[AMERICAN JOURNAL OF SCIENCE, VOL. 288, MAY 1988, P. 405-457]

American Journal of Science

MAY 1988

HYDROTHERMAL ALTERATION OF TERTIARY LAYERED GABBROS, EAST GREENLAND

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ABSTRACT. In the early Tertiary, layered gabbro intrusions of central East Greenland represented heat sources for large-scale hydrothermal circulation during the initial stages of the opening of the North Atlantic ocean. Field and petrographic investigation of the Skaergaard and Nordre Aputitêq intrusions, the Kruuse Fjord and Kap Edvard Holm complexes, and the Miki Fjord macrodike suggest that the style and complexity of hydrothermal alteration in each pluton is closely related to its magmatic and structural history during emplacement and cooling. Characteristic assemblages of hydrothermal minerals are found within all the intrusions, but each gabbro is characterized by a unique distribution and abundance of mineralized veins, miarolitic cavities, and metasomatized gabbros. The earliest hydrothermal alteration consists of calcic amphibole ± pyroxene-bearing assemblages concentrated in and near veins that are oriented normal or subparallel to the walls of the intrusions. These vein systems were formed between 600° to 900°C, probably due to cooling and contraction of the intrusion, and were sealed by secondary minerals between ~500° to 600°C. Mass transfer associated with the hydration and oxidation of olivine probably caused reactions that led to fracture sealing. The combination of high temperature and low water/rock mass ratios led to conditions in which compositions of the early hydrothermal minerals were determined within microscopic domains that vary on a grain size scale. Later assemblages characterized by modally abundant calcic amphiboles, epidote, albite, chlorite, or quartz occur in localized areas of the gabbros, formed at temperatures <500° to 600°C, and are associated with more extensive metasomatic alteration. Orientations of the vein sets that host these later alteration assemblages are closely related to the trends of granophyres, pegmatites, or regional dike swarms. Geometric relations of the various vein sets suggest that the permeability in the cooling gabbros changed spatially and temporally as older fracture systems and cavities were sealed by secondary minerals and as new fractures formed.

INTRODUCTION

The emplacement and cooling of gabbroic magmas is an important process of crustal rifting in continental and oceanic environments. Active geothermal systems, such as those found at the East Pacific Rise, in Iceland, and near the Gulf of California, attest to the role played by the circulation of heated aqueous solutions during the cooling of mafic intrusions in these tectonic settings. Similar magma-hydrothermal systems were associated with early Tertiary continental rifting that led to the formation of oceanic crust in the North Atlantic basin. Remnants of this activity occur on both sides of the North Atlantic and include extensive basaltic lavas, mafic dike swarms, and gabbroic, granitic, and syenitic intrusions (fig. 1). The intrusions found in the North Atlantic

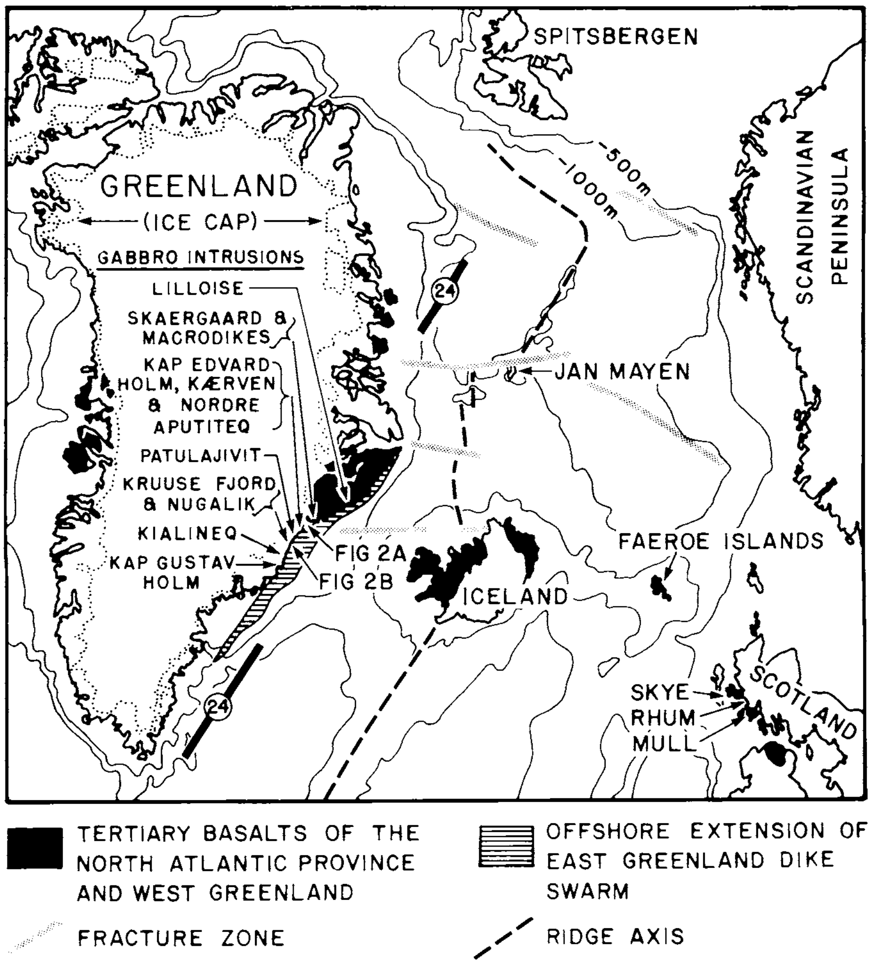


Fig. 1. Generalized map of the North Atlantic region showing distribution of Tertiary basalts, dikes, and gabbro intrusive complexes (modified from Escher and Watt, 1976; Wager, 1934, 1947; Wager and Deer, 1938, 1939; Talwani and Eldholm, 1977; Brooks and Nielsen, 1982a, b; and Larsen, 1978, 1980, 1984). The lines labelled "24" correspond to oceanic magnetic anomaly number 24 reported by Larsen (1978).

Tertiary igneous provinces caused extensive circulation of heated meteoric waters (Forester and Taylor, 1976, 1977; Taylor and Forester, 1979; Norton and Taylor, 1979). These hydrothermal systems facilitated mineralogic and isotopic alteration of the fractured, cooling intrusions and their host rocks (Norton, Taylor, and Bird, 1984; Bird and others, 1985; Ferry, 1985a, b; Bird, Rogers, and Manning, 1986; Manning and Bird, 1986; Ferry, Mutti and Zuccala, 1987).

In this paper we present data on hydrothermal systems in five Tertiary gabbros of East Greenland: the Skaergaard and Nordre Aputitêq intrusions, the Kruuse Fjord and Kap Edvard Holm complexes, and the Miki Fjord macrodike (see figs. 1 and 2 for locations). Alteration mineralogy observed in veins, cavities, and adjacent gabbros are classified based on crosscutting relations among vein sets, and paragenetic relations, textures, modal abundances, and compositions of secondary minerals. Mineral compositions and stabilities are used to infer temperatures of alteration in the individual intrusions. These data provide a basis for discussion of the mineralogic alteration in the gabbros and the extent to which it records the evolution of the hydrothermal systems.

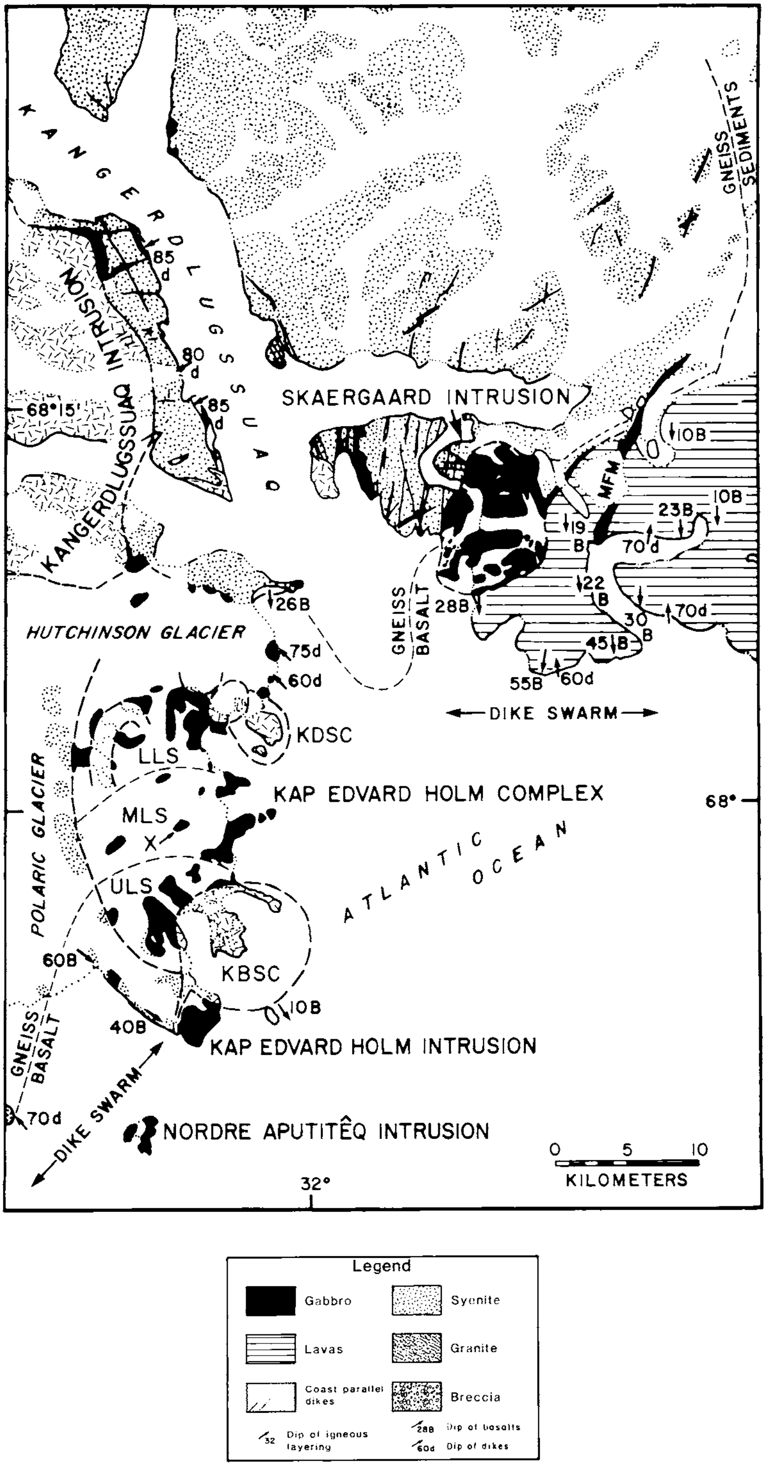
GEOLOGIC BACKGROUND

Regional Setting

Layered gabbros exposed between Kap Gustav Holm and the Kangerdlugssuaq Fjord region were intruded into Precambrian basement gneisses, Upper Cretaceous to Lower Tertiary sedimentary rocks, and overlying Tertiary flood basalts (figs. 1 and 2; see Wager, 1934). The gabbro intrusions of East Greenland are spatially and temporally associated with a regionally extensive, coast-parallel mafic dike complex and a related zone of inland-dipping normal faults that cause the dip of Tertiary strata to increase toward the coast (Wager and Deer, 1938; Wager and Brown, 1967; Nielsen, 1975, 1978; Deer, 1976; Myers, 1980; Brooks and Nielsen, 1982a, b). The dike complex extends ~780 km along the coast (fig. 1; Larsen, 1978, 1980, 1984) and represents the formation of new ocean crust in the region. Gabbroic magmas were intruded within or near this dike complex just after the first dikes were emplaced (Nielsen, 1978; Myers, 1980). The occurrence of dikes crosscutting some of the gabbros indicates that dike emplacement continued after crystallization of the intrusions. Later syenitic, dioritic, and granitic intrusions occur in close proximity to many of the gabbro complexes (Wager, 1934, 1947).

The gabbros and the dike complex were emplaced in the early Tertiary just before the formation of oceanic magnetic anomaly 24 (Nielsen, 1978; Brooks, 1980; Larsen, 1978, 1980, 1984). A 54.6 ± 1.7 Ma fission track age on zircon from the Skaergaard intrusion (Brooks and Gleadow, 1977) is the only absolute age determination on the gabbros studied, but the other gabbros are probably of similar age (Gleadow and Brooks, 1979). The Kap Gustav Holm complex has been

A.


