5°N

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MINISTRY OF CLIMATE AND ENERGY

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Abstract

Mafic rocks with roughly basaltic bulk composition are useful relative indicators of metamorphic grade in southern West Greenland and South-West Greenland. Ideally, these rocks are mafic granulites within the granulite-facies conditions and amphibolite at amphibolite-facies conditions. In the field, good evidence for prevailing amphibolite-facies conditions is the presence of amphibolite ± clinopyroxene ± garnet ± epidote that displays the typical L to L-S fabric. In low-Ca mafic rocks the equilibrium coexistence with hornblende + Fe-Mg amphibole + plagioclase is another indication of amphibolite-facies conditions. Granulite-facies conditions in these same rock compositions would show clinopyroxene + orthopyroxene with plagioclase ± hornblende at pressures (below about 6-7 kbar) over a range of temperatures starting at about 700°C. Above these pressures, mafic bulk compositions would contain clinopyroxene + plagioclase + hornblende + garnet in the granulite facies, but this is not a diagnostic mineral assemblage, because clinopyroxene-garnet amphibolite is stable in the upper amphibolite facies

Aluminous gneisses, which on older maps are mapped as metasediments (“mica schist and gneiss” on new maps), are good indicators of metamorphic grade and P-T trajectory. Cordierite reaction rims around aluminosilicate are indicators uplift (P-decrease) at high temperature. Staurolite is part of the equilibrium mineral assemblage at some metasediment/mica schist and gneiss localities, which indicates metamorphic conditions within amphibolite facies.

The extent of hydration and subsequent metamorphism of ultramafic rocks is highly variable. Primary assemblages are olivine + orthopyroxene ± clinopyroxene ± spinel ± plagioclase. Metamorphic assemblages commonly contain anthophyllite + talc ± actinolite ± chlorite ± serpentine. Talc-bearing metamorphic assemblages limit the metamorphism to amphibolite facies; anthophyllite-bearing assemblages are not definitive and could be upper amphibolite- to lower granulite-facies.

In places, cross-cutting pegmatite dykes have interacted extensively with the ultramafic rocks. Fluids from the dykes enhance the reactions, which gives coarse-grained reaction products. Plagioclase, K-feldspar, and quartz (pegmatite) react with the ultramafic minerals to give calcium amphibole, biotite, and anthophyllite/talc. This depletes the remaining fluid in K, Si, Ca, and Na. Where large amounts of calcic plagioclase and fluid are involved in producing calcium amphibole, these reactions can produce excess Al, which forms aluminous minerals like gedrite, sapphirine, kornerupine, cordierite, and pink corundum.

Introduction

The TTG (tonalite, trondhjemite, granodiorite) gneisses are the most common rock in the Archaean of southern West Greenland and South-West Greenland, and these are interlayered with mafic rocks that may have volcanic protoliths and suites of anorthosite plus gabbro. Also present throughout the region, but volumetrically less extensive, are small ultramafic bodies and units mapped as —metasediments” on older paper maps. The metasediments have been redesignated —mica schist and gneiss” in recent versions of the maps. In addition to these rock types, rare examples of calc-silicate rocks are also present. The origin of these rock sequences has been explained both by uniformitarian and non-uniformitarian mechanisms (see Polat *et al*., 2009 and references therein), but the view favoured by most workers in the region is that multiple generations of TTG intruded into an existing dominantly mafic crust. The most abundant remnants of this crust are the amphibolite and mafic granulite units.

The best means of understanding the metamorphic history of the region is through analysis of mafic rocks (amphibolites) and aluminous gneisses (included in among the rock types mapped as metasediments/mica schist and gneiss). These rock types can be used for P-T estimates by various methods and, in places; they display reaction textures that give clues about P-T trajectory.

Rock compositions and metamorphic assemblage

The correct interpretation of changes in mineral assemblage requires recognizing the roles of both bulk composition and changes in metamorphic conditions. The mafic rocks (amphibolites and mafic granulites) are the best geochemically characterized of the rock types useful for the study of the metamorphic history of southern West Greenland (*e.g.*, Kalsbeek & Leake 1970; Szilas, PhD project at Copenhagen in progress). These rocks show variations in ACF components (Fig. 1A) as well as in $Fe^{2+}/(Fe^{2+}+Mg)$ ratios (Fig. 1B). The whole-rock compositional variations will control the mineral assemblage as well as the P-T of appearance or disappearance of phases like garnet, clinopyroxene, and orthopyroxene.

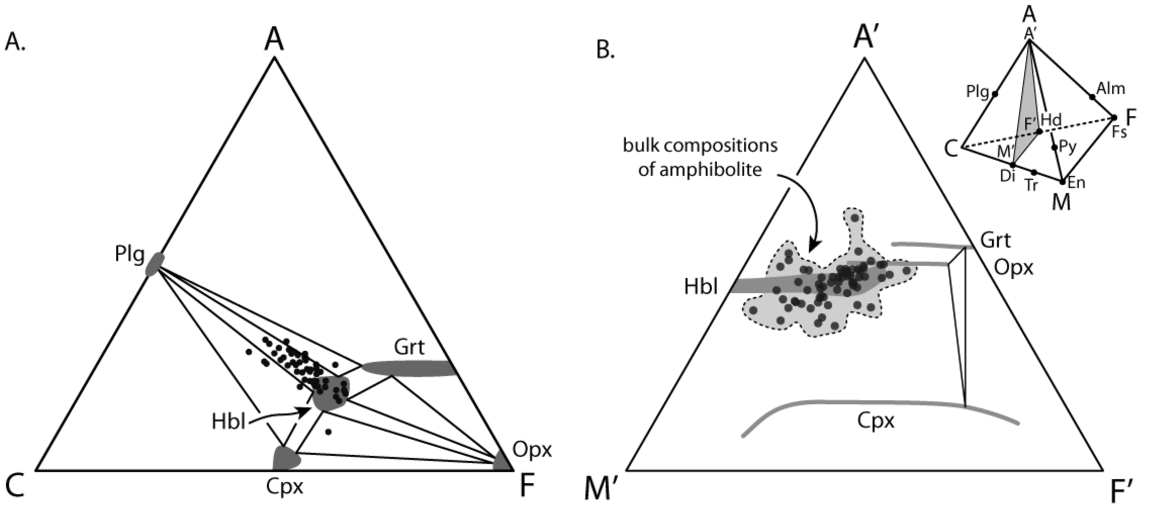

Fig. 1. Bulk compositions of amphibolites. A. Eskola type (ACF) ternary diagram (molar components) projected from apatite, biotite, plagioclase (Plg). A= Al_2O_3+Fe_2O_3+Cr_2O_3+ TiO_2-Na_2O-K_2O; C=CaO- 10P_2O_5; F=MgO+FeO+MnO-TiO_2-6K_2O. B. Ternary AFM diagram projected from apatite, biotite, plagioclase showing variation in Fe-Mg ratio on the plane A-Di-Hd. A'=Al_2O_3+Fe_2O_3+Cr_2O_3+ TiO_2+MgO+FeO+MnO-Na_2O-(CaO-10P_2O_5)-K_2O; M'=MgO; F' = FeO+MnO-TiO_2. Filled circles=whole rock analyses selected from Kalsbeek & Leake (1970) and Szillas (2009, pers. comm., and PhD project at CPH). Hbl=hornblende; Grt=garnet; Opx=orthopyroxene; Cpx=clinopyroxene; Di=diopside; Hd=hedenbergite; Tr=tremolite; Py=pyrope; Alm=almandine; En=enstatite; Fs=ferrosilite

Within the project area, aluminous rocks, where mapped, are commonly mapped as metasediments/mica schist and gneiss. Dymek & Smith (1990) give whole rock compositions for 12 samples from the Godthåbsfjord region. These analyses show the rocks to be very low in K_2O+Na_2O+CaO (average ≈ 1.5 ± 1.0 wt %) relative to Al_2O_3 (average ≈ 11.6 ± 1.7 wt %), but there can be considerable variation in the compositions of these rocks (Dymek & Smith, 1990). These rocks are not exceptionally Al-rich, and the presence of aluminous mineral assemblages is due to loss of alkali elements and calcium and growth of chlorite in the protolith. These rocks are commonly rich in biotite and garnet ± aluminosilicate ± cordierite ± staurolite ± chlorite ± plagioclase ± orthoamphibole ± quartz or corundum. The presence of abundant garnet or sillimanite seems to be the principle criteria for classifying these rocks metasediments/mica schist. In the field, these rocks are commonly compositionally layered on a meter scale or less. The gneisses are felsic, but commonly weather to a brown or yellow-brown due to the presence of Fe-Mg amphibole (cummingtonite or orthoamphibole) or sulfide minerals. The compositional layering is manifest as variations in modal amounts of the minerals, and amphibolites and garnet amphibolites may also be interlayered with the aluminous rock types (Fig 2).

The aluminous gneiss varieties of southern West Greenland is much poorer in K_2O than true pelitic rocks. The only K-bearing phase present in these rocks is biotite; whereas, in true pelitic bulk compositions, biotite will coexist with either muscovite at lower temperatures or K-feldspar + an aluminosilicate polymorph at higher temperatures. In metapelitic rocks, the assemblage cordierite + garnet + sillimanite indicates metamorphic conditions near or within the granulite facies; however, in low-K_2O, aluminous rocks cordierite + garnet + sillimanite ± orthoamphibole stability extends to the middle amphibolite facies.

The protolith of these aluminous rocks is debatable. The rocks are probably not clay-rich sediments deposited in a low-energy marine environment. Similar aluminous rocks have been described elsewhere as the products of high-temperature hydrothermal alteration of mafic to felsic volcanic rocks at or near the sea floor, possibly in combination with some low-temperature alteration (Robinson *et al.*, 1982; Schumacher & Robinson,1987; Schumacher, 1988; Dymek & Smith, 1990).

It should be noted that not all rocks mapped as —metasediment” are the aluminous gneisses discussed above. At one locality (08JCS039: 63.91642°N, 51.37852°W), interaction between a large ultramafic body and a set of crosscutting pegmatites formed a large zone of hornblendite that was mapped as —metasediment”. At another locality (08NTK125: 62.90242°N, 50.14662°W), a cataclasite was mapped as —metasediment”.

The ultramafic rocks are restricted in composition and mineral assemblage. Most of their compositional variations are controlled by the proportions of primary phases olivine, orthopyroxene, and clinopyroxene. No ultramafic body visited during the project completely escaped the effects of hydration. Hydration was commonly found at gneiss-ultramafic contacts, at pressure shadows created by the ultramafic bodies, or associated with cross cutting fractures, felsic dykes, and pegmatite dykes. Small (<10m) ultramafic bodies encountered in the area were commonly completely recrystallized to hydrous minerals. The most common compositions encountered were (1) dunitic/harzburgitic or (2) lherzolitic protoliths.

In addition to these rock types, calc-silicate rocks are also present, but these are too rare to be very helpful in understanding variations in the metamorphic conditions across the region.

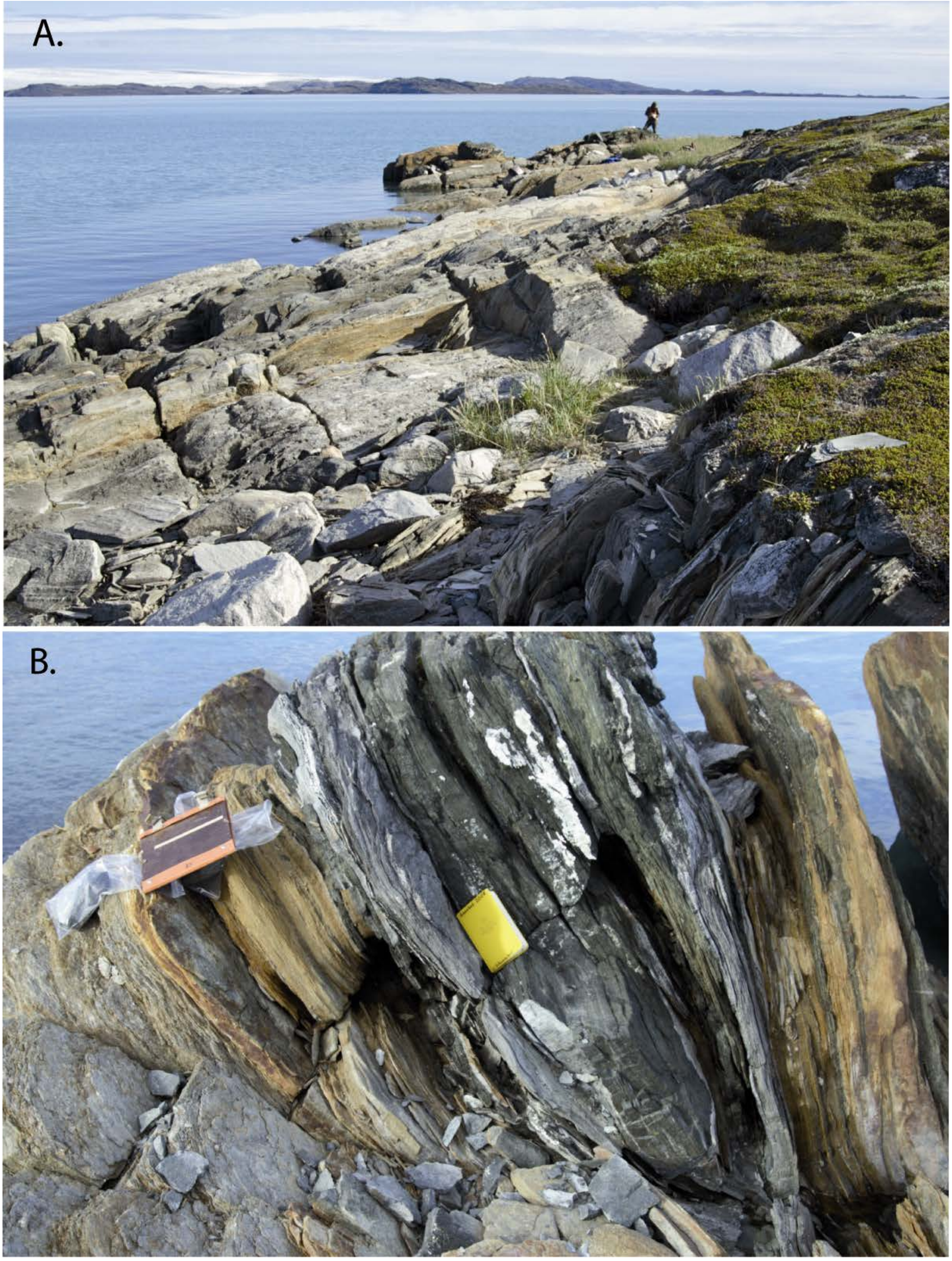

Fig. 2. Outcrop photographs from locality C in Fig. 3 (08JCS054: 63.74180°N, 51.06840°W). A. Outcrop consists of layered orthoamphibole + plagioclase + quartz ± garnet ± staurolite gneisses that are layered on about a meter scale. B. A 0.7-meter wide band of amphibolite within the aluminous gneisses.

Metamorphic facies

Limits on metamorphic conditions

All the field studies of southern West Greenland and South-West Greenland have shown that the metamorphic grade varies from amphibolite to granulite facies in most of the Archaean. In most of the areas visited in connection with this project, the transitions between the amphibolite-facies and granulite-facies rocks appear gradational (see also McGregor & Friend, 1992). The metamorphism of the area south of Frederikshåb Isblink is more homogeneous. In the amphibolites, both garnet and clinopyroxene are much rarer and epidote is more likely to be found as an additional phase. These observations suggest that middle to upper amphibolite-facies conditions prevailed in south of Frederikshåb Isblink.

The mafic supracrustals of the Tartoq Group in the southernmost part of the area show metamorphic grades ranging from lower greenschist facies conditions to granulite conditions (van Hinsberg et al. 2010). However, these rocks represent fragments of dismembered oceanic crust that were infolded into the TTG dominated Greenland craton (Kisters et al. 2011), and their metamorphic grades are therefore unrelated the regional metamorphism discussed here.

Figure 3 and the new geologic map show our current best estimate of the extent of granulite-facies and amphibolite-facies assemblages. Most petrologists place the amphibolite-granulite facies boundary at about 700°C. Nevertheless, identifying a mineral assemblage that is diagnostic of the granulite facies in the field is not completely straightforward. In lower pressure rocks the granulite facies are the conditions at which hornblende in rocks with basaltic bulk composition breaks down to orthopyroxene + clinopyroxene + plagioclase. At higher pressures in granulite-facies these same rock compositions would contain clinopyroxene + garnet + plagioclase +quartz ± hornblende, because orthopyroxene + plagioclase => clinopyroxene + garnet. However, it is important to note that amphibolites with clinopyroxene + garnet are stable within the amphibolite facies and are not alone distinctive of the granulite facies. An additional complication is that low-Ca amphibolites may be cummingtonite- or orthoamphibole-bearing. In these rocks, cummingtonite/orthoamphibole would breakdown to orthopyroxene at temperatures below the generally accepted amphibolite-granulite facies boundary (Hollocher, 1991).

The area around Fiskenæsset (Fig. 3 and metamorphic map) provides the best examples of preserved granulite-facies assemblages. Here, mafic rock units (e.g., 08JCS09: 63.13746°N, 50.83992°W) enclosed within the gneiss have the same appearance in the field as amphibolite units (e.g., 08JCS027: 63.92857°N, 51.26101°W) common throughout the region. At Fiskenæsset, hand specimens of mafic rock units have two pyroxenes, hornblende, and plagioclase and the typical granular appearance of rocks from the granulite facies.