KANGERDLUGSSUAQ
KANGERDLUGSSUAQ INTRUSION
SKAERGAARD INTRUSION
GNEISS SEDIMENTS
MFM
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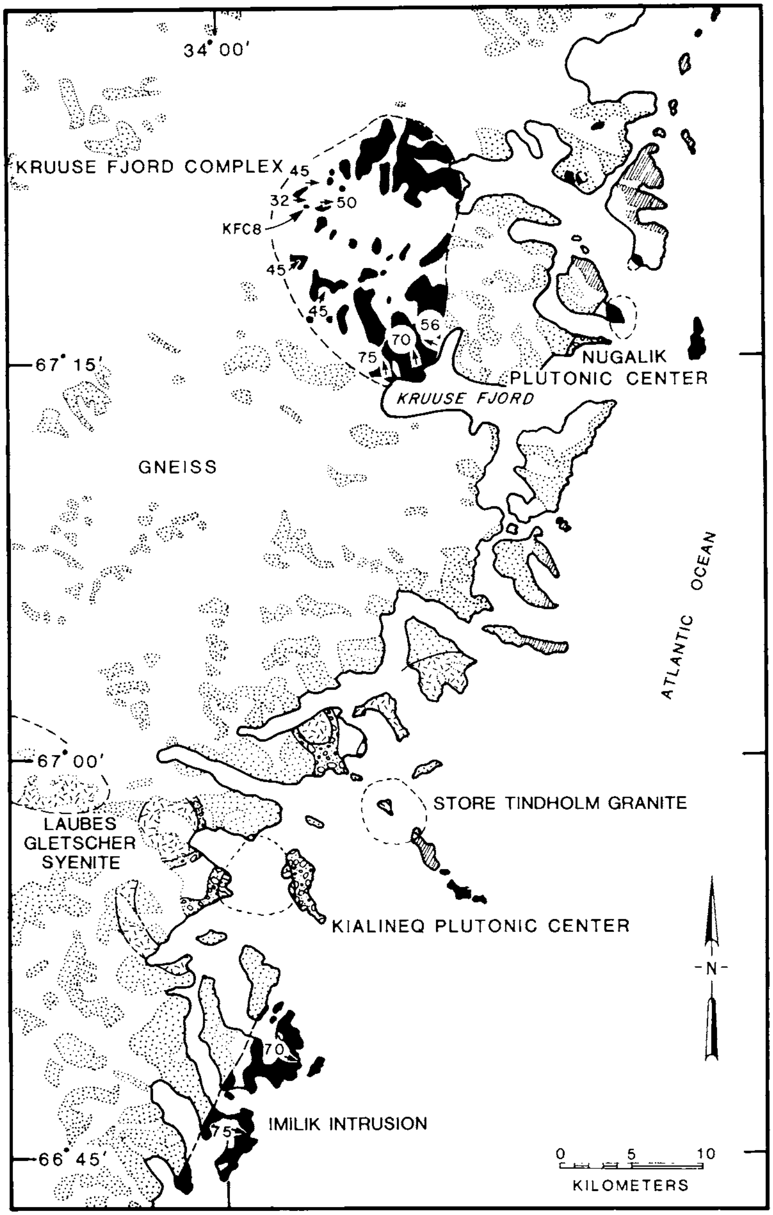
GNEISS BASALT
HUTCHINSON GLACIER
DIKE SWARM
KDSC
LLS
KAP EDVARD HOLM COMPLEX
MLS
ULS
KBSC
68°
ATLANTIC OCEAN
POLARIC GLACIER
KAP EDVARD HOLM INTRUSION
NORDRE APUTITÊQ INTRUSION
32°
0 5 10
KILOMETERS
Legend
Gabbro
Syenite
Lavas
Granite
Coast parallel dikes
Breccia
Dip of igneous layering
Dip of basalts
Dip of dikes



B.

Fig. 2. Geologic map of the Kangerdlugssuaq Fjord (A) and Kruuse Fjord (B) regions (see fig. 1 for locations). Maps show exposures of mafic dikes and gabbroic intrusions (solid black lines and areas, respectively), Tertiary sedimentary rocks and lavas, and the Precambrian basement. In map (A) X is the location of samples KEH 14 and 19, KDSC is the Kap Deichman syenite complex, and KBSC is the Kap Boswell syenite complex. The Kap Edvard Holm complex, which is distinct from the smaller Kap Edvard Holm intrusion to the south (Brooks and Nielsen, 1982b), is divided into three units as shown in map (A): Lower Layered Series (LLS), Middle Layered Series (MLS), and Upper Layered Series (ULS). Maps are compiled from Wager (1934, 1947), Wager and Deer (1938, 1939), Kempe and Deer (1970), Abbott and Deer (1972), Brown and Farmer (1972), Brown and others (1977), Rex and others (1979), Nielsen and others (1981), and Brown and Becker (1986).

dated at ~55 Ma (D. Rex, personal commun. to T. F. D. Nielsen); and granites in the Nûgâlik plutonic complex (fig. 2B) at 55 ± 7 Ma (Rex and others, 1979).

Tertiary Gabbros

Magmatic features of the five East Greenland gabbros are summarized below, with emphasis on the petrologic and structural features that influenced the composition and distribution of secondary minerals in the intrusions. The Skaergaard and Nordre Aputitêq intrusions, Kap Edvard Holm and Kruuse Fjord complexes, and Miki Fjord macrodike all crystallized from magmas similar to those found along spreading axes (Brooks and Nielsen, 1978). All the intrusions exhibit varying degrees of mineralogic layering defined by differences in the modal abundance of oxide, pyroxene, olivine, and plagioclase (fig. 3). Representative bulk rock compositions of the gabbros investigated are plotted in an AFM diagram in figure 4. This figure illustrates that the gabbros have similar compositional trends with varying degrees of iron enrichment, and that there are distinct compositional contrasts between layers with different modal mineral abundance.

Complicated emplacement, crystallization, and subsolidus histories characterize most gabbros in the province (Myers, 1980; Brooks and Nielsen, 1982b; Bird and others, 1985; Rose and Bird, 1987). Inclusions of plagioclase-rich gabbro, metabasalt, metasediment, gneiss, and anorthosite in the Skaergaard intrusion, the Middle Layered Series of the Kap Edvard Holm complex, and portions of the Nordre Aputitêq intrusion and the Miki Fjord macrodike indicate that stoping was an important process during the formation of these magma chambers (figs. 3B and 5; Wager and Deer, 1939; Deer, 1976; Kays, McBirney, and Goles, 1981; Kays and McBirney, 1982; Brooks and Nielsen, 1982b; Bird and others, 1985). Folding and small-scale faulting of the layering in the five intrusions studied here (fig. 6) and at Kap Gustav Holm, Kialineq, Nûgâlik, and Patûlâjivit suggest that synmagmatic deformation was locally important during the geologic histories of the gabbros. Deformation was probably associated with subsidence within the magma chambers and regional stresses related to rifting. In addition, multiple magma injections occurred to varying degrees in all gabbro complexes in the province and include replenishment of gabbroic liquids in magma chambers, as well as subsolidus emplacement of gabbro pegmatites, granophyres, mafic sills and dikes, diorites, and/or granites.

Skaergaard intrusion.—The petrology, chemistry, and structure of the Skaergaard intrusion has been extensively studied since it was recognized by L. R. Wager in 1930. After solidification of the Marginal Border Group gabbros near the walls of the intrusion, the magma crystallized from the bottom upward forming the Layered Series and from the top downward forming the Upper Border Group (fig. 7A). The two crystallization fronts met at the Sandwich Horizon. The well-preserved, highly fractionated sequence of gabbros is exposed over a

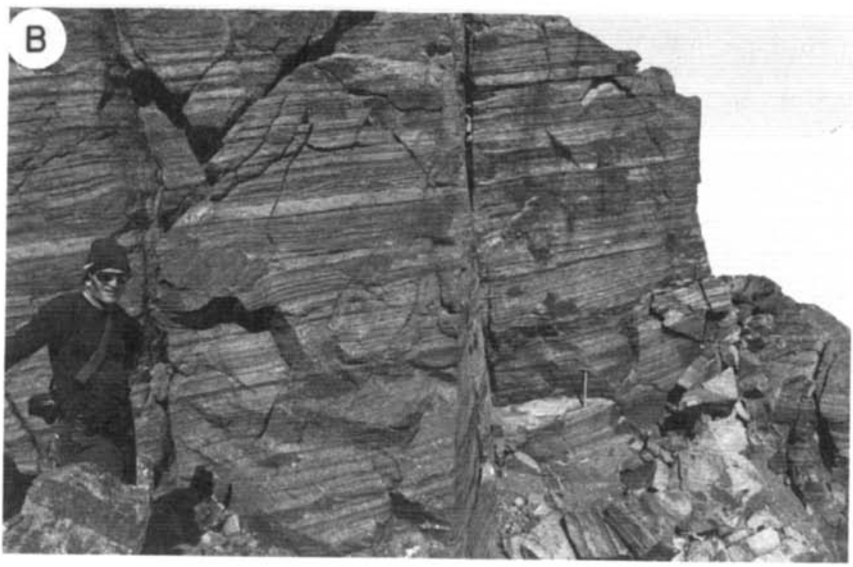


Fig. 3(A) Modal layering in the Lower Layered Series of the Kap Edvard Holm complex showing olivine-rich (dark) and plagioclase-rich (light) gabbros. Width of photo is 1.5 m. (B) Modal layering in the Miki Fjord Macrodike. In both examples the mineralogic layering provides sharp contrasts in the modal proportions of reaction sites, represented by olivine, pyroxene, oxides, and plagioclase, that are transected by near-vertical hydrothermal vein systems.

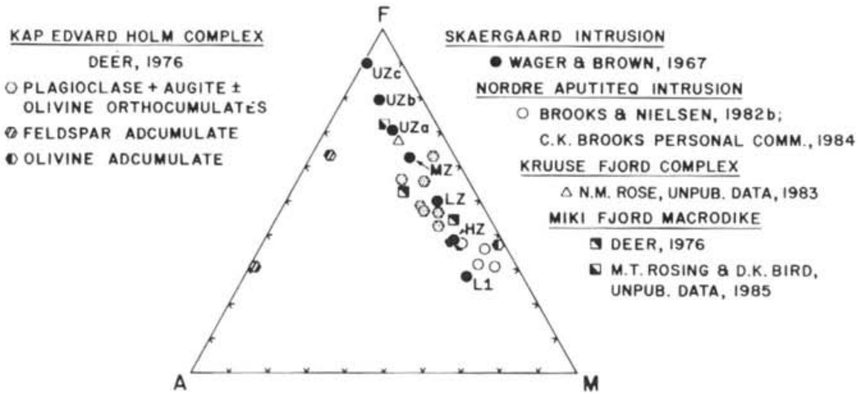


Fig. 4. Bulk compositions of East Greenland gabbros in terms of wt percent Na_2O + K_2O (A), FeO (F), and MgO (M). Symbols represent individual rock analyses except for those from the Skaergaard intrusion, which are the average compositions reported in table 6 of Wager and Brown (1967) for first layered rock (L1), hidden zone (HZ), Lower Zone (LZ), Middle Zone (MZ), and Upper Zone a, b, c (UZa, UZb, UZc).

Fig. 5. Stope block of Upper Border Group gabbro in the Middle Zone of the Skaergaard intrusion. Note deformed layering near block and the pegmatitic reaction zone between the base of the block and the underlying layered gabbro. Here and in other areas of stope blocks in the East Greenland gabbros, these inclusions represent sharp compositional gradients in the wall rocks for the near vertical hydrothermal vein systems.

stratigraphic thickness of ~3.8 km (Wager and Deer, 1939; Wager and Brown, 1967). The uniformity of the differentiation trend and lack of large-scale deformation of layering led Wager and Deer (1939) to conclude that the magma chamber formed by rapid emplacement of tholeiitic magma, with a relatively simple cooling history thereafter. The Basistoppen sheet, a 500 m thick and >4 km long basic sill, was emplaced into the intrusion above the Sandwich Horizon just after solidification of the Skaergaard gabbros (Douglas, 1964; Wager and Brown, 1967; Naslund, 1986). Layering in the Skaergaard intrusion dips to the south due to tilting and minor faulting associated with the monoclinal flexure.

Kap Edvard Holm complex.—The Kap Edvard Holm complex (fig. 2A), located 15 km southwest of the Skaergaard intrusion, is one of the largest gabbro complexes in the East Greenland Tertiary igneous province (Wager, 1934; Wager and Deer, 1939; Abbott and Deer, 1972; Deer 1976). The gabbros of the complex outcrop over ~360 km^2 with a cumulative thickness that exceeds 7 km (Deer and Abbott, 1965; Brooks and Nielsen, 1982b).

The intrusion has been divided into three gabbro units (fig. 7; Elsdon, 1969). The Lower Layered Series is well layered with relatively few inclusions (fig. 3A). The base of the Middle Layered Series is marked by abundant anorthosite, gabbro, and basalt inclusions and a sharp discontinuity in the compositional trends of the cumulate minerals of the Lower Layered Series (fig. 7B). Variations in mafic indices and iron enrichment and differences in the foci of saucer-shaped forms defined by the layering mark the division between the Upper and Middle Layered Series. These petrologic and structural features suggest that the three lithologic units represent at least three separate injections of undifferentiated magma (Deer and Abbott, 1965; Elsdon, 1969; 1971; Deer, 1976). Age relations among these intrusive phases is at present unknown. The gabbros of the Kap Edvard Holm complex are intruded by several syenitic complexes (fig. 2A). Radiometric ages of ~50 Ma for these syenites show that they were intruded 3 to 5 Ma after the probable time of gabbro emplacement (Beckinsdale; Brooks, and Rex, 1970; Pankhurst, Beckinsdale, and Brooks, 1976; Gleadow and Brooks, 1979).

Miki Fjord macrodike.—En echelon dike segments with average widths of 600 m and lengths of ~4 km comprise the Miki Fjord macrodike. The total exposed length of the dike complex is ~16 km. The macrodike is composed of at least two units (Deer, 1976; Bird and others, 1985). The earliest unit consists of north- to northeast-trending bodies of olivine gabbro with well-developed modal layering (fig. 3B) and numerous inclusions of metabasalt, plagioclase-rich gabbro, and metasediment. Metabasalt inclusions are most abundant in the exposed gabbros (fig. 3B). The olivine gabbros are locally intruded and deformed by a coarse-grained unlayered gabbro with abundant gabbroic pegmatites and leucocratic granophyres. Blocks of the earlier

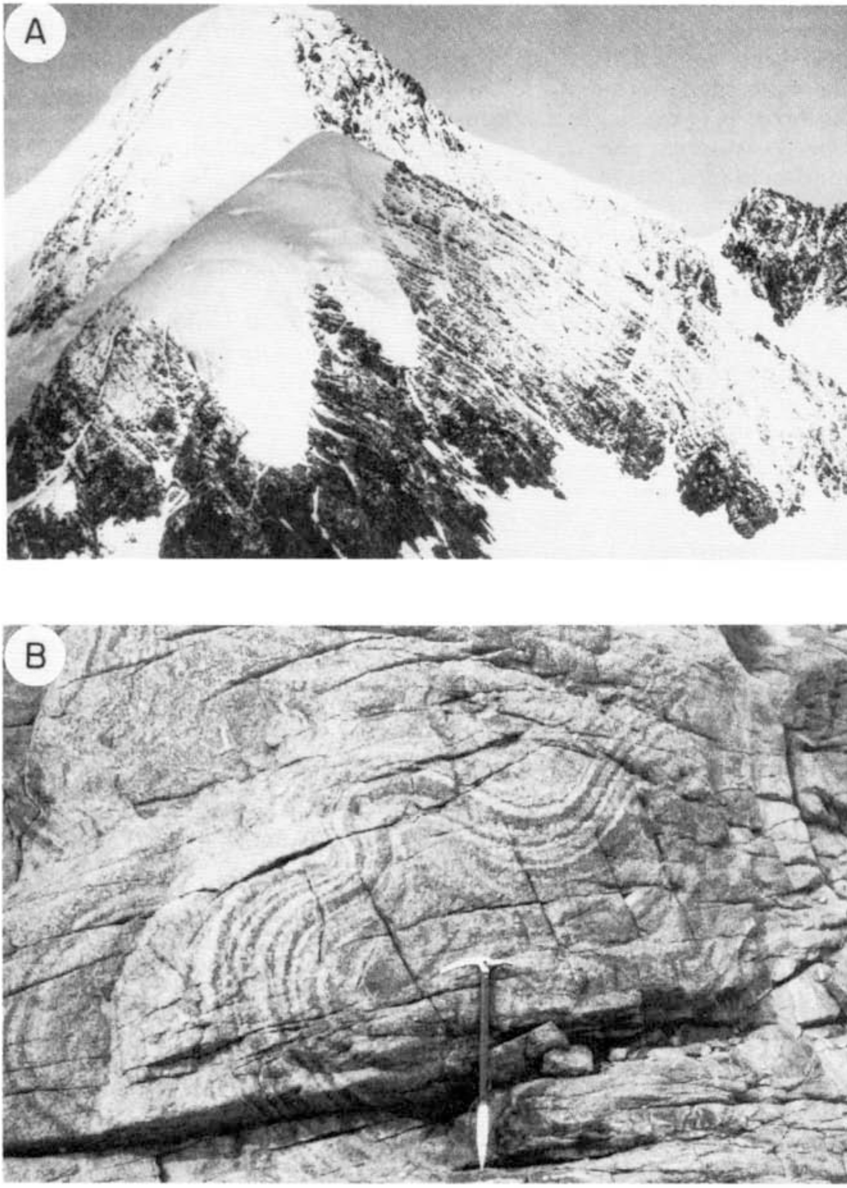


Fig. 6(A) Large-scale flexure in the layered gabbro of the Kruuse Fjord intrusion. Vertical elevation shown in photo is ~700 m. (B) Deformed layering in the olivine gabbro of the Miki Fjord macrodike associated with the intrusion of the unlayered gabbro.

Fig. 6. (continued)
(C) Synmagmatic faulting and slumping of the olivine gabbro of the Miki Fjord macrodike. Pencil is 13 cm long. (D) Deformed layering in the Lower Layered Series of the Kap Edvard Holm complex. Knife is 15 cm long.

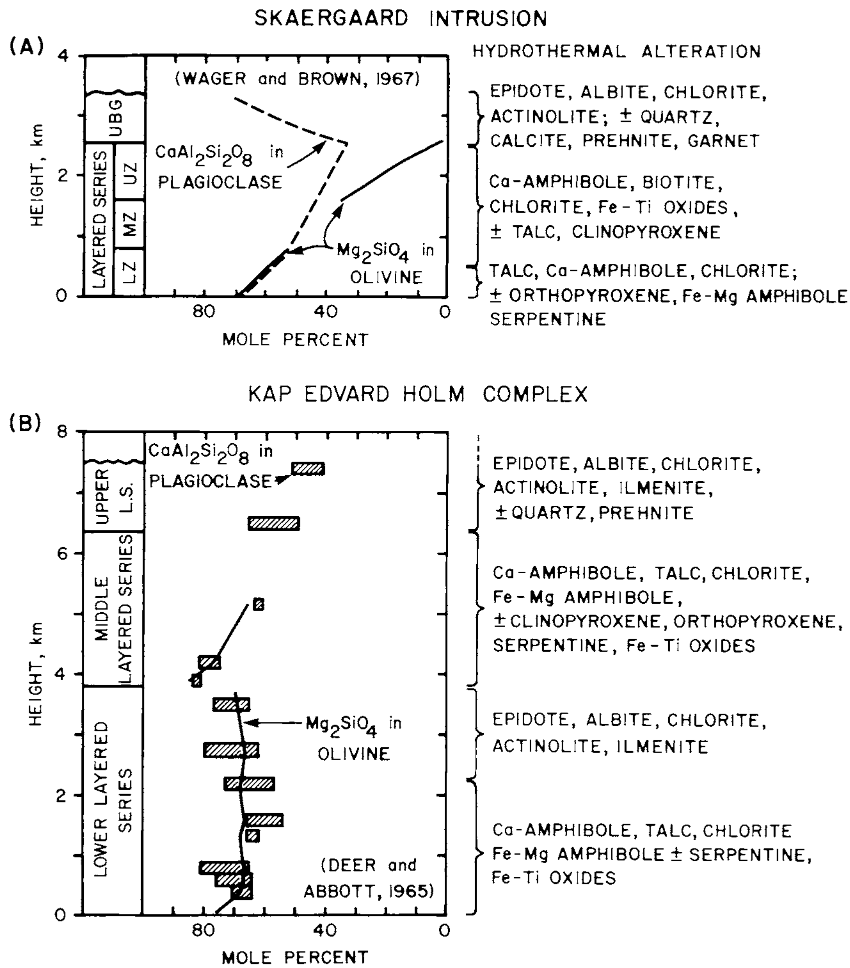


Fig. 7. Stratigraphy, magmatic plagioclase and olivine compositions, and the dominant hydrothermal alteration mineralogy of the Skaergaard (A) and Kap Edvard Holm complex (B) gabbros. Stratigraphic columns and magmatic mineral compositions are after Wager and Brown (1967), Deer and Abbott (1965), and Elsdon (1969, 1971). UBG = Upper Border Group; other abbreviations as in figure 4. Not shown in (A) is the Basistoppen sill which is intruded into the base of the Upper Border Group.

layered olivine gabbro occur in the unlayered gabbro near mutual contacts. Ductile deformation characterizes the well-exposed intrusive contacts between the two gabbros near the northern portion of the dike (fig. 6B).

Nordre Aputitêq intrusion.—Layered gabbros of the Nordre Aputitêq intrusion are exposed on a small island 15 km south of the Kap Edvard Holm complex (fig. 2A). Although the intrusion is not crosscut by dikes, age relations between Nordre Aputitêq and the coastal dike complex are uncertain because the intrusion is located between an inferred en echelon offset of the dike complex where dike abundance is minimal (Myers, 1980). Complex slump and fold structures in the igneous layering indicate that the intrusion underwent synmagmatic tilting and deformation (Brooks and Nielsen, 1982a). Reversals in the trends of cryptic compositional variation of cumulate phases imply that magma was periodically added to the chamber (T. F. D. Nielsen, personal commun.). The magmatic phases have very basic compositions and include olivine (up to Fo_{80}), plagioclase (up to An_{90}), clinopyroxene (X_{Mg} = 0.75), chromite, and ilmenite (T. F. D. Nielsen, unpub. analyses: Rose and Bird, 1987).

Kruuse Fjord complex.—The Kruuse Fjord complex, first reported by Bridgwater and others (1978) and Rex and others (1979), is a large gabbroic complex located to the west of the Nûgâlik plutonic center (fig. 2B). The complex is elliptical in plan with long and short axes of 21 and 13 km and is thus comparable in size to the Kap Edvard Holm complex (fig. 2B). Little is known about the structural and magmatic evolution of the Kruuse Fjord complex or its age relative to the dike complex. Our field studies (with C. K. Brooks, Copenhagen Univ.) show that the western and southeastern parts of the complex consist of >2 km of layered olivine and magnetite gabbros. In the southeast the gabbros are intruded by an arcuate body of peridotites, troctolites, and olivine gabbros. The layering in the host gabbros is locally deformed and disrupted near the contact with this body but dips toward the center of the complex elsewhere (figs. 2B and 6A). This suggests that subsidence within the magma chamber occurred shortly after emplacement in a manner similar to that proposed by Brown, Chambers, and Becker (1987) for the Lilloise intrusion (fig. 1).

The extent of cryptic variation in igneous minerals over the entire complex is not known. Within a 2000 m vertical exposure in the western portion of the intrusion magmatic plagioclase and augite compositions range from An_{80} to An_{32} and X_{Mg} = 0.57 to 0.37.

HYDROTHERMAL MINERAL ASSEMBLAGES

Hydrothermal solutions reacted with the cooling gabbros to form secondary mineral assemblages within and near complex systems of fractures and cavities.[1] Hydrothermal veins occur in all gabbros (see examples in figs. 8 and 9). These structures are usually traceable for tens of meters in outcrop and range from <1 mm up to 2 cm in width. Miarolitic cavities up to 20 cm in diameter are spatially related to some gabbro pegmatite segregations (fig. 10C). Although the most abundant alteration of pegmatites is associated with cavities, gabbroic pegmatites that do not contain cavities occur in all gabbros and commonly contain

[1]The term fracture is used to designate structures now represented by veins, and the term cavities is used synonymously with miarolites and miarolitic cavities.

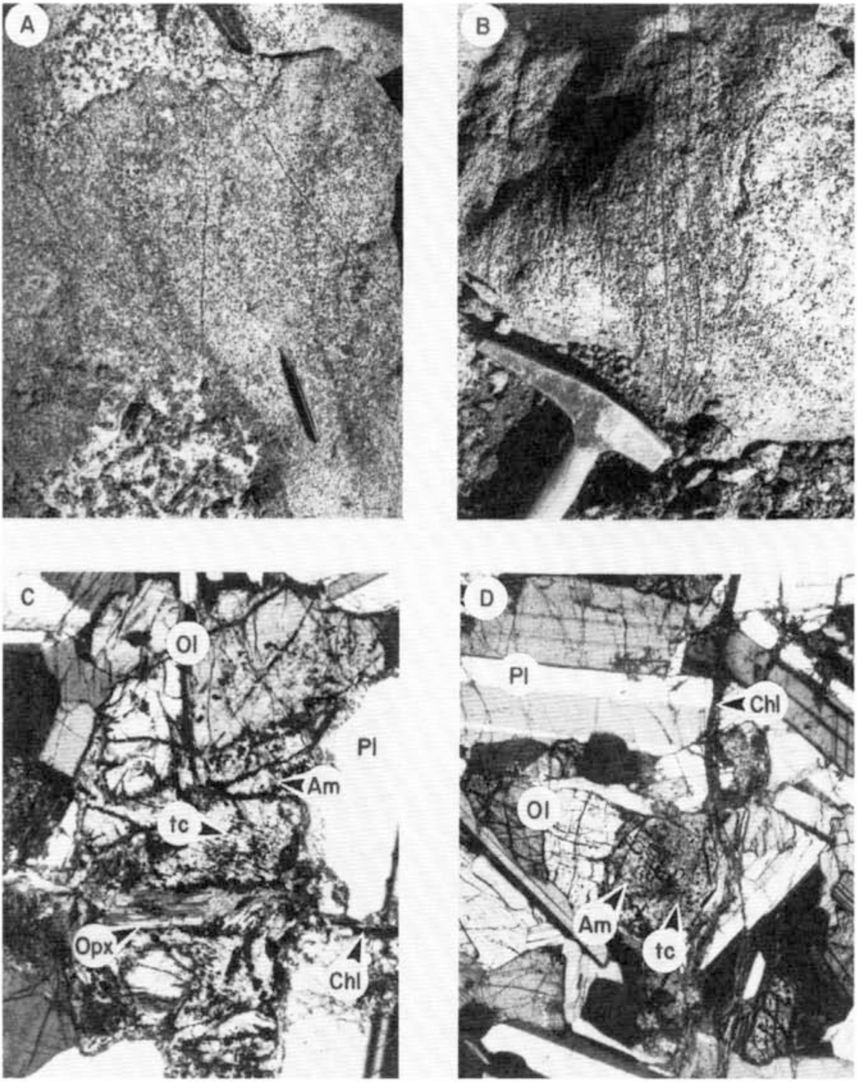


Fig. 8. Calcic amphibole veins in the Middle Layered Series of the Kap Edvard Holm complex. (A) Exposure of calcic amphibole + pyroxene veins in average gabbro with numerous plagioclase-rich xenoliths. Pencil is 13 cm long. (B) Exposure of later vein set associated with actinolitic hornblende + chlorite + talc alteration. Hammer head is 20 cm long. (C) Photomicrograph of calcic amphibole + pyroxene vein (KEH-19), showing metasomatic replacement of olivine (Ol) by Fe-Mg amphibole (Am) → talc (tc) → actinolite + talc in the presence of magnetite. Where olivine is crosscut the vein (horizontal in the photograph) is filled by orthopyroxene (Opx) + talc + actinolite. See figure 12A for mineral compositions. Photograph is 2.5 mm wide. (D) Photomicrograph of actinolitic hornblende + chlorite + talc vein (KEH-14). The vein is vertical in the photograph. Wall-rock olivine (Ol) is replaced by talc (tc) and Fe-Mg amphibole (Am). See figure 12B for mineral compositions. Photograph is 5 mm wide. In both vein types shown in photos C and D chlorite (Chl) fills fractures in plagioclase (Pl), and calcic amphibole fills fractures in pyroxene.