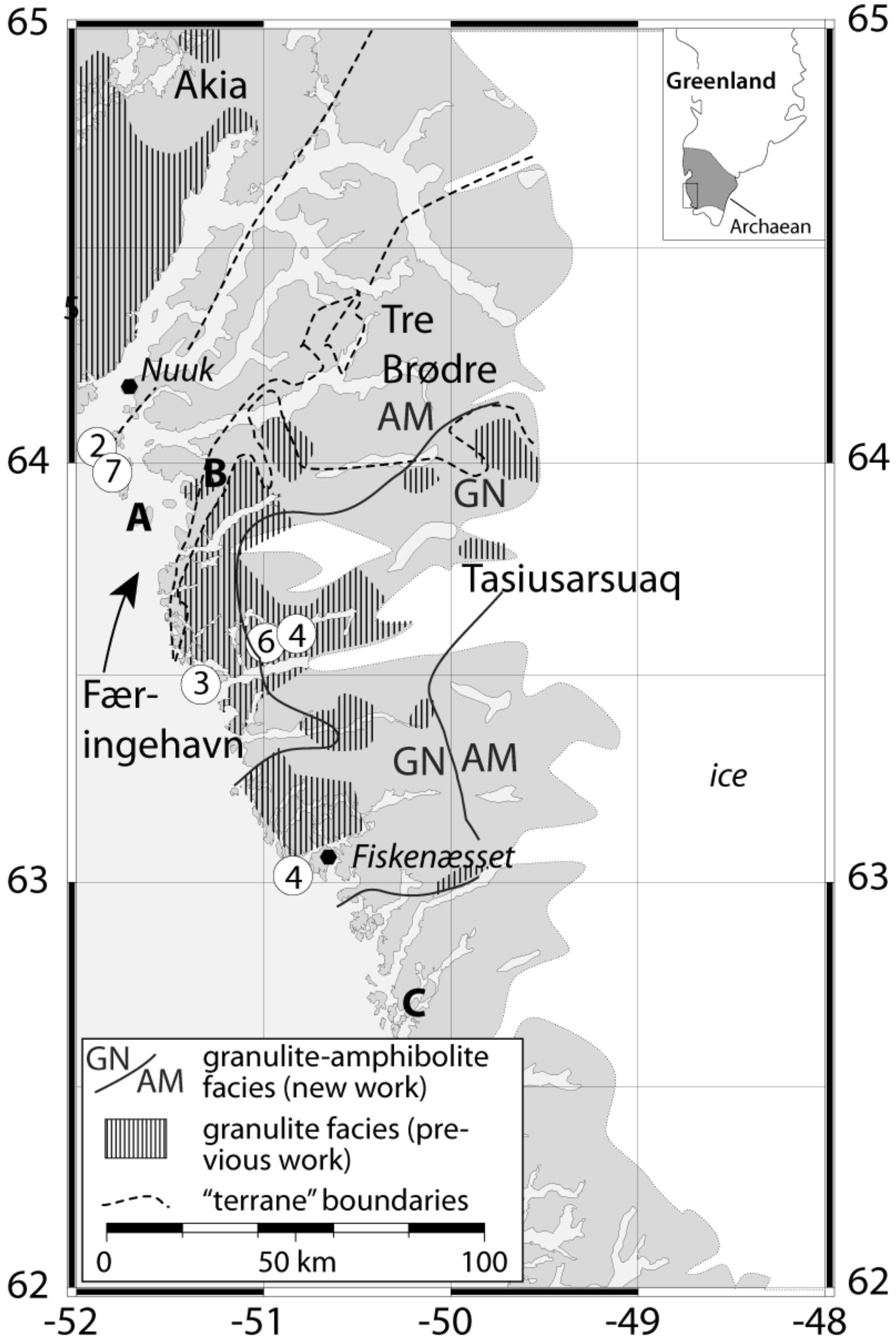

Fig. 3. Map of southern West Greenland showing extent of exposed bedrock and two proposed terrain boundaries. Granulite-facies areas from previous fieldwork (after and simplified from Riciputi et al. 1990; Friend et al. 1988, 1997) and granulite facies boundaries based work from 2007-2010. Numbers enclosed in circles = localities of P-T estimates: (2) Dymek 1984; (3) Griffin et al., 1980; (4) Riciputi et al. 1990; (6,7) Wells 1976, 1979. A, B, C = location of P-T estimates and P-T trajectories (A= 07JCS046: 63.85775°N, 51.64847°W; B= 07JCS046: 63.97535°N, 51.30010°W; C= 08JCS054: 63.74180°N, 51.06840°W).

Criteria for placement of the facies boundaries

The facies boundaries on the geologic map and in Figure 3 indicate the approximate extent of granulite-facies rocks based primarily on the appearance of orthopyroxene and clinopyroxene in fine- to medium-grained mafic rocks. Locality descriptions of all team members were reviewed for references to metamorphic orthopyroxene, the mineralogy of the amphibolites, and the metamorphic facies classification. If the described mineralogy and assigned metamorphic facies agreed for localities taken in the same area, then metamorphic facies was designated. It should be noted that the work of various team members was concentrated on rock types that were not necessarily optimal for estimating metamorphic facies, so many localities could not be used to constrain facies boundaries.

Other textural criteria were also sought in estimating the metamorphic grade. The felsic gneisses within the granulite-facies zone near Fiskenæsset also contain orthopyroxene from the breakdown of Fe-rich biotite (biotite => K-feldspar + orthopyroxene + water), and the felsic gneisses (*e.g.*, 08JCS093: 63.13907 N, 50.87035 W) that are associated with amphibolite localities were checked for orthopyroxene and textures in the gneisses that could represent the retrograde hydration of orthopyroxene. Amphibolites were also checked to see whether they displayed (1) the typical L to L-S fabric associated with amphibolites or (2) a fabric suggestive of hydration of a two-pyroxene mafic granulite.

McGregor & Friend (1997) have interpreted knots of hornblende as fully retrogressed orthopyroxene. This field criterion has been extended by other researchers to identify retrogressed granulite-facies areas in the region. While the interpretation may be correct in places, fieldwork from 2007-2010 suggests that much of the retrogressed granulite-facies terrain might have never realized metamorphic conditions above the amphibolite facies. At least in places, knots of hornblende could be just as validly be interpreted as (1) primary or (2) replacement of clinopyroxene in rocks with originally gabbroic textures.

Another argument against pervasive retrograde hydration of large areas of rocks of any facies by a subsequent lower temperature event is that the process seems to have been too successful. Generally, rehydrating rocks is more difficult than dehydrating the same rocks—this is the reason metamorphic rocks are preserved at the Earth's surface. During prograde metamorphism, coarsening of mineral grains will slightly decrease the total volume of space available at grain boundaries where fluid resides. Water liberated during prograde dehydration reactions is driven out along these grain boundaries. Pervasive retrograde hydration faces several obstacles: (1) the lack of a driving force capable of causing water to reinfiltrate, (2) a reservoir of enough fluid to accomplish the complete rehydration, (3) volume increase that accompanies the initial rehydration that would tend to block further ingress of fluid, and (4) cooling along a retrograde P-T path causes reaction kinetics to slow at exponential rates, which would further reduce the efficiency of rehydration reactions and the likelihood that they would achieve nearly 100% success rates. Therefore, a terrain undergoing large-scale rehydration would be expected to preserve many examples of incomplete or partial hydration in the area of the transition from complete hydration to pristine granulite facies, but such textural evidence is absent at the localities visited from 2007-2010.

The metamorphic significance of staurolite and Fe-Mg amphiboles

Aluminous gneisses, which are among the rock types mapped as metasediments, are scattered through the Archaean of southern West Greenland. Some of the rocks contain staurolite (07JCS055: 63.85775°N, 51.64847°W) or staurolite + quartz (07JCS046: 63.97535°N, 51.30010°W; 08JCS054: 63.74180°N, 51.06840°W). Staurolite breaks down on its own composition at temperatures below the granulite facies, so its presence at these localities supports the metamorphic conditions at these localities and did not exceed amphibolite-facies conditions.

Fe-Mg amphiboles (cummingtonite and orthoamphibole) are found in both amphibolites (some basaltic and basaltic andesite protoliths) and aluminous gneisses commonly mapped as metasediments/mica schists. Hollocher (1991) has suggested that cummingtonite will breakdown to orthopyroxene in low-Ca and Fe-richer mafic rocks over the temperature interval of about 640-690°C, which is in the uppermost amphibolite facies. Orthoamphibole replaces cummingtonite as the stable Fe-Mg amphibole in low-Ca mafic rocks that have higher Mg ratios. Orthoamphibole + plagioclase breaks down to hornblende + orthopyroxene in these rocks over a narrow temperature interval from about 680-710°C, right at the granulite-facies boundary. So, stable cummingtonite or orthoamphibole coexisting with hornblende in amphibolites is strong evidence of pervasive amphibolite-facies conditions.

Besides the restriction of orthoamphibole to the amphibolite facies, these amphiboles can be used to demonstrate other limits on P-T conditions. At temperatures below 600°C (Spear 1980; Schumacher, 2007), a solvus exists within the solid solution of low Na-Al to higher Na-Al orthorhombic amphibole. Metamorphic assemblages with two coexisting orthoamphiboles, anthophyllite (low Na + Al) and gedrite (higher Na + Al) are well known (*e.g.*, Spear 1980). Above the crest of the solvus, complete solid solution occurs. Upon slow to moderate cooling below 600°C, homogeneous supersolvus orthoamphibole can exsolve submicroscopic and optically visible lamellae of gedrite or anthophyllite. The submicroscopic exsolution is the cause of iridescence in orthoamphibole. Iridescent orthoamphibole was found at numerous localities (*e.g.*, 07JCS055: 63.85775°N, 51.64847°W; 07JCS046: 63.97535°N, 51.30010°W; 08JCS079: 62.123°N, 49.825°W; 09JCS017: 62.951°N, 49.763°W). These iridescent orthoamphibole are locally known as “nuumite” and collected and sold as a semiprecious gemstone. Petrologically, iridescent orthoamphibole suggests that the rocks equilibrated above 600°C, although knowing the actual minimum temperature requires determining the tetrahedral Al content of the orthoamphibole.