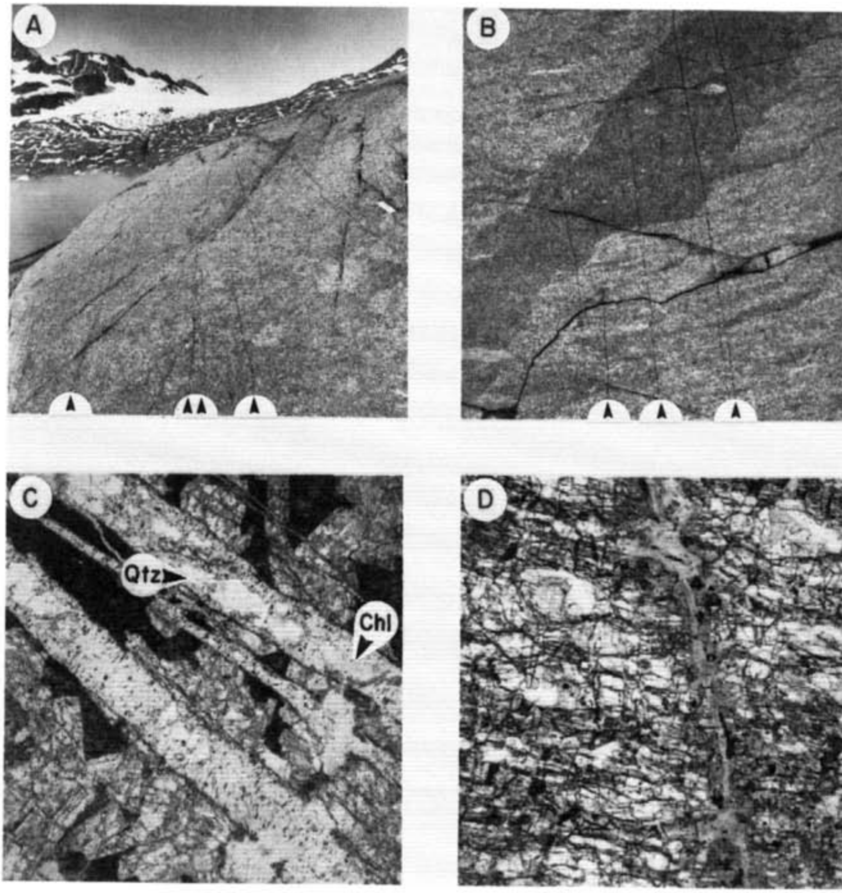


Fig. 9. Vein systems in the Miki Fjord macrodike. (A) Chlorite veins in the unlayered olivine-free gabbro of the macrodike. Scale is 15 cm long. Mountains in the center skyline are part of the Upper Border Group of the Skaergaard intrusion. (B) Actinolitic hornblende + chlorite + talc veins in metabasalt xenolith and adjacent layered olivine gabbro. Photo is ~1 m wide. (C) Chlorite (Chl) + quartz (Qtz) veins in the olivine-free gabbro. Note extreme alteration of wall rock near vein set. Photograph is 5 mm wide. (D) Near-vertical actinolitic hornblende + chlorite + talc vein in metabasalt xenolith and numerous near-horizontal serpentine veins. Photograph is 5 mm wide.

more alteration minerals than the host gabbros (fig. 10A and B). Secondary minerals occur in all the samples studied but are in most cases abundant (>5 volume percent of sample) only in and near veins, cavities, and pegmatites. Exceptions to this occur in the upper portions of the Kap Edvard Holm complex and the Skaergaard intrusion, where extensive replacement of magmatic minerals commonly cannot be correlated with visible vein sets or cavities in the sampled exposures.

Seven general types of hydrothermal mineral assemblages have been distinguished in the East Greenland gabbros. These types are given

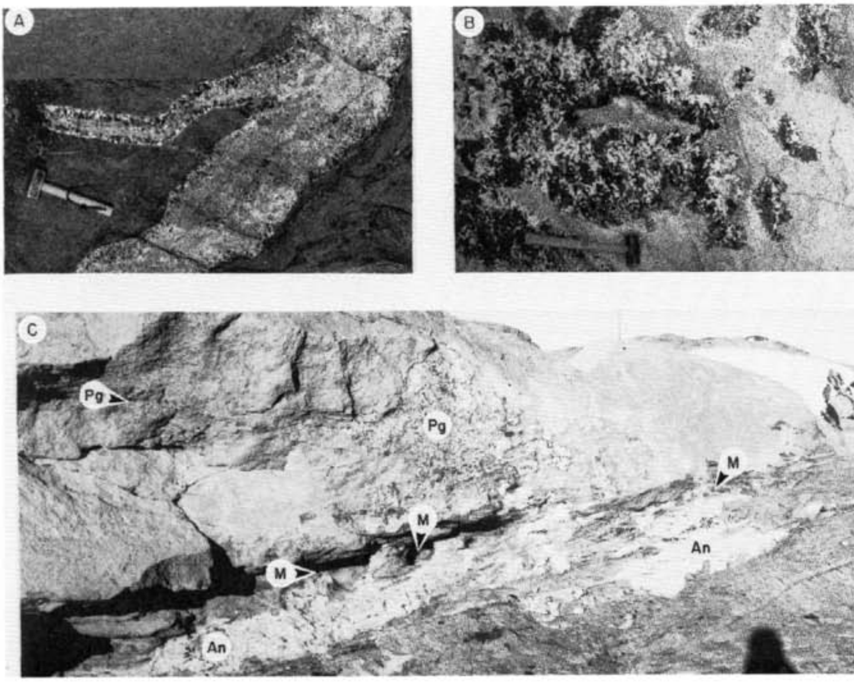


Fig. 10(A) Plagioclase + pyroxene pegmatite in the Kruuse Fjord intrusion. (B) Plagioclase + pyroxene + hornblende pegmatite in the Nordre Aputitêq intrusion. Photo is located near the exposure shown in (C). (C) Pegmatites (Pg) and miarolitic cavities (M) associated with anorthositic bodies (An) in the Nordre Aputitêq intrusion. Width of photo is ~10 m.

the following names based on diagnostic secondary minerals: calcic amphibole, calcic amphibole + epidote + albite, epidote + albite, quartz, chlorite, serpentine and zeolite + calcite. Secondary mineral assemblages containing calcic amphiboles or epidote + albite are the most common types of alteration. Chlorite, quartz, serpentine, and zeolite assemblages are either not abundant or are interpreted as having formed during the latest stages of the gabbros' cooling histories (Rogers and Bird, 1987) and are not considered beyond brief description of field and petrographic characteristics.

Distinction between the seven alteration types is based on mineralogical criteria that can be distinguished in the field, allowing easy identification of relative ages of veins based on crosscutting relations. This classification scheme involves mineral associations; the occurrence of minerals together in the same alteration type does not imply that the minerals formed at the same time or that they were ever in chemical equilibrium. The occurrence of the seven hydrothermal mineral assemblages in veins and cavities from the five gabbros is outlined in table 1.

TABLE 1

Summary of occurrence of hydrothermal mineral assemblages

Alteration type	Mode of occurrence	Intrusion: Skaergaard intrusion	Kap Edvard Holm complex	Miki Fjord macrodike	Nordre Aputitêq intrusion	Kruuse Fjord complex
Calcic Amphibole						
Calcic Amphibole + Pyroxene	veins	+	+	–	–	+
Actinolitic Hornblende Chlorite + Talc	veins in Mg-rich gabbros	+	+	+	–	–
Actinolite + Hornblende	veins in magnetite-rich gabbros	+	+	–	–	–
Calcic Amphibole + Epidote + Albite	veins and cavities	+	–	–	+	+
Epidote + Albite	veins and cavities	+	+	–	+	+
Quartz	veins near granophyres	+	+	+	+	+
Chlorite	veins near mafic dikes	+	+	+	–	–
Serpentine	veins in Mg-rich gabbros and metabasalt xenoliths	+	+	+	–	+
Zeolite ± Calcite	fault zones and pore fill	+	+	+	+	+

+: Alteration type occurs in intrusion.
–: Alteration type has not been observed in intrusion.

Selected analyses of representative secondary minerals in these five gabbros are given by Abbott and Deer (1972), Elsdon (1982), Naslund, Hughes, and Birnie (1983), Bird, Rogers, and Manning (1986), Manning and Bird (1986), Rogers and Bird (1987), and Rose and Bird (1987).

Calcic Amphibole[2]

Calcic amphibole-bearing assemblages occur as vein-filling and associated wall-rock replacement and constitute the earliest observed hydrothermal alteration in the East Greenland gabbros. These alteration assemblages have been observed in all the gabbros studied except Nordre Aputitêq. Calcic amphibole veins are typically near vertical and continuous for meters to several tens of meters. In the Layered Series and Marginal Border Group of the Skaergaard intrusion, where this alteration is the most common type found, calcic amphibole veins occur with frequencies of 0.2 to >1.5 and 1.4 to >20 fractures/meter, respectively (Bird, Rogers, and Manning, 1986). A similar distribution of vein densities occurs at Kap Edvard Holm, although the average abundance of calcic amphibole veins is locally greater in the Middle Layered Series than in the Layered Series of the Skaergaard intrusion. There are restricted areas of several tens to hundreds of square meters where veins are absent in both gabbros.

This alteration type is distinct from the other types discussed below in that calcic amphibole is the most volumetrically abundant open space-filling secondary mineral. In the host gabbro between calcic amphibole veins secondary minerals comprise <1 to 5 volume percent of the rock and consist of hornblende, pargasite, biotite, chlorite, and talc. Vein-filling calcic amphiboles in all intrusions range in composition from tremolite through tremolitic hornblende, magnesio- or edenitic hornblende, to pargasitic hornblende, or their ferroan or ferric analogues. These compositions represent a combination of $[(Na + K)^{A}Al^{IV}][\square^{A}Si^{IV}]_{-1}$ (edenite) and $[Al^{VI}Al^{IV}][Mg^{VI}Si^{IV}]_{-1}$ (tschermakite) substitutions, where the superscripts A, IV, and VI correspond to the A, octahedral, and tetrahedral sites in the amphibole structure, respectively, and □ represents a vacancy in the designated site (Leake, 1978; Hawthorne, 1981). Calculated Ti and $(Na + K)^{A}$ contents are <0.2 and <0.9 atoms per 23 anhydrous oxygens, respectively.

The calcic amphibole alteration type can be subdivided into three groups: calcic amphibole + pyroxene assemblages, actinolitic hornblende + chlorite + talc assemblages, and hornblende + actinolite assemblages. This subdivision is not easily made in the field and usually requires detailed petrographic examination of vein and wall-rock assem-

[2] All amphibole nomenclature is after Leake (1978). the term *calcic amphibole* is used in this paper to refer to amphiboles ranging in composition from tremolite to pargasitic hornblende with no specific connotation for Mg/Fe^{+2}. Amphibole compositions were determined from electron microprobe analyses assuming that Fe^{+3} content is the midpoint between the minimum and maximum required by charge balance. See Bird, Rogers, and Manning (1986) for representative analyses and analytical methods.

blages. Crosscutting relations between these subgroups can be ambiguous, even on microscopic scales. Evidence of age relationships between subgroups of the calcic amphibole alteration type is established by crosscutting relations where available and supplemented by petrographic observations.

Although there are three distinct calcic amphibole assemblages, all have two features in common not evident in other alteration types. First, the type and abundance of vein-filling minerals varies along these fractures as a function of the wall-rock mineralogy (table 2; Bird, Rogers, and Manning, 1986). In addition, molecular proportions of $(Na + K)^{total}$, Fe^{+2}, and Mg of vein-filling calcic amphiboles are closely related to the host gabbro composition (fig. 11). Calcic amphibole-bearing alteration assemblages from all five East Greenland gabbros exhibit this feature, but the Skaergaard intrusion is used in figure 11 for illustration because it shows the greatest range in molecular Mg/Fe^{+2} in both secondary amphiboles and host rock.

Calcic amphibole + pyroxene.—Secondary assemblages of this group are found in and near <2 mm wide veins that weathered black to rust brown. The calcic amphibole + pyroxene veins are the earliest veins found in the Skaergaard intrusion and the Kruuse Fjord and Kap Edvard Holm complexes (fig. 8A and C). In general, these veins are oriented perpendicular to the walls of the intrusions, forming a radial vein network within the gabbros. This group of veins is characterized by fracture filling of calcic amphiboles ± orthopyroxene, with metasomatic replacement of wall-rock magmatic augites by secondary calcic clinopyroxene.

Hornblendes are the most abundant amphiboles, although more and less aluminous compositions are common. Within a single vein sample the concentrations of tetrahedral Al or alkalis as a function of X_{Mg} are continuous, with no obvious compositional gaps (see fig. 21 of Bird, Rogers, and Manning, 1986). In Mg-rich gabbros vein-filling orthopyroxene occurs where fractures cut igneous olivine and Ca-poor pyroxene (fig. 8C), and bytownite ($\sim An_{80}$) is commonly found where igneous plagioclase ($\sim An_{70}$) is crosscut. Fayalitic olivine occurs in veins in iron-rich gabbros such as the Upper Zone c of the Skaergaard intrusion. Chlorite, although not abundant, is present in all these veins.