In aluminous gneisses, the stability of orthoamphibole + aluminosilicate can place limits on the pressure of metamorphism. Orthoamphibole + sillimanite/kyanite are not stable below 5-6 kbar (Spear, 1993) and the breakdown of these two minerals always produces spectacular reaction textures that include cordierite (Fig. 4). If the newly grown cordierite is coarse grained, these textures would be interpreted to represent uplift occurring at or near the peak metamorphic temperature.

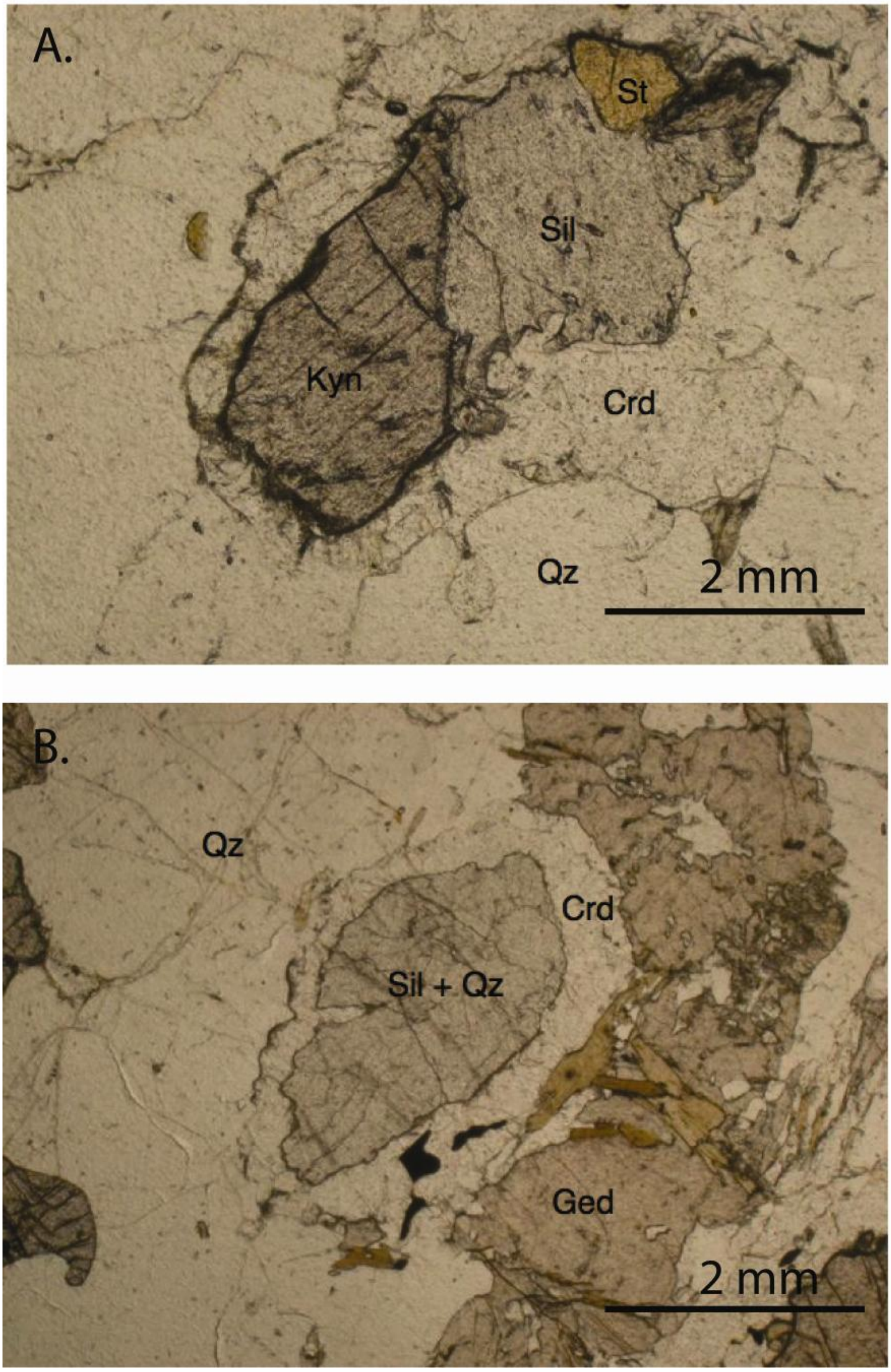

Fig. 4. Photomicrographs of reaction textures in aluminous gneisses (metasediments). A. Shows kyanite (Kyn) being replaced by sillimanite (Sil), which followed by the reaction of gedrite (Ged) (out of the picture) + aluminosilicate + quartz (Qz) forming cordierite (Crd) reaction rims on aluminosilicate. St = staurolite. B. Shows the complete reaction: Ged + Sil + Qz = Crd. Locality is 07JCS046: 63.97535°N, 51.30010°W.

P-T estimates in mafic rocks and aluminous gneisses (metasediments/ mica schist and gneiss)

Previous work

A handful of metamorphic studies (Figs. 3 and 5) that included P-T estimates have been published (Wells 1976, 1979; Griffin *et al.* 1980; Dymek 1984; Riciputi *et al.* 1990). The most recently published P-T estimates appeared in 1990. None of this work addresses regional distribution of either P-T trajectories or peak-metamorphic conditions. Within the project area, the published P-T estimates are broadly concentrated in the area from Buksefjorden to Fiskenæsset (Fig. 2).

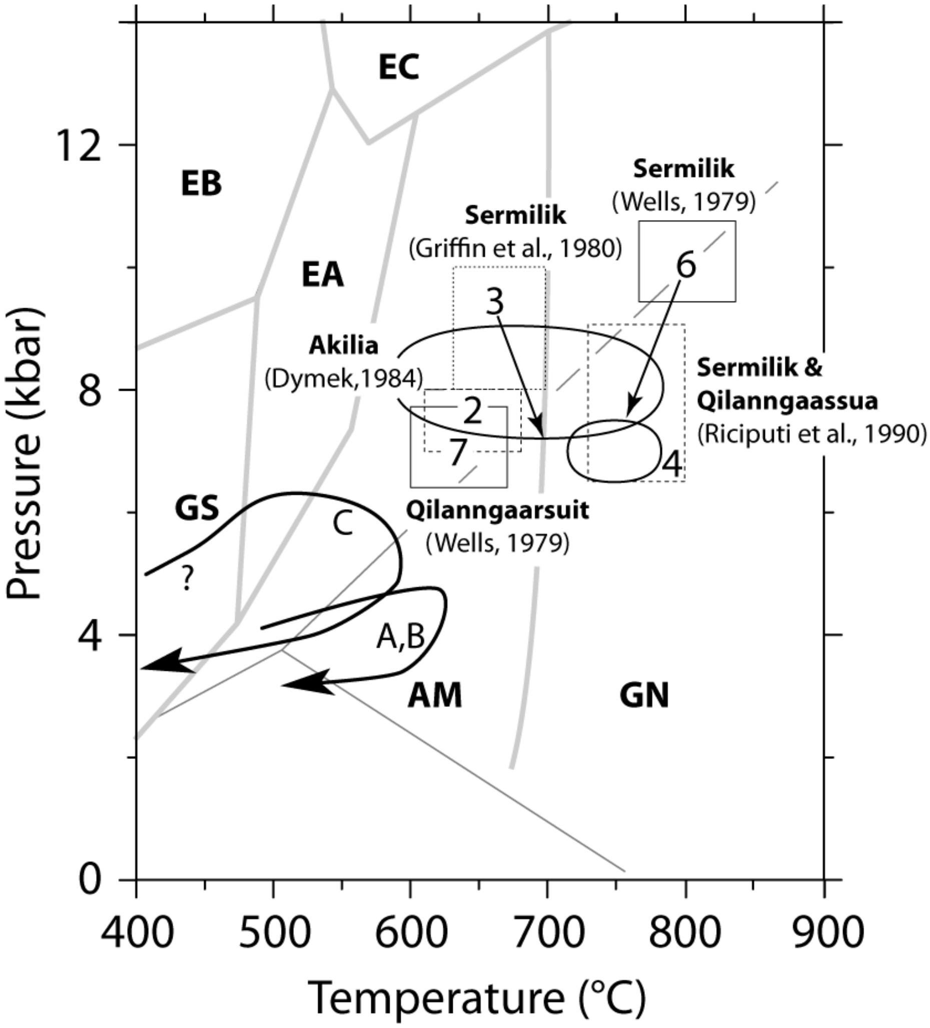

Fig. 5. Boxes show estimated peak metamorphic conditions at locations shown on Fig. 2. Ellipses and arrows show re-evaluated P-T estimates using more recent geothermo-barometric calibrations for data used for locations 3 and 6. A,B,C = P-T trajectories and estimated peak metamorphic conditions (see Fig. 3 for locations). AM= amphibolite facies; EA=epidote-amphibolite facies; EC= eclogite facies; GN=granulite facies; GS=greenschist facies.

P-T estimates in mafic rocks

Figure 2 summarizes the range of existing P-T determinations. All these estimates have large ranges for upper and lower limits (Fig. 5). The uppermost limit for any of these temperature estimates are slightly above 800°C, while the uppermost pressure is over 10 kbar. Some of the data given in the published P-T estimates could be recalculated using new calibrations of the same equilibria (Ekert *et al.*, 1991) or using methods developed after the original work was published *(e.g.*, Kohn & Spear, 1989, 1990). The most significant change is that the highest reported P (6, Fig. 5) is 2-3 kbar lower and nearly 100°C cooler than the original estimate.

Recent advances in the application and expansion of thermodynamic data allow the use of whole-rock geochemistry of the major elements to produce isochemical P-T diagrams (pseudosections) for individual metamorphic rocks. These diagrams show all the potential mineral assemblages a rock would develop over a range of P-T, and allows the matching of the observed mineral assemblage to a subrange of P-T. If multiple whole-rock analyses are available from rocks in the same area, several isochemical P-T diagrams can be overlain to further restrict the subrange of possible P-T. Figure 6 shows two estimates of P-T from data provided by Kalsbeek and Leake (1970). P-T estimates were done for rocks from between Neria and Qasigialik fjords and at the end and north side of Sermiligaarsuk fjord (Kalsbeek & Leake, 1970). Both areas suggest amphibolite facies conditions. The range of possible pressures and temperatures from this method is wide, but the locality from Neria and Qasigialik fjords suggest a median set of conditions of about 650°C and 5 kbar (Fig. 6A). The locality from Sermiligaarsuk fjord gives a median set of conditions of 600°C and 4 kbar.

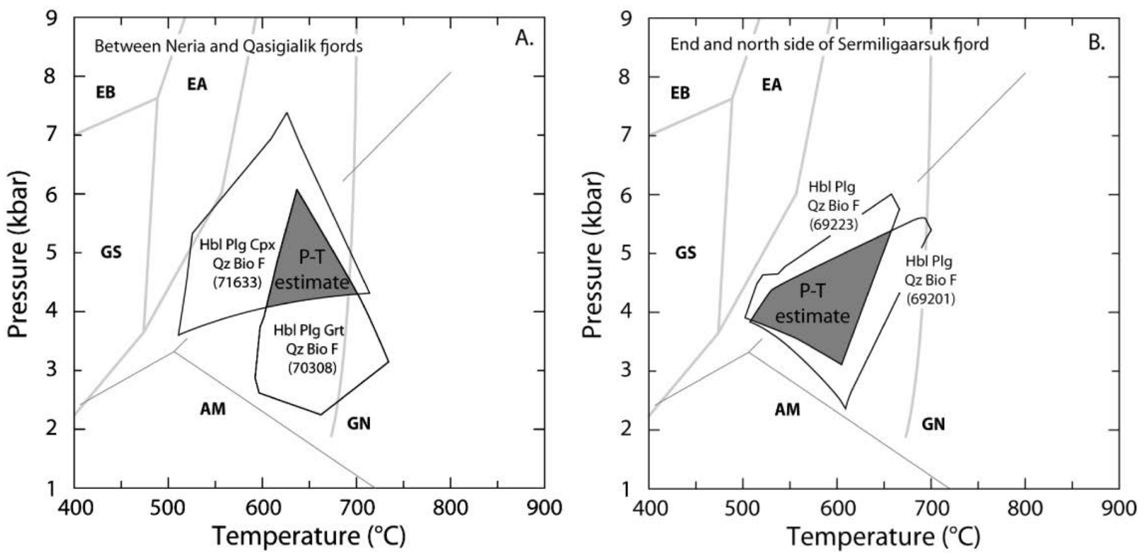

Fig. 6. P-T estimates using isochemical P-T sections and mineral assemblages found in these rocks. A. Between Neria and Qasigialik fjords. B. At the end and north side of Sermiligaarsuk fjord. Data from Kalsbeek & Leake (1970). Hbl=hornblende; Plg=plagioclase; Qz=quartz; Bio=biotite; Cpx=clinopyroxene; Grt=garnet; F=fluid. Facies boundaries (heavier gray lines): AM = amphibolite; EA=epidote-amphibolite; GN = granulite; GS = greenschist. Numbers in parentheses are GEUS sample numbers. Lighter gray lines: aluminosilicate tability fields.

P-T trajectories

The only P-T trajectory work we are aware of was done as honors projects by Charlotte Stamper and Gemma Sherwood in 2010 at the University of Bristol, UK. This work involved study of three aluminous gneiss localities of the kind that is usually mapped as metasediment/mica schist and gneiss. Two localities in the northern part of the study area (Qilangaarsuit island and east of Qarajat Iluat fjord; A, B respectively on Figs. 2 & 3) and one farther to the south (Ikkattup Nunaa; C on Figs. 2 & 3) both give amphibolite facies conditions, but suggest different peak metamorphic conditions and uplift histories. Work on all the localities involved P-T estimates using mineral compositions and equilibria calculated with Perplex (Connolly 2005) and conventional geothermobarometry. All three of these localities studied for P-T trajectories contain staurolite, which places their maximum P-T conditions within the amphibolite facies. The localities A and B (Fig. 3) suggest maximum temperatures of 600-650°C at about 4-5 kbar based on the temperature ranges of observed assemblages.

These P-T estimates are consistent with minimum temperatures suggested by the orthoamphiboles. The orthoamphiboles from these rocks span the range of compositions from anthophyllite to gedrite, which suggests the orthoamphiboles crystallize above the peak of the orthorhombic-amphibole solvus (about 600°C). The presence of amphibolites suggests upper amphibolite-facies conditions and temperatures below about 700°C. Reaction sequences (*e.g.*, Fig. 5) suggest a roughly clockwise P-T trajectory for rocks from both localities A and B on Figure 3. The locality C (Fig. 3) gives lower peak temperature. The P-T estimates suggest maximum T of about 480-580°C at P below 6-5 kbar. The Al contents in the orthoamphibole from a number or rocks suggest that temperatures were below the 600°C crest of the orthoamphibole solvus. Textures involving the reaction of staurolite and garnet in several rocks were used to estimate the trajectory, and P-T estimates from an interlayered hornblende gneiss with the assemblage hornblende + garnet + plagioclase + quartz were used to estimate P and T (Kohn & Spear, 1990).

Metamorphism of Ultramafic Rocks

Occurrence

Ultramafic bodies can range from the meter (08JCS024: 63.93988°N, 51.20239°W) to hundreds of meters scale (10JCS054: 61.84149°N, 49.21862°W) and may be partially to completely hydrated. Smaller ultramafic bodies are more likely to be completed hydrated and consist of only metamorphic minerals, while larger bodies are more likely to be partially hydrated and contain relict primary minerals (olivine + orthopyroxene ± clinopyroxene ±spinel). However, at locality 08JCS019 (63.93222°N, 51.21995°W) a 30 x 15 meter ultramafic body contains primary plagioclase. This is the only locality encountered that contains a confirmed high-temperature retrograde metamorphic reaction. Orthopyroxene forms rims around or replaces primary olivine and clinopyroxene forms rims between primary plagioclase and orthopyroxene. This diffusion-controlled reaction texture forms via the reaction: olivine + plagioclase = orthopyroxene + clinopyroxene + spinel. The presence of plagioclase in an ultramafic rock limits the upper pressure to about 7.5-8.5 kbar at 900-1100°C; the metamorphic reaction probably occurred as the ultramafic rock cooled through the granulite facies to at least amphibolite-facies conditions (Keulen et al., 2009).

There are several potential protoliths for the ultramafic rocks: komatiite, ultramafic cumulate, or mantle ultramafic rock. None of the ultramafic localities visited from 2007-2010 preserve the typical dendritic olivine quench texture, but many have features that could be interpreted as magmatic layering, which would be more consistent with either mantle or cumulate origin. However, the abundant smaller and totally hydrated and recrystallized ultramafic bodies could have any protolith. In fact, a komatiite protolith could fit since these rocks should be the most easily hydrated of any of the suggested protoliths.

Ultramafic rocks are chemically simple systems compared to most of the other rocks in southern West Greenland. Chemically, these rocks are principally SiO_2 and MgO with lesser FeO, minor Al_2O_3, and variable CaO. Most of the smaller ultramafic bodies are completely hydrated with none of the primary minerals remaining. These hydrated rocks commonly contain anthophyllite + talc ± actinolite ± chlorite, and they may be completely homogeneous or show the effects metasomatism, *i.e.*, zoned layers of monomineralic or dimineralic assemblages (Fig. 7). In particular, silica, magnesium, and calcium are mobile during metasomatism. The mineral assemblages that develop during the hydration and/or metasomatism that affects the ultramafic rocks can give rough estimates of the P-T conditions while the mineral assemblages formed. Figure 8 shows two temperature versus log activity of quartz diagrams. These diagrams were constructed from Ca-free and Ca-bearing ultramafic rock compositions.

Fig. 7. Cross-section of a completely metasomatised ultramafic inclusion. The green areas contain actinolite; the pale brown areas are dominantly anthophyllite; the grey areas are mainly talc. Locality 10JCS034: 62.333°N, 49.177°W.

P-T estimates

There is no single diagnostic metamorphic mineral that signals the transition from the amphibolite to granulite facies, but the stable mineral assemblages in the ultramafic rocks provide a rough guide to metamorphic conditions. Depending on silica activity, talc will be restricted to the amphibolite facies in most metamorphosed ultramafic rocks. All amphiboles will begin to breakdown at 700±100°C around the granulite-amphibolite facies transition. Higher in the granulite-facies amphibole would disappear and the metamorphic assemblages in ultramafic rocks would contain metamorphic orthopyroxene, olivine + clinopyroxene, olivine + spinel, or olivine + sapphirine (Fig. 8).

During the course of this project none of the ultramafic rocks visited contained metamorphic orthopyroxene, clinopyroxene or olivine suggesting that if these rocks attained granulite-facies conditions, they probably were under 800°C.