In the wall rock, igneous augites cut by these veins are metasomatically replaced by hydrothermal calcic clinopyroxenes up to 2 mm from the vein margins. Hydrothermal clinopyroxenes are compositionally distinct from the magmatic augites they replace. For example, hydrothermal clinopyroxenes in the Skaergaard intrusion contain more Ca and Si and less Fe^{+2} and minor elements; Mg is depleted in hydrothermal clinopyroxenes below Upper Zone B and enriched above (Manning and Bird, 1986). Limited (<0.10 mm wide) metasomatic replacement of wall-rock plagioclase by chlorite in Mg-rich gabbros and by Fe-rich calcic amphiboles in Fe-rich gabbros also occurs near these types of veins. Trace amounts of biotite occur in the wall rock near, and in veins

TABLE 2

Wall-rock and vein-filling mineralogy associated with calcic amphibole, calcic amphibole + epidote + albite, and epidote + albite alteration types

Alteration type	Alteration site	Magmatic Phase: Augite	Plagioclase	Olivine[a]	Orthopyroxene	Fe-Ti Oxide
Calcic Amphibole *Calcic Amphibole + Pyroxene*	Wall Rock:	cpx + br hbd + oxide	plag ± chl ± br & bg hbd	mt + tlc ± [cum, act]	act	bio + oxide
	Vein:	br hbd + oxide	br hbd ± [plag, bg hbd, opx, chl]	br hbd ± opx	br hbd ± opx	br hbd ± bio ± oxide
Actinolitic Hornblende + Chlorite + Talc	Wall Rock:	gr hbd	chl	mt ± [tlc, cum act, chl]	tlc + cum ± act	bio
	Vein:	gr hbd ± cpx	chl ± bio ± gr hbd	act + chl ± [tlc, cum, mt]	chl + gr hbd	gr hbd + chl
Hornblende + Actinolite	Wall Rock:	act + mt	bg hbd + alb ± chl ± ser	mt + tlc ± cum	tlc ± cum	bio
	Vein:	act + br hbd	chl + act + br hbd	tlc ± chl	act + br hbd	chl + act + br hbd
Calcic Amphibole + Epidote + Albite	Wall Rock:	act ± chl	alb ± chl ± ep ± pre	idd + mt	act ± chl	ilm ± [sph, pre chl, bio]
	Vein:	←	←	bg & gr hbd ± [pre, act, ep][b]	→	→
Epidote + Albite	Wall Rock:	act + chl	ep + alb ± [ksp, ser, pre, chl]	chl + idd + ilv + mt	act	ilm + sph ± pre ± chl
	Vein:	←	←	ep ± [alb, pre, ilm, qtz cpx, gnt, cc, ksp, chl]	→	→

[a]Olivine wall-rock alteration in calcic amphibole veins is metasomatically zoned. The phases listed do not always coexist.

[b]Arrows across all columns indicate that vein-filling assemblage is independent of wall-rock mineralogy.

Abbreviations: act = actinolite, alb = albite, bio = biotite, bg hbd = blue-green hornblende, usually ferro-pargasitic hornblende, br hbd = brown hornblende, usually edenitic or magnesio-hornblende or their ferroan analogs, cc = calcite, chl = chlorite, cpx = calcic clinopyroxene, cum = Fe-Mg amphibole, ep = epidote, gnt = grandite garnet, gr hbd = green hornblende, usually actinolitic hornblende or magnesio hornblende or their ferroan analogs, generally containing less Al^{total} than br hbd in the same alteration type, idd = iddingsite, ilm = ilmenite, ilv = ilvaite, ksp = K-feldspar, mt = magnetite, opx = orthopyroxene, pre = prehnite, qtz = quartz, ser = sericite, sph = sphene, tlc = talc.

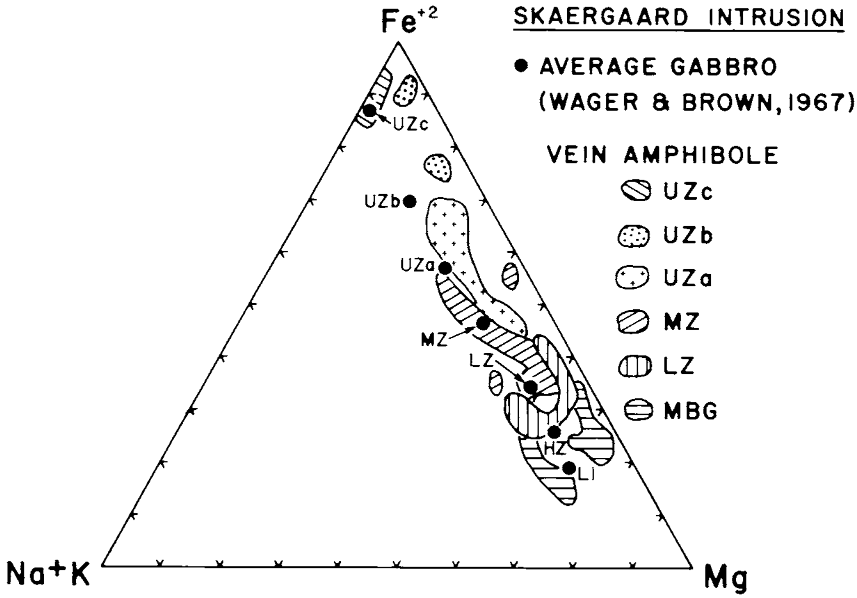


Fig. 11. Molecular proportions of Fe^{+2}-Mg-$(Na + K)^{total}$ in vein-filling calcic amphiboles and average gabbros from the Layered Series of the Skaergaard intrusion. Gabbro compositions from Wager and Brown (1967: table 6). Fe^{+3} in calcic amphiboles is assumed to be the midpoint between minimum and maximum required by charge balance. See figure 4 caption for abbreviations.

through, igneous Fe-Ti oxides. Metasomatic replacement of magmatic olivine up to 2 mm into the wall rock is usually zoned from magmatic olivine (wall rock) → Fe-Mg amphibole → talc + Fe-Mg amphibole → talc ± actinolite → talc + actinolitic hornblende ± orthopyroxene (vein fill), with magnetite present throughout (fig. 8C). However, in some veins olivine is replaced by talc + magnetite without the development of Fe-Mg amphibole. Compositional relations among talc, orthopyroxene, and Fe-Mg amphibole associated with olivine replacement near these veins in the Middle Layered Series of the Kap Edvard Holm complex are given in figure 12A. Note that vein-filling talc (open square) is slightly enriched in Fe^{total} relative to wall-rock talc (solid squares). In general, all the vein-filling secondary Fe-Mg silicates are Fe-rich compared to secondary wall-rock Fe-Mg silicates.

The compositional relations among calcic amphiboles, pyroxenes, and olivines in veins from the Skaergaard intrusion and Kap Edvard Holm and Kruuse Fjord complexes are given in figure 13. Figure 13 illustrates that (1) molecular Mg/Fe^{+2} in the average gabbros and in the secondary minerals are similar, and that (2) secondary orthopyroxene is restricted to Mg-rich gabbros, and secondary olivine is restricted to Fe-rich gabbros. Compositions of clinopyroxenes from the Kap Edvard

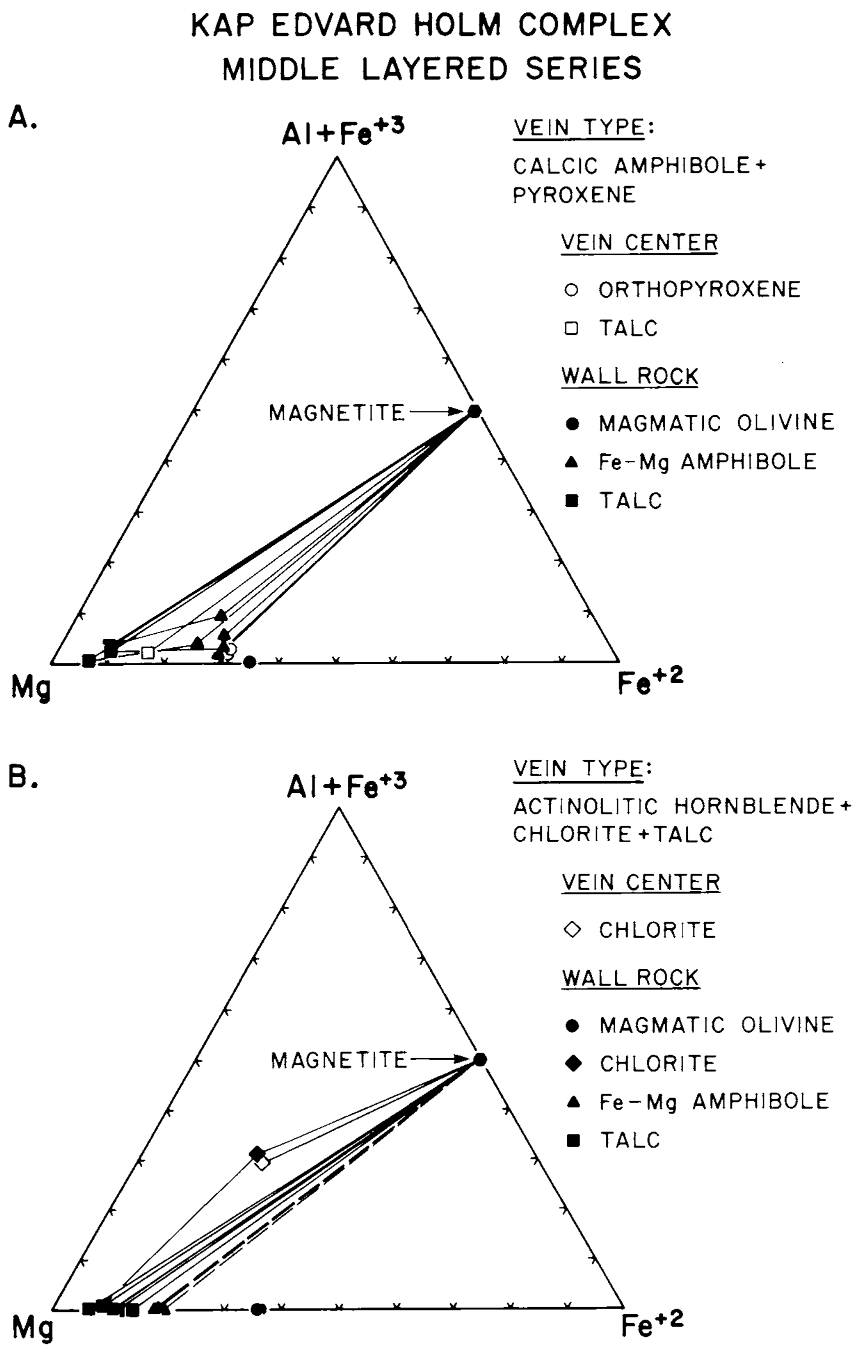
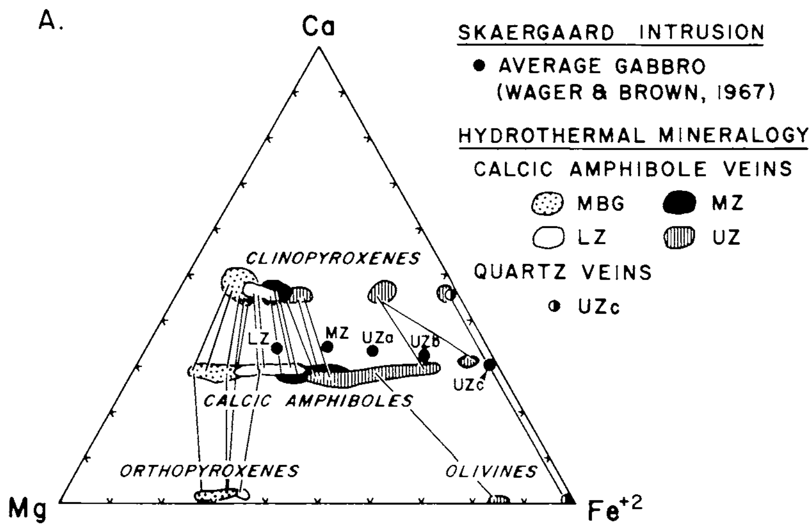


Fig. 12. Molecular proportions of (Al + Fe^{+3}), Mg, and Fe^{+2} in chlorite, talc, amphibole, orthopyroxene, and olivine from calcic amphibole + pyroxene (A) and actinolitic hornblende + chlorite + talc (B) vein and wall-rock assemblages in the Middle Layered Series of the Kap Edvard Holm complex. All Fe is assumed to be Fe^{+2} in chlorite, talc, and olivine. Fe^{+3} calculated by charge balance in orthopyroxene. Tie lines denote analyses at grain boundaries for coexisting phases. In diagram (B) solid tie lines represent phase relations in the presence of actinolite and dashed lines represent phase relations that do not coexist with actinolite. Photomicrographs of the assemblage in (A) (sample KEH-19) and (B) (sample KEH-14) are given in figure 8, C and D, respectively.



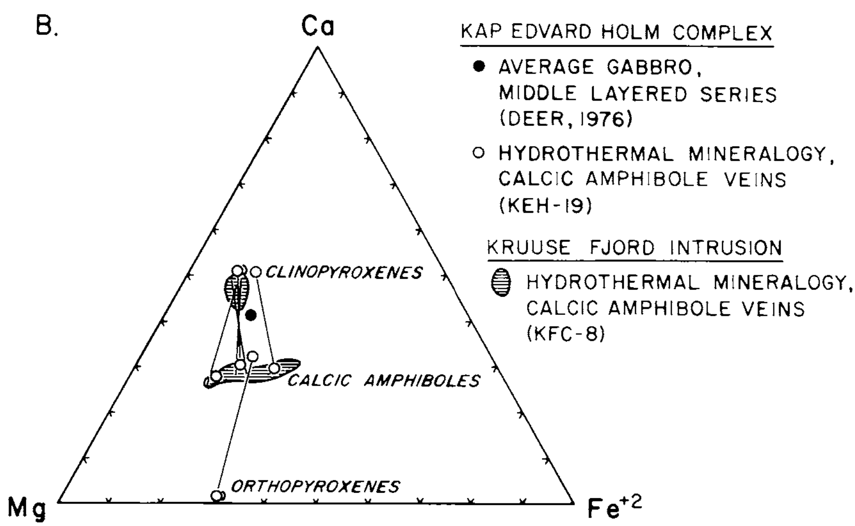


Fig. 13. Molecular proportions of Ca, Fe^{+2}, and Mg of secondary calcic amphiboles, clinopyroxenes, orthopyroxenes, and olivines in calcic amphibole and quartz veins from the Skaergaard intrusion (A), and the Kap Edvard Holm complex and Kruuse Fjord intrusion (B). Methods of analysis recalculation are given in captions to figures 11 and 12. For representative mineral compositions of plotted phases, see Bird, Rogers, and Manning (1986), Manning and Bird (1986), and Rose and Bird (1987). MBG = Marginal Border Group; other abbreviations given in figure 4 caption.