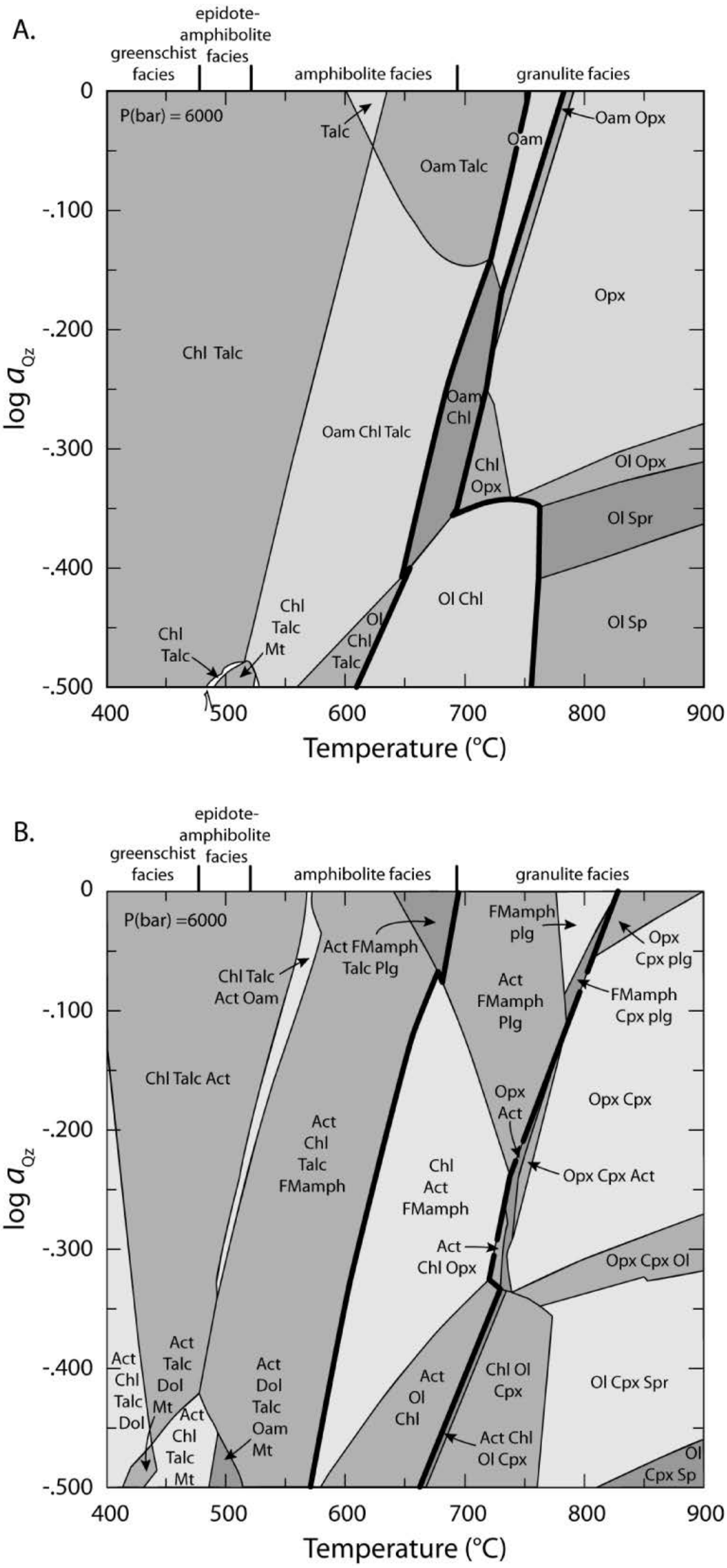

Fig. 8. Temperature versus log activity of quartz diagrams for two ultramafic rock compositions at 6000 bar. A. GGU sample 117981 (Rosing and Rose, 1993). B. GEUS sample GGU 468764 ASCH from Szilas (2009, pers. com.). Act=actinolite, Amph=calcic amphibole solid solution, Chl=chlorite, Cpx=clinopyroxene, Mt= magnetite, Oam=orthoamphibole, Ol=olivine, Opx=orthopyroxene, plg= plagioclase, Sp=spinel.

Metasomatic and advective interaction of ultramafic rocks and pegmatites and the origin of aluminous assemblages

Scattered across the Archaean amphibolite- to granulite-facies areas of southern West Greenland are places where pegmatites form metasomatic reaction zones with ultramafic bodies enclosed in anorthositic, gabbroic, or quartzo-feldspathic gneisses. These pegmatites postdate peak amphibolite- to granulite-facies metamorphism. The products of the interaction of ultramafic rocks and the pegmatites vary across southern West Greenland. At most localities, the principal products are calcic amphibole and coarse biotite, which may be accompanied by small-scale sulfide mineralization. However, in the Fiskenæsset complex region, the reactions produces metasomatism/advective transport among pegmatites, ultramafic rocks, and enclosing gneisses/anorthosites resulted in spectacular reaction zones with coarse grained anthophyllite, sapphirine, cordierite, and kornerupine, as well as, ruby corundum + Cr-bearing calcic amphibole assemblages at many localities. The type of assemblage that develops will depend on the rock types and proportions of rock types forming the reactive system, as well as, the amount and composition of the fluid associated with the pegmatite.

The ultramafic bodies vary in their primary assemblage olivine ± clinopyroxene ± orthopyroxene and the extent of hydration. At most localities, the reaction zones consist of coarse biotite + calcic amphibole ± serpentine ± talc ± anthophyllite. Samples from a more typical locality were studied in detail by Anna Probst as an honours project at Bristol in 2009. This work concentrated on an ultramafic body that measured about 30 x 70 m and was cut by granitic pegmatites (07JCS045: 63.99438°N, 51.37995°W). In this reaction zone, modal clinopyroxene and calcic amphibole vary antithetically. This demonstrates that existing Ca-phases are consumed during the reactions. Further, evidence of the role of the pegmatites is seen in the newly formed calcic amphibole, biotite and apatite. These phases are enriched in pegmatite-derived F and Cl. Molybdenite was also found at this locality in the biotite-rich metasomatic zones adjacent the crosscutting pegmatites. Both the enrichment of F and Cl in the hydrous phases and the formation of molybdenite suggest that, at this locality, the fluid-rock reactive system was closed or at least closed in places. Growth of the hydrous minerals would deplete the pegmatite-derived fluid in its principal component H_2O and, consequently, drive up the concentration of the remaining more volatile and less compatible components, like F, Cl, Mo, and S. As a result, the F and Cl were enriched in the (OH)-bearing silicates that were in contact with this fluid and in places the fluid reached saturation of MoS. Work done at this locality suggests these metasomatic reactions occurred after the peak amphibolite facies temperatures below about 550°C.

In the Fiskenæsset region, the petrography of sapphirine-, kornerupine- and corundum-bearing rocks was well known, but the genesis of these aluminous assemblages is not completely understood. Based on observations made in the summer of 2008, we became convinced that these aluminous assemblages result from the interaction of fluid-rich granitic pegmatites with ultramafic bodies and the anothositic or quartzofelspathic rocks that enclose them, but differently than the interaction described immediately above. Like in other parts of southern West Greenland, the scenario appears to be that granitic pegmatites intruded these rocks near, but probably after, the peak metamorphic event. However, the extent of the metasomatism as well as the extremely coarse grain size of many metasomatic minerals suggest that these pegmatites were much richer in fluid than elsewhere in the Archaean terrain. This fluid could facilitate reactions and exchange of material among ultramafic, country and pegmatitic rocks at at least outcrop scale. Evidence of the metasomatism is seen in Figures 9 and 10. Figure 9 shows part of the ultramafic body that has been converted to amphibolite. Phlogopite veins mark the positions of the crosscutting pegmatite veins, and the enrichment in phlogopite is resulting from the concentration of K-feldspar in the veins. Figure 10 shows a pegmatitic vein in which the metasomatic mineral zoning is shown, and large relicts of partially reacted K-feldspar are present at the central parts of the zone. The extent of the metasomatism/advective transport supports the view that the pegmatites were rich in a fluid that drove the reactions and exchange of material. These aluminous zones may extend up to hundreds of meters with material apparently transported beyond outcrop scale.