Holm sample require 0.005 to 0.010 atoms Ca per 6 oxygens in the M1 site and are near the maximum M1 Ca contents known to occur (see Robinson, 1980). These clinopyroxenes contain 50.2 to 50.6 mole percent $CaSiO_3$ component after subtracting Ca equal to $CaAl_2SiO_6$, $CaMnSi_2O_6$, and other calcic pyroxene molecules and therefore plot slightly above the diopside-hedenbergite join in figure 13B.

Actinolitic hornblende + chlorite + talc.—This assemblage is associated with <2 mm wide rust brown weathering veins found only in the Mg-rich olivine gabbros of the Skaergaard Lower Zone, the Kap Edvard Holm complex, and the Miki Fjord macrodike (figs. 8B and D and 9B and D). In the Skaergaard intrusion and the Miki Fjord macrodike, the veins are perpendicular to the walls of the intrusions with densities of generally <2 veins/meter. Crosscutting relations observed in the Middle Layered Series of the Kap Edvard Holm complex indicate that this vein type is later than the calcic amphibole + pyroxene veins and oriented parallel to the trend of the dike complex in this region. These veins are distinguished from the calcic amphibole + pyroxene veins by vein-filling calcic amphiboles with a restricted range of Al^{IV} (0.25–1.25 atoms Al^{IV} per 23 anhydrous oxygens; see fig. 16 of Bird, Rogers, and Manning, 1986), sporadic occurrence of vein-filling salite, more abundant chlorite and talc in the vein assemblage, and metasomatic replacement of wall-rock magmatic augite by actinolitic hornblende + magnetite (table 2).

Fracture-filling minerals include actinolitic hornblende, chlorite, and talc ± salite and ferrosalite (table 2). Amphiboles fill the fractures in igneous pyroxenes, and chlorite is most abundant in the portions of the fracture that transect igneous plagioclase (fig. 8D). Portions of veins that crosscut olivines contain actinolite + talc ± Fe-Mg amphibole, magnetite, and chlorite. Fine intergrowths with fibrous actinolite and Fe-Mg amphibole occur throughout many of these veins.

The metasomatic replacement of the gabbro mineralogy marginal to these veins is outlined in table 2. Three olivine alteration assemblages have been identified: (1) talc, (2) chlorite + Fe-Mg amphibole, and (3) zoned replacement from magmatic olivine (wall rock) → talc + Fe-Mg amphibole → talc → talc + actinolite → talc + chlorite + actinolite → actinolite + chlorite (vein fill). The latter zoning sequence is shown in figure 8D and representative replacement mineral compositions are given in figure 12B. Magnetite is present in all types of metasomatic replacement of olivine. Magnesium is preferentially partitioned into secondary hydrous Fe-Mg silicates relative to the olivine host during the metasomatic process (fig. 12B). Differences in olivine alteration between actinolitic hornblende + chlorite + talc veins and calcic amphibole + pyroxene veins include: (1) Fe-Mg amphibole and talc are more aluminous, and Fe-Mg amphibole is more Fe-rich in calcic amphibole + pyroxene assemblages in gabbros with the same olivine composition (compare fig. 12A and B); and (2) orthopyroxene fills fractures where olivine is cut by calcic amphibole + pyroxene veins, whereas actinolite +

talc ± Fe-Mg amphibole ± magnetite fill fractures in olivines in actinolitic hornblende + chlorite + talc veins.

Hornblende + actinolite.—This alteration type is characterized by: (1) 1 to 4 mm wide veins that weather black and commonly display brecciation of angular wall-rock fragments <1 mm wide; (2) light gray metasomatic reaction zones extending up to 5 mm from the black, amphibole-rich vein centers; and (3) abundant microfractures parallel to the vein. The principal difference between this alteration type and the other calcic amphibole alteration assemblages is the coexistence of brown hornblende with green actinolite or actinolitic hornblende that forms overgrowths on, or fine intergrowths within, the brown hornblende. These veins have been found only in the magnetite-rich gabbros of the Skaergaard intrusion and the Kap Edvard Holm complex and are commonly found adjacent and subparallel to, or at terminations of, granophyres. Veins containing this alteration type also occur trending parallel to the later regional mafic dike complex. Many of these veins are not completely filled with secondary minerals.

Fracture-filling calcic amphiboles from a single vein of this type have a wide range in composition and define a compositional gap in Al^{IV} and A site occupancy (fig. 14). Green ferro-pargasitic hornblendes and ferro-actinolites occur as a late-stage pore filling in this sample. Because several paragenetically distinct types of calcic amphiboles are shown in figure 14, the distribution of data represents a section through the compositional gap defined by phases that did not necessarily coprecipitate. The widening of the gap in Al^{IV} with increasing Fe^{+2} shown by the brown hornblendes and the actinolite overgrowths and intergrowths has been recognized in regional metamorphic rocks as well (Tagiri, 1977). The gap in the A site occupancies in the calcic amphiboles also widens with increasing Fe^{+2} content. Grunerite forms overgrowths on the earlier open space-filling calcic amphiboles in this alteration type.

In the wall rock, actinolite + magnetite replaces igneous pyroxenes, and biotite is found adjacent to cumulate oxides. Where olivine is present it is replaced by talc + magnetite; Fe-Mg amphibole usually does not occur as an alteration product of olivine. Plagioclase is altered to Fe- and Al-rich calcic amphiboles and albite at vein margins and along microcracks near the macroscopic veins. The light gray metasomatic reaction zones observed about this vein type in outcrop are due to numerous mineral and fluid inclusions in plagioclase and to partial replacement of plagioclase by albite and sericite.

Calcic Amphibole + Epidote + Albite

This assemblage is found to occur within and near veins in restricted areas (<500 m^2) of the Skaergaard and Nordre Aputitêq intrusions and the Kruuse Fjord complex (table 1; fig. 15A and B) These vein systems are easily recognized in the field by extensive bleaching and metasomatic replacement of the host gabbros. Veins are filled by calcic amphibole and epidote. Vein amphiboles include actinolites, actinolitic

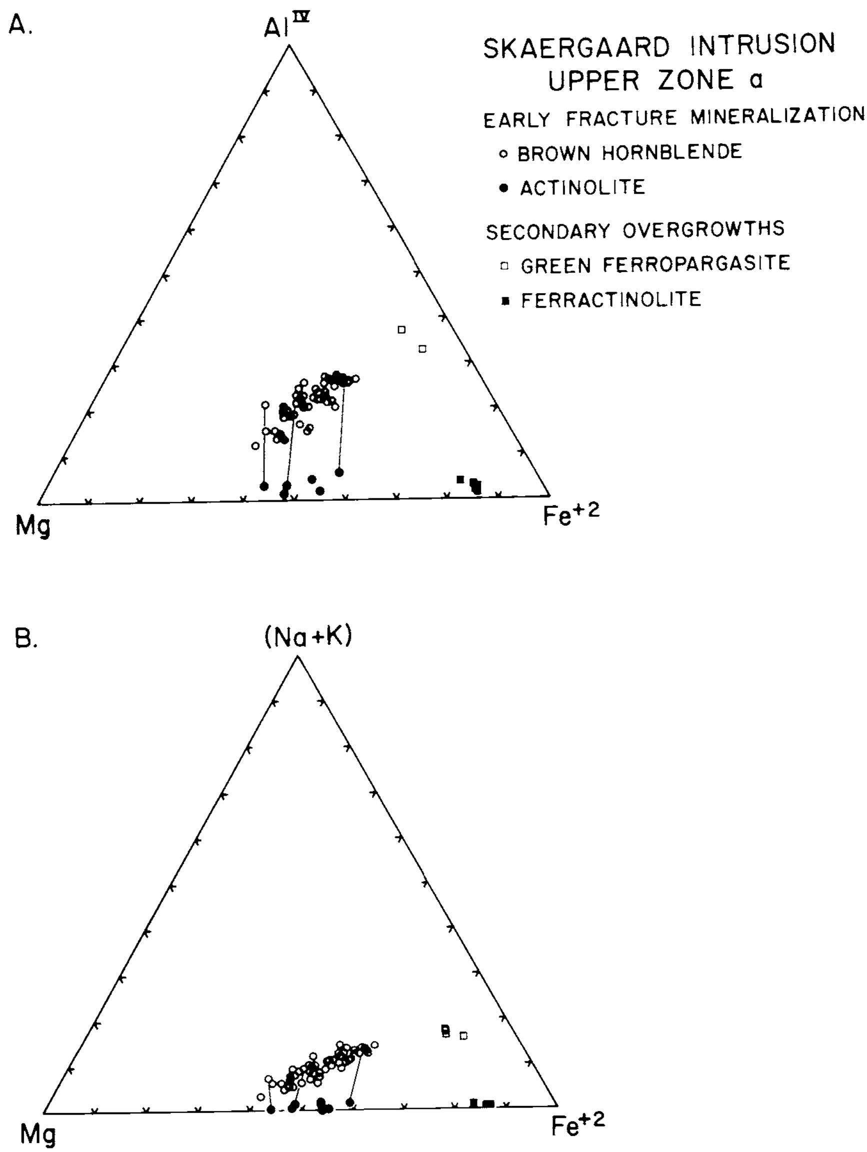


Fig. 14. Calcic amphibole compositions from an actinolite + hornblende vein and associated wall rock alteration in UZa of the Skaergaard intrusion. (A) amphiboles plotted in terms of molecular proportions of Al^{IV}-Mg-Fe^{+2}; (B) amphiboles plotted in terms of molecular proportions of $(Na + K)^{A}$-Mg-Fe^{+2}. See figure 11 caption.

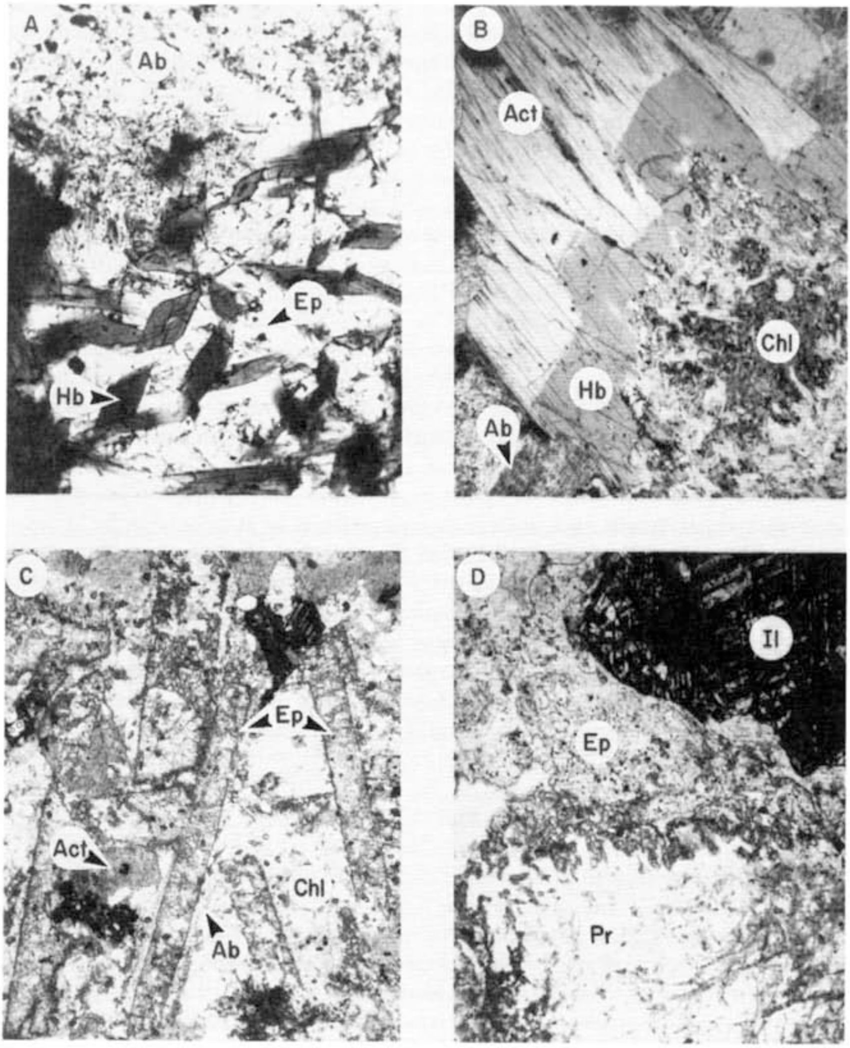


Fig. 15. Photomicrographs of epidote + albite assemblages. (A) Epidote (Ep) + albite (Ab) + edenitic hornblende (Hb) vein assemblage from the Upper Zone gabbros within trough band H in the Skaergaard intrusion. Photo is 2.5 mm wide. (B) Edenitic hornblendes (Hb) overgrown by actinolite (Act) at Nordre Aputitêq. Wall rock is altered to epidote (not shown) + albite (Ab) + chlorite (Chl). Photo is 5 mm wide. (C) Epidote (Ep) + albite (Ab) replacement of plagioclase in Upper Layered Series of Kap Edvard Holm complex. Mafic minerals are altered to actinolite (Act) and chlorite (Chl). Photo is 5 mm wide. (D) Alteration of magmatic Fe-Ti oxides to trellis intergrowths of ilmenite (Il) and calc-silicates in a prehnite (Pr), epidote (Ep), and albite (not shown) altered gabbro near a pegmatite pocket at Nordre Aputitêq. Photo is 5 mm wide.

hornblendes, and pargasitic hornblende. Magmatic pyroxenes in the wall rock are altered to actinolite ± chlorite; plagioclase is replaced by albite, usually in association with prehnite, chlorite, and epidote; and igneous olivine is replaced by magnetite and fine-grained iddingsite (table 2). Wall-rock Fe-Ti oxides are recrystallized to fine trellis networks of ilmenite that may enclose chlorite, sphene, prehnite, and minor amounts of biotite. Figure 15, A and B, clearly shows that hornblende was the earliest phase to precipitate in veins, followed by epidote and actinolite. Although no definitive crosscutting relations have been observed, the occurrence of aluminous calcic amphibole with epidote and albite suggests that these veins are transitional between the calcic amphibole vein types described above and the epidote + albite veins described below.

Epidote + Albite

Assemblages characterized by modally abundant epidote + albite occur in veins, miarolitic cavities, and metasomatized portions of all the gabbros except the Miki Fjord macrodike (table 1). Epidote + albite alteration is most abundant in and near the Basistoppen Sheet in the Skaergaard intrusion and in the upper portions of the Lower and Upper Layered Series at Kap Edvard Holm. Epidote + albite veins are usually <2 mm wide, although veins up to 2 cm wide have been found. Crosscutting and paragenetic relations observed in the Upper Border Group of the Skaergaard intrusion and the Kruuse Fjord intrusion indicate that this alteration type postdates the calcic amphibole assemblages discussed above. Vein- and cavity-filling minerals include epidote and albite in association with variable amounts of chlorite, actinolite, salite, grandite garnet, prehnite, calcite, microcline, ilmenite, and quartz (table 2). In contrast to the calcic amphibole alteration, the distribution of vein-filling phases in epidote + albite alteration is independent of the wall-rock mineralogy.

Plagioclase in the wall rock is altered to varying combinations of epidote, prehnite, sericite, albite, or chlorite (fig. 15C): olivine is replaced by chlorite, ilvaite, or serpentine; and magmatic pyroxenes are altered to actinolite and chlorite. Igneous Fe-Ti oxides are recrystallized to trellis networks of ilmenite + sphene ± prehnite ± chlorite (fig. 15D). The extent of this wall-rock replacement is commonly greater than that associated with calcic amphibole alteration, with up to 30 to 40 volume percent replacement of magmatic phases in some localities. In general, complex compositional zoning and paragenetic relations of secondary minerals are characteristic features of the epidote + albite type of alteration (Elsdon, 1982; Rose and Bird, 1987).

Quartz

Quartz-rich veins are not abundant in the East Greenland gabbros. They occur locally near transgressive granophyres in all the gabbros, and quartz + albite veins with centers of green fibrous actinolite also occur near pegmatites in the marginal gabbros of the intrusions. North-northeast-trending quartz veins containing varying amounts of fayalitic olivine, hedenbergite, ferro-actinolite, and magnetite occur in the iron-rich gabbros near the Sandwich Horizon of the Skaergaard intrusion (fig. 13A) and were probably derived from fluids exsolved during emplacement and crystallization of granophyres (Norton, Taylor, and Bird, 1984; Bird, Rogers, and Manning, 1986).

Chlorite

Two types of chlorite-rich veins have been identified. Both types are 1 to 3 mm wide and rust-colored in weathered outcrops. The earliest veins are filled with well-crystallized chlorites and minor amounts of actinolite and quartz. Locally intense replacement of the igneous mineralogy occurs marginal to some of the veins (fig. 9C); however, most exposures of these veins are not associated with obvious alteration of the gabbros. The youngest chlorite veins are in close spatial and geometric associations with individual mafic dikes and are filled with fine-grained silica-rich chlorites (Rogers and Bird, 1987). In general these chlorite veins trend parallel to the local orientation of the dike complex: that is, east-west in the Skaergaard region and northeast-southwest near Kap Edvard Holm and in the intrusions to the southwest (see fig. 2A). Based on crosscutting relations, all chlorite veins are later than the calcic amphibole veins described above, but their relation to the epidote + albite alteration assemblages and quartz veins is unclear. Field relations indicate that chlorite veins formed before, during, and after the emplacement of thin (<5 m wide) mafic dikes that transect the gabbros. Most of these mafic dikes have chilled margins with the host rock and were thus emplaced late in the cooling histories of the gabbros.

Serpentine

Veins filled with serpentine occur in the magnesium-rich gabbros, peridotites, and metabasalt inclusions in the Skaergaard intrusion, the Kap Edvard Holm and Kruuse Fjord complexes, and the Miki Fjord macrodike (fig. 9D). Chlorite and Fe-oxides may also occur in these veins. Serpentine veins are <2 mm wide and near vertical, with no visible metasomatic reaction zone marginal to the veins. Where present in metabasalt inclusions, they form anastomosing networks that, in general, parallel the upper and lower margins of the inclusion.

Zeolite ± Calcite

Fractures and breccia zones partially filled with a variety of zeolites and calcite are found in high angle faults that transect the gabbros where they may be associated with epidote, prehnite, and quartz. These minerals also fill vugs that occur in some of the other vein types. Bird, Rogers, and Manning (1986) report late stage stilbite filling pores in calcic amphibole and epidote albite veins. Thomsonite + muscovite veins occur at Nordre Aputitêq (Rose and Bird, 1987).

TEMPERATURES OF HYDROTHERMAL ALTERATION

Temperatures of hydrothermal mineral assemblages in the Skaergaard and Nordre Aputitêq intrusions and the Kruuse Fjord complex were estimated by Bird, Rogers, and Manning (1986), Manning and Bird (1986), and Rose and Bird (1987) using clinopyroxene geothermometry and Ca-Al-Fe^{+3} silicate phase relations in experimental and active geothermal systems. In this investigation, these methods were combined with evaluation of Fe^{+2}–Mg–Mn exchange equilibria and phase relations in the system $MgO–SiO_2–H_2O$ for appropriate assemblages to constrain and compare temperatures of the calcic amphibole and epidote + albite vein and wall-rock assemblages in the East Greenland gabbros. A summary of these temperature estimates is given in table 3 and below. The temperature estimates reported below represent minimum temperature limits for fracture formation. Maximum temperatures of fracture formation were probably ~1000°C (Norton, Taylor, and Bird, 1984).

Calcic Amphibole Assemblages

The maximum temperature for hornblende stability in this alteration assemblage at fluid pressures of ~0.5 kb, which approximate hydrostatic conditions in the East Greenland gabbros (Norton, Taylor, and Bird, 1984), is ~900°C (Spear, 1981). If fluid pressures are greater than hydrostatic at the time of the early, high-temperature fracturing in gabbros, as suggested by Norton, Taylor, and Bird (1984) and Kelly and Delaney (1987), the maximum temperature for hornblende stability is ~950°C. Maximum temperatures of hydrothermal clinopyroxene formation near calcic amphibole veins cannot be constrained from available experimental data.

Fe^{+2}–Mg–Mn exchange equilibria.—Empirically derived Fe^{+2}–Mg–Mn exchange equilibria among hornblende, biotite, and clinopyroxene or orthopyroxene (Perchuk, 1969) have been used to estimate equilibration temperatures of calcic amphibole + pyroxene and actinolitic hornblende + chlorite + talc alteration types (fig. 16). Compositions used in this study were determined by electron microprobe analyses of mineral pairs taken <20 μ apart across mutual grain boundaries. In calcic amphibole + pyroxene assemblages from the Skaergaard intrusion, clinopyroxene-hornblende and clinopyroxene-biotite exchange equilibration ranged from 700° to 750°C in the Lower Zone to 650° to 675°C in the Upper Zone. Early veins in the Skaergaard Marginal Border Group show a similar temperature range. The highest exchange temperatures are in the Kap Edvard Holm complex ranging from 725° to 900°C for orthopyroxene-hornblende and clinopyroxene-hornblende pairs in a Middle Layered Series vein. Coexisting clinopyroxene and hornblende in the Kruuse Fjord sample also record a high equilibration temperature of 825°C. Orthopyroxene-biotite pairs from the Miki Fjord macrodike yield a temperature of 675°C. Although Mg–Fe^{+2} exchange between clinopyroxene and orthopyroxene is well-calibrated, the mineral pair is never found in contact since orthopyroxene is a

TABLE 3

Summary of temperature estimates for calcic amphibole, calcic amphibole + epidote + albite, and epidote + albite alteration assemblages

Alteration type		Intrusion				
		Skaegaard intrusion	Kap Edvard Holm complex	Miki Fjord macrodike	Nordre Aputitêq intrusion	Kruuse Fjord intrusion
Calcic Amphibole + Pyroxene	T (°C)	525–825	500–875	—	—	825
	method(s):	a,b,c,d	a,c,d		—	a
Actinolitic Hornblende Chlorite + Talc	T (°C)	550–600	500–600	560–675	—	—
	method(s):	a,d	d	a,d	—	—
Actinolite + Hornblende	T (°C)	<500	—	—	—	—
	method(s):	b				
Calcic Amphibole + Epidote + Albite	T (°C)	380–560	380–560	—	—	—
	method(s):	e,f	e,f			
Epidote + Albite	T (°C)			← 200–560[a] →		
	method(s):			e,f		

[a]Temperatures apply to all occurrences of this assemblage. Alteration type has not been observed in the Miki Fjord Macrodike (table 1).
Methods: a = Perchuk (1969), b = Lindsley (1983), c = Kretz (1982), d = phase equilibria using data of Helgeson and others (1978), e = comparison with phase relations and measured temperatures in active geothermal systems, and f = experimental stability of epidote.

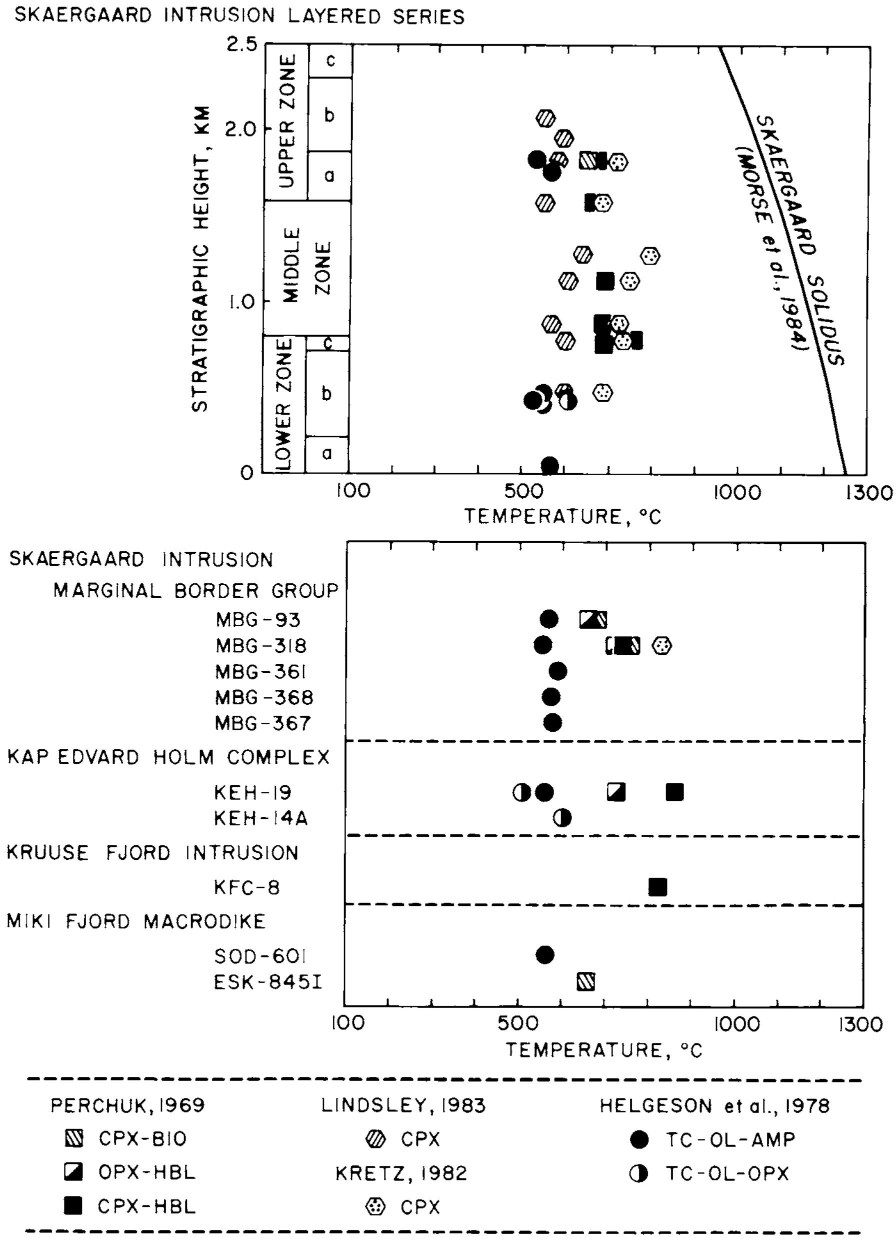


Fig. 16. Mineral thermometry of calcic amphibole + pyroxene and actinolitic hornblende + chlorite + talc veins in the Skaergaard intrusion, the Kruuse Fjord and Kap Edvard Holm complexes and the Miki Fjord macrodike. Abbreviations: CPX = clinopyroxene, OPX = orthopyroxene, BIO = biotite, OL = olivine, HBL = hornblende, AMP = Fe-Mg amphibole. The references Perchuk (1969), Lindsley (1983), Kretz (1982), and Helgeson and others (1978) refer to the data used in the geothermometry. See text.

vein-filling phase, occurring where fractures crosscut igneous orthopyroxene and olivine, whereas clinopyroxene forms as wall-rock alteration of igneous augite (table 2).

Clinopyroxene geothermometry.—Lindsley (1983) and Kretz (1982) have shown that compositions of calcic clinopyroxenes constrain the minimum temperature of pyroxene formation. Manning and Bird (1986) used this technique to estimate minimum temperatures of the hydrothermal clinopyroxenes that replace wall-rock augites near calcic amphibole veins in the Skaergaard intrusion (fig. 16). Temperature estimates derived from the average clinopyroxene compositions presented by Manning and Bird (1986) for calcic amphibole + pyroxene assemblages based on the Lindsley (1983) graphical geothermometer range from 550° to 650°C (fig. 16). Temperatures using individual clinopyroxene analyses are as high as 750°C. These temperature estimates are uniformly lower than temperatures of exchange equilibria discussed above (fig. 16), consistent with the fact that this method provides a minimum temperature estimate (Lindsley and Anderson, 1983; Lindsley, 1983). Temperatures of clinopyroxenes from calcic amphibole + pyroxene assemblages based on the Kretz thermometer (690° to 790°C, fig. 16) are comparable to those obtained using the Perchuk exchange thermometers. Vein-filling clinopyroxenes in actinolitic hornblende + chlorite + talc veins yield minimum temperatures of <500°C using Lindsley's geothermometer. Secondary salitic pyroxenes in wall-rock alteration associated with hornblende + actinolite veins also yield temperatures <500°C (Manning and Bird, 1986).