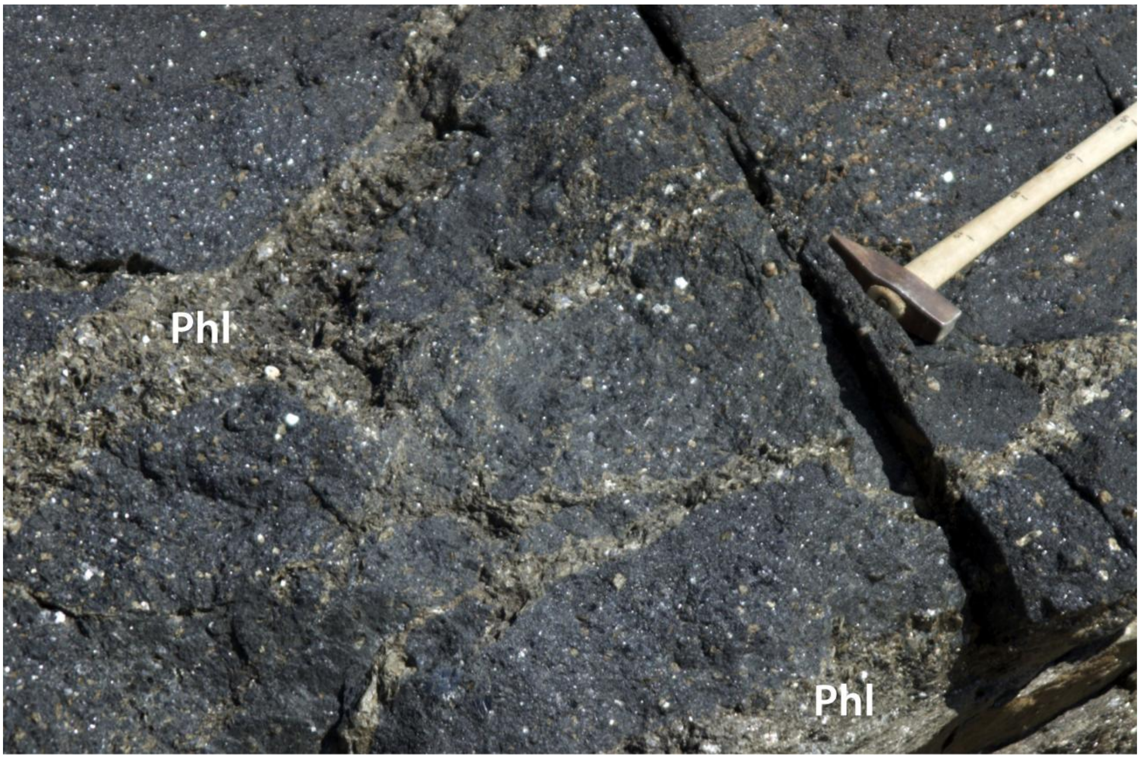

Fig. 9. Ultramafic rock that has been metasomatised by granitic pegmatite fluids. The matrix is phlogopite (Phl)-bearing amphibolite crossed by a network of phlogopite veins that are probably former pegmatite veins. Locality 08JCS081: 63.12623°N, 49.82325°W.

Observations of the metasomatism suggest quartz, plagioclase, and K-feldspar from the pegmatites and the enclosing gneisses are consumed in reactions with the ultramafic bodies. The metasomatic reactions have several basic types:

(1a) forsterite/serpentine + plagioclase => Ca-amphibole + "Al_2O_3" (component in Al-rich minerals) ± albite;
(1b) forsterite/serpentine + plagioclase + diopside => Ca-amphibole ± albite;
(2) forsterite/serpentine + SiO_2(fluid) => anthophyllite;
(3) forsterite/serpentine + K-feldspar => biotite + anthophyllite;
(4) diopside + K-feldspar => biotite + calcic amphibole.
(5) "K-feldspar" (component in the fluid) + anthophyllite => biotite

An essential bulk compositional requirement is that enough olivine/serpentine is available both to convert all the anorthite of component of the plagioclase to hornblende + "Al_2O_3" and to eliminate free quartz from the environment. These twin effects lead to the formation of Al-rich silicates like cordierite, sapphirine, and kornerupine and corundum, which would be incompatible with free quartz, set in assemblages with abundant phlogopite, Ca-amphibole and orthoamphibole.

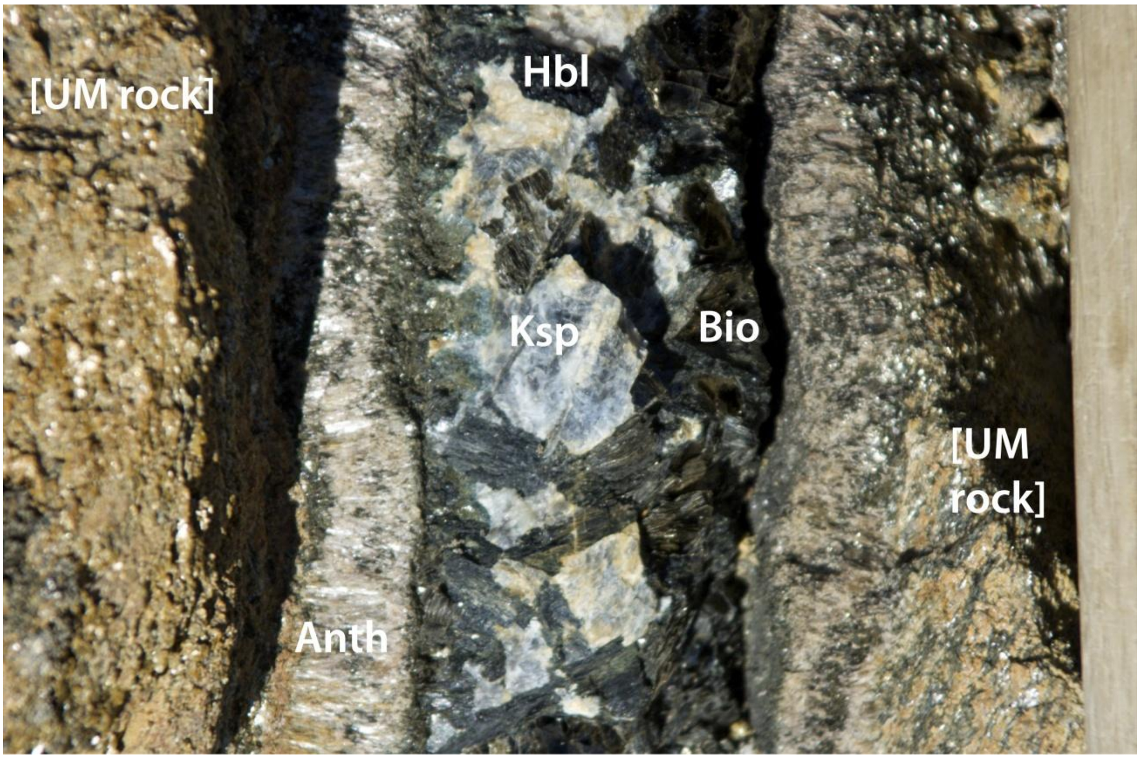

Fig. 10. Granitic pegmatite vein partially converted to biotite (Bio) + hornblende (Hbl) by metasomatic reaction with the ultramafic rock (UM rock). Large K-feldspar (Ksp) crystals are relicts from the pegmatitic vein much of which has been converted to Bio and Hbl. Labels: minerals or rocks that are enclosed with square brackets represent material present at the start of the metasomatic reactions. Anth=anthophyllite. Locality 08JCS081: 63.12623°N, 49.82325°W.

The phase relations in metasomatic systems are challenging to model, but it is possible to demonstrate the ability of some of the proposed reactions to produce the observed textures by using end member compositions of phases. Figure 11 shows the effects of variable K and Si on an ideal ultramafic rock (MgO) and ideal aluminous metasomatic rock ($MgO+Al_2O_3$). This essentially simulates the situation after reactions (1a) and (2) have produced a Si-undersaturated and a K-bearing fluid, and left an Al- and Mg-rich rock that can interact with the remaining fluid. The diagram shows that, as observed, phlogopite will be generated from the ultramafic rock where the fluid has access and corundum + phlogopite, a common assemblage, would only be stable where the ultramafic rock has been completely converted to phlogopite (*i.e.*, corundum + phlogopite field lies entirely within the phlogopite stability of the ultramafic rock, Fig. 11).

The important factors that determine the metasomatic assemblage are reactive or effective Ca/Al and Si-content of the local reaction zone, and metamorphic grade. Generally, reactions (1b) and (4) dominate, but in Fiskenæsset lower Ca/Al, lower free quartz in the associated rocks, and higher temperatures favoured reactions (1a, 2, 3, 5).

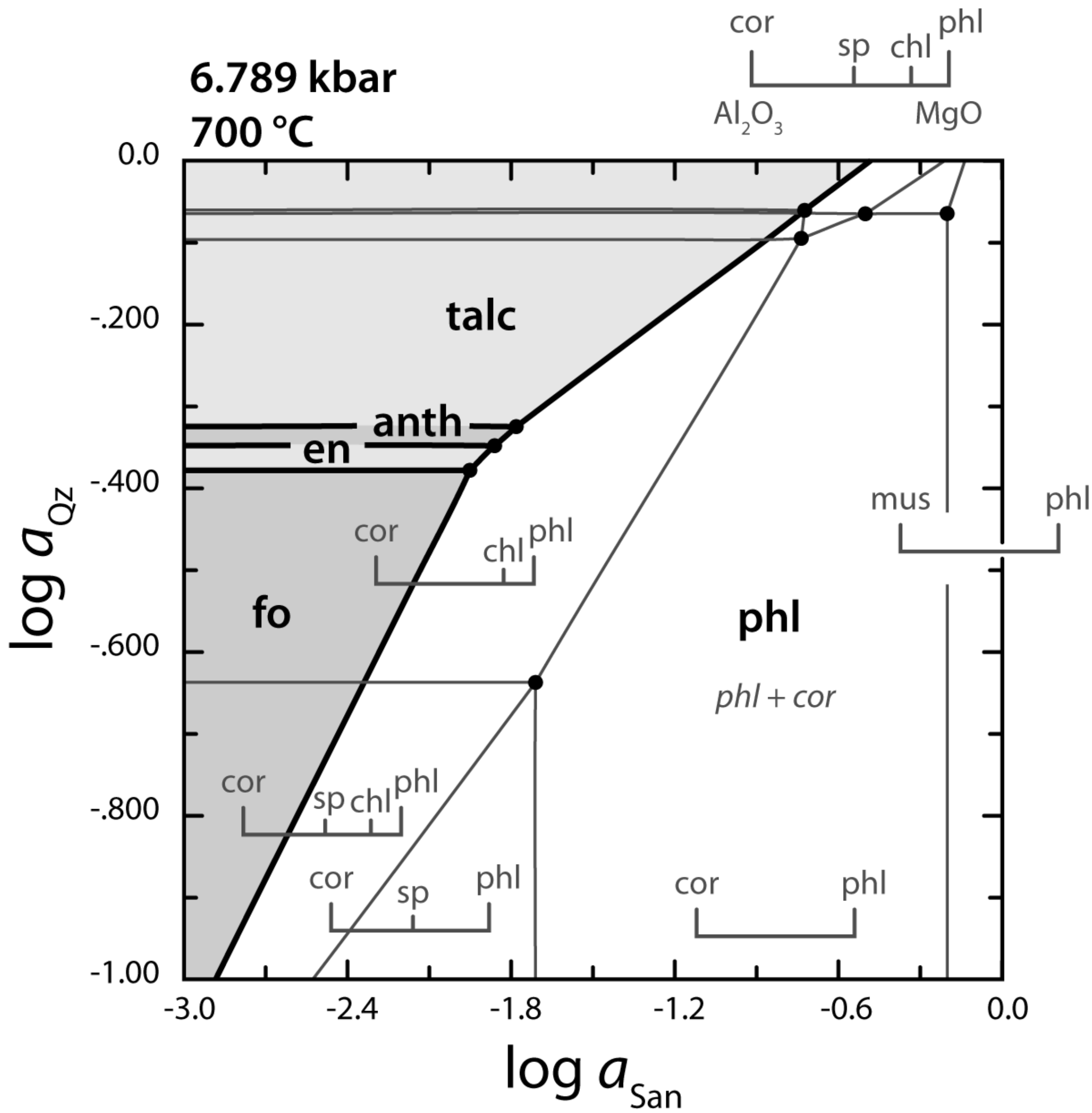

Fig. 11. Log activity quartz - log activity sanidine diagram that illustrates the mineral stability of an ultramafic rock (Mg-Si system, black lines and labels) and mixed composition (Mg-Si-Al system, gray lines and labels), where Si and K are mobile. anth= anthophyllite, cor=corundum, en=enstatite, fo= forsterite, phl=phlogopite. The P and T of the diagram lie on an arc-type geotherm.

The development of ruby corundum

The conditions required to produce the aluminous metasomatic rocks found in Fiskenæsset region do not completely explain the development of ruby corundum. Ruby requires that some Cr be incorporated in the crystal structure. Cr is an element that under most geologic conditions is essentially immobile. However, the extensive occurrence of Cr-bearing calcic amphibole and ruby corundum suggests Cr was mobile. The source of this chrome is likely the chromite from the ultramafic rocks, but trivalent chrome, its valence in chromite, is considered immobile under most conditions, so producing a local environment that could lead to chrome mobility is unusual. Some insight in to the high-temperature behaviour of Cr may be gained from the Eh-pH relations of chrome species at 600°C. This temperature is probably close to the temperatures the metasomatic zones formed, since outcrops nearby contain supersolvus orthoamphibole indicating that the orthoamphibole grew above 600°C. Figure 12 shows that hexavalent Cr, which is highly soluble (and hence mobile) in oxidizing and alkaline solutions. If this is also true at high temperature, then oxidizing and/or high-pH pegmatitic fluids may play a role in the mobilizing Cr at the time of ruby formation. Another possibility is that boron in the fluid could complex with Cr. Boron must have been present, because both kornerupine and tourmaline formed in some of the reaction zones; however, more study of the interaction of minor species in geologic fluids is needed to confirm these possible mechanisms.

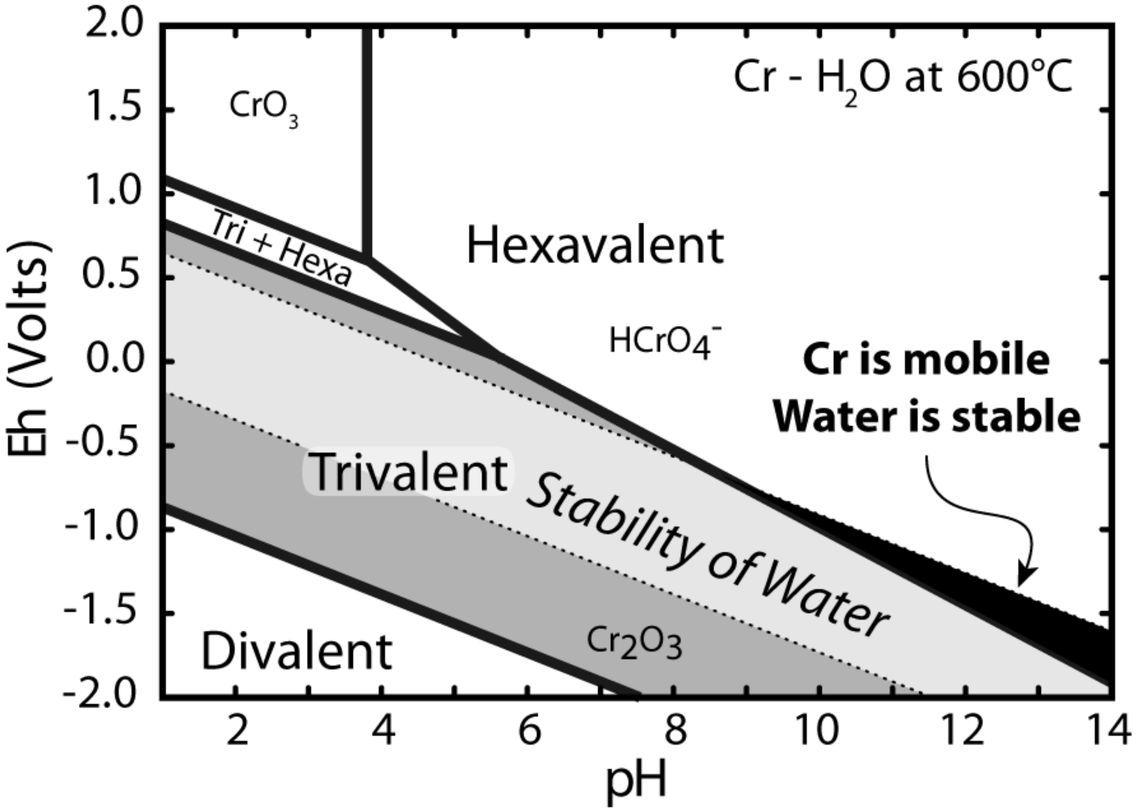

Fig. 12. Eh-pH diagram showing the valance and species of Cr along with the stability of water.

Summary

The granulite-amphibolite facies boundary is defined by the stability of hornblende in amphibolites of roughly basaltic bulk composition. At low pressures, amphibolite within the granulite facies clinopyroxene and orthopyroxene should form the breakdown of hornblende. These hornblende-orthopyroxene-clinopyroxene assemblages are present in mafic rocks in the granulite-facies terrain in the region and around Fiskenæsset. However, in the higher pressure granulite-facies, orthopyroxene is not stable in amphibolite, which makes the conclusive recognition of granulite-facies conditions in the field more difficult. In the higher pressure granulite-facies, amphibolites would contain clinopyroxene + garnet, but clinopyroxene-garnet amphibolite is also stable in the upper amphibolite facies.

In low-Ca amphibolites, cummingtonite or orthoamphibole has been found in various localities. The presence of these Fe-Mg amphiboles with hornblende is a good indicator of amphibolite-facies conditions.

Aluminous gneisses, which are commonly mapped as metasediments/mica schists, are not true pelitic sediments. These rocks are poorer in K_2O than pelitic rocks, and biotite is the only K-bearing phase. This is in contrast to metamorphosed pelites, which always contain either muscovite or K-feldspar + aluminosilicate in addition to biotite. This difference is important because the stability of assemblages like garnet + cordierite + sillimanite in pelitic sediments could indicate granulite-facies conditions; whereas, in low-K aluminous rocks garnet + cordierite + sillimanite is stable in the amphibolite facies. Staurolite is found in some of these aluminous gneisses, and it is a good indicator of metamorphic facies. Primary staurolite or staurolite + quartz is stable only within the amphibolite facies. The presence of cordierite at a few of the studied localities gave some of the best indications of metamorphic P-T path, which appears to be clockwise suggesting uplift began at or near peak metamorphic conditions.

The assemblage in hydrated ultramafic rocks is talc + orthoamphibole ± actinolite, depending on the bulk composition of the protolith. These assemblages are stable in the amphibolite facies. Metamorphic growth of orthopyroxene, olivine, or spinel was not observed in the localities that were visited, but, if found, would indicate conditions well within the granulite facies.

Metasomatic reactions and textures are common where ultramafic rocks interact with pegmatites. These reactions commonly produce biotite and calcic amphibole from K-feldspar, plagioclase, and quartz from the pegmatite reacting with olivine, orthopyroxene, and in the ultramafic rock. However, at sufficient ambient metamorphic conditions, where fluid-rich pegmatites intrude, these reactions can cause the reacting volume of rock to become silica undersaturated and peraluminous, resulting in the growth of anthophyllite, sapphirine, cordierite, and kornerupine, as well as ruby corundum + Cr-bearing calcic amphibole.

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