Talc ± Fe-Mg amphibole replacement of olivine.—Analysis of isobaric phase relations in the model system MgO–SiO_2–H_2O shows that replacement of olivine is sensitive to variations in temperature and fluid composition. Phase relations among talc, anthophyllite, forsterite, enstatite, and an aqueous solution have been reviewed by Hemley and others (1977), Delany and Helgeson (1978), Helgeson and others (1978), Chernosky, Day, and Caruso (1985), Day, Chernosky, and Kumin (1985), and Berman and others (1986). As discussed by these authors there is considerable uncertainty in both the topology of the predicted phase relations involving the stability of anthophyllite and the location of the quartz-absent and forsterite-absent invariant points.

Phase relations in the system MgO–SiO_2–H_2O are shown in figure 17 in terms of aqueous silica activity ($a_{SiO_{2(aq)}}$) and temperature at $P_{H_2O} = 2$ kb using the data of Helgeson and others (1978) and McKenzie and Helgeson (1984). The 2 kb fluid pressure was chosen because the high-temperature (>600°C) equation of state for aqueous silica reported by McKenzie and Helgeson (1984) was derived at this pressure. Because the general topology of equilibria depicted on the diagram does not change in the pressure range 0.5 to 2.0 kb using the phase relations proposed by Helgeson and others (1978), Day, Chernosky, and Kumin (1985), Berman and others (1986), or Hemley and others (1977), the diagram is used to interpret the metasomatic replacement of olivine marginal to the calcic amphibole veins.

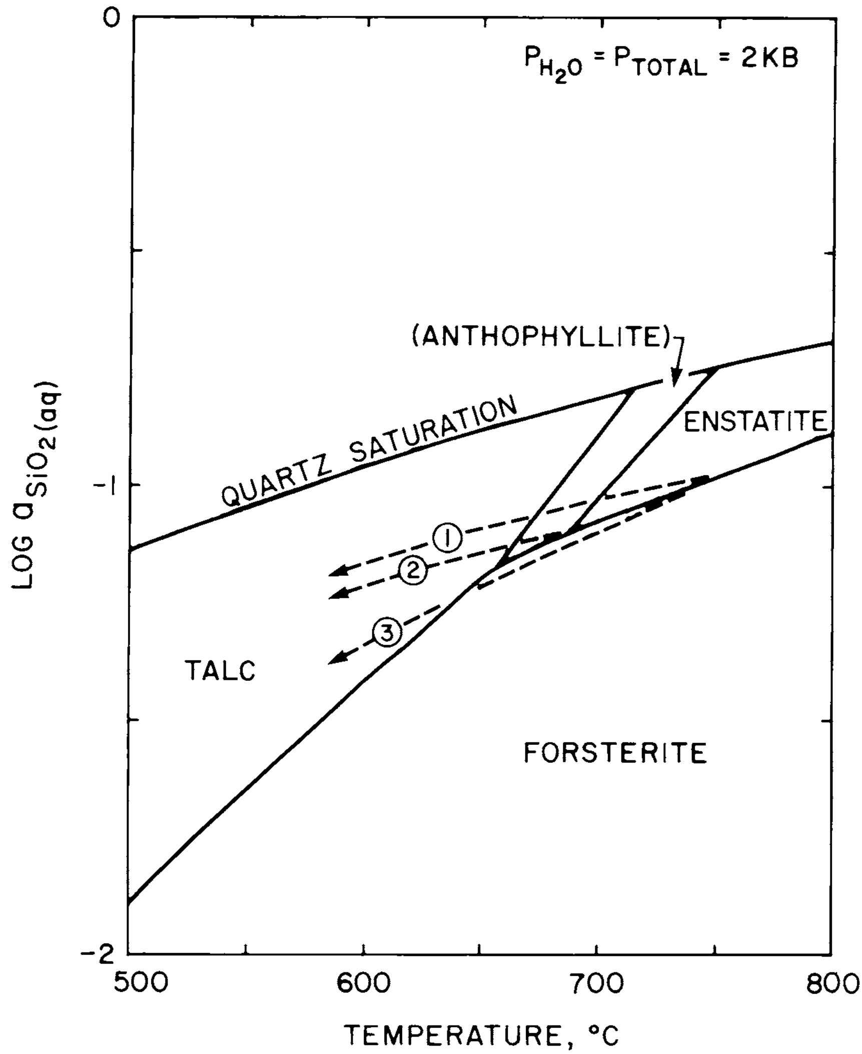


Fig. 17. Phase relations in the system $MgO-SiO_2-H_2O$ as a function of the activity of aqueous silica and temperature calculated from equations and data reported by Helgeson and Kirkham (1974), Helgeson and others (1978), and McKenzie and Helgeson (1984) at P_{H_2O} = 2.0 kb and a_{H_2O} = 1. Dashed lines represent paths that reproduce metasomatic replacement of olivine marginal to calcic amphibole veins as described in the text.

Three hypothetical isobaric cooling paths are illustrated in figure 17. Curve (1) denotes the mineral zoning marginal to calcic amphibole + pyroxene veins (for example, KEH 19; see fig. 2A for location and fig. 12A for mineral compositions). Where olivine is crosscut the vein is partially filled by orthopyroxene, and olivine in the wall rock is replaced by Fe-Mg amphibole and then by talc. In actinolitic hornblende + chlorite + talc veins that have the same sequence of olivine replacement, but lack vein-filling orthopyroxene (for example, KEH 14A; figs. 2A and 12B), the metasomatic zoning in the olivine could be represented by curve (2) in figure 17. Many calcic amphibole veins of the Lower Zone of the Skaergaard intrusion and of the Miki Fjord macrodike contain wall rock olivine partially replaced by talc without Fe-Mg amphibole. This metasomatic replacement defines a reaction path such as (3) in figure 17, requiring lower $a_{SiO_{2(aq)}}$ values at any given temperature between ~600° to 700° than required by paths (1) or (2). These phase relations indicate that small variations in aqueous silica concentration of the hydrothermal fluids may determine both the temperature at which olivine becomes unstable and the metasomatic zoning of replacement minerals. In addition, overstepping of the Fe-Mg amphibole stability field boundary by 10° to 30°C could preclude the stable formation of this phase. This is possible in light of the narrow isobaric temperature range of amphibole stability and the predicted rapid cooling rates of the fractured gabbros between 1000° and 500°C (Norton and Taylor, 1979).

Minimum equilibrium temperatures for the formation of talc from Fe-Mg amphibole replacing olivine were estimated from the following equilibrium:

$$\underset{talc}{9\,Mg_3Si_4O_{10}(OH)_2} + \underset{olivine}{4\,Mg_2SiO_4} = \underset{amphibole}{5\,Mg_7Si_8O_{22}(OH)_2} + \underset{solution}{4\,H_2O}. \quad (1)$$

The maximum temperatures for replacement of olivine by talc in the absence of Fe-Mg amphibole are approximated from the metastable equilibrium (Ferry, 1985a)

$$\underset{talc}{Mg_3Si_4O_{10}(OH)_2} + \underset{olivine}{Mg_2SiO_4} = \underset{pyroxene}{5\,MgSiO_3} + \underset{solution}{H_2O}. \quad (2)$$

The temperatures of equilibria (1) and (2) were computed from equations and data presented by Helgeson and Kirkham (1974) and Helgeson and others (1978) assuming (1) the $Mg_7Si_8O_{22}(OH)_2$ component in Fe-Mg amphiboles can be approximated by the standard state thermodynamic properties of anthophyllite, (2) unit activity of H_2O, and (3) hydrostatic pressure of P_{H_2O} = 0.5 kb. Activity-composition relations for Fe^{+2} substitution for Mg in forsterite, enstatite, anthophyllite, and talc are accounted for by assuming a random distribution of Fe^{+2} and Mg in the octahedral sites of these minerals using equations summarized by Helgeson and Aagaard (1985).

Predicted equilibrium temperatures using averaged compositions of secondary Fe-Mg amphibole, talc, and magmatic olivine marginal to calcic amphibole veins in the Kap Edvard Holm complex and Skaergaard intrusion (equilibrium 1) range between ~500° and 600°C (fig. 16). Temperature estimates using averaged compositions of metasomatic talc and magmatic olivine and orthopyroxene from the East Greenland gabbros (equilibrium 2) range from 530° to 590°C (fig. 16).

The latter temperature range is only slightly larger than that of 525° to 545°C estimated by Ferry (1985a) for talc alteration of olivines in the Isle of Skye gabbros.

Epidote + Albite Assemblages

Because epidote does not occur in the calcic amphibole vein or wall-rock assemblages in which olivine is partially replaced by talc + magnetite, the temperature of epidote formation was probably less than the temperature of talc formation; that is, less than ~500° to 600°C. This is consistent with a maximum temperature of 560°C for the stability of iron-rich epidote ($X_{Ca_2Fe_3Si_3O_{12}(OH)}$ = 0.33) in equilibrium with hematite + magnetite + quartz at 0.5 kb (Liou, 1973). This maximum temperature decreases with decreasing iron content in epidote and with decreasing oxygen fugacity (Holdaway, 1972; Liou, 1973). Ferry (1985a) reports epidote formation temperatures of 436° to 570°C in the Isle of Skye gabbro. The minimum temperature of epidote formation in the gabbros was probably ~200° to 250°C based on the first occurrence of epidote in active geothermal systems (Bird and others, 1984).

Additional phases coexisting with epidote + albite place further temperature constraints on this alteration type. The first occurrence of epidote + albite + hornblende at measured temperatures of ~380°C in the Nesjavellir geothermal system in Iceland (Hreggvidsdottir, ms) provides the best minimum temperature estimate for the formation of this alteration type. The maximum temperature at which prehnite can coexist with epidote + albite (~350° to 400°C) decreases with increasing Fe^{+3} content in coexisting prehnite and epidote solid solutions (Bird and Helgeson, 1981; Rose and Bird, 1987). Assemblages including salite + epidote + albite are limited to temperatures of ≥325°C based on the observed occurrence of hydrothermal clinopyroxenes in active geothermal systems (Bird and others, 1984). Prehnite + epidote + actinolite + chlorite are in equilibrium only below ~400°C based on the experiments of Liou, Maruyama, and Cho (1985). Thermodynamic analysis of prehnite + muscovite + epidote phase relations in the Nordre Aputitêq intrusion suggests that this assemblage formed at <300°C (Rose and Bird, 1987).

Summary of Alteration Temperatures

The temperature estimates derived for the calcic amphibole and epidote-bearing assemblages are summarized in table 3. Based on the above discussion, the alteration types can be divided into high-temperature (>500°–600°C) and low-temperature (<500°–600°C) assemblages. High-temperature alteration includes calcic amphibole + pyroxene and actinolitic hornblende + chlorite + talc assemblages, and low-temperature alteration includes actinolite + hornblende, calcic amphibole + epidote + albite, and epidote + albite assemblages.

MINERALOGIC ALTERATION AND EVOLUTION OF THE HYDROTHERMAL SYSTEMS

The extent to which the gabbros are mineralogically altered during their cooling histories is a complex function of the structural evolution of the fracture systems, the timing and extent of fracture sealing by secondary minerals, temperature, pressure, reaction kinetics, host-rock composition and mineralogy, the source and composition of hydrothermal fluids, and the transport of mass by the fluid (Norton, 1979, 1984). The field, petrographic, and compositional data that bear on these interrelated elements of gabbro-hosted magma-hydrothermal systems in East Greenland are discussed below.

Structural Histories of Fracture Systems

Macroscopic fracture systems.—The modal abundance of alteration minerals and field and paragenetic relations discussed above, as well as by Norton, Taylor, and Bird (1984), Bird, Rogers, and Manning (1986), and Rogers and Bird (1987), indicate that the evolution of hydrothermal circulation systems and water-rock reactions is closely related to the magmatic and structural controls on fracture formation in the gabbros. Although the distribution, abundance, and geometry of fractures, cavities, and altered gabbro are unique to each intrusive complex, the types of secondary mineral assemblages (table 1) and the general trends of certain fracture systems are similar in the gabbros.

The earliest hydrothermal fractures systems to form in the Marginal Border Group and Layered Series of the Skaergaard intrusion host calcic amphibole + pyroxene and locally actinolitic hornblende + chlorite + talc vein assemblages. These vein sets are oriented approximately parallel or perpendicular to the margins of the intrusion in the Marginal Border Group gabbros (rose diagrams A through F in fig. 18) and have a radial distribution within the Layered Series gabbros (bars within the Layered Series, fig. 18). Later fracture systems that host actinolite + hornblende, calcic amphibole + epidote + albite, epidote + albite, quartz, and chlorite vein types in the Layered Series and Marginal Border Group of the Skaergaard intrusion have close geometric relations to granophyres and mafic dikes and sills (Bird, Rogers, and Manning, 1986; Rogers and Bird, 1987). Many of these veins are oriented east-west (rose diagrams G and H in fig. 18), which is parallel to the dike complex near the Skaergaard intrusion. Similar structural relations are observed in the Kap Edvard Holm complex, where the earliest fractures in the central portion of the Middle Layered Series contain calcic amphibole + pyroxene veins that trend northwest (fig. 19), a direction we interpret as part of a radial set of fractures in this portion of the complex (fig. 2A). Crosscutting actinolitic hornblende + chlorite + talc veins at the same locality are oriented northeast (fig. 19), which is parallel to local dike orientations.

The geometric relations of the vein types described above suggest that the early fracture systems were closely related to the geometry of the intrusion, probably formed by stresses associated with the cooling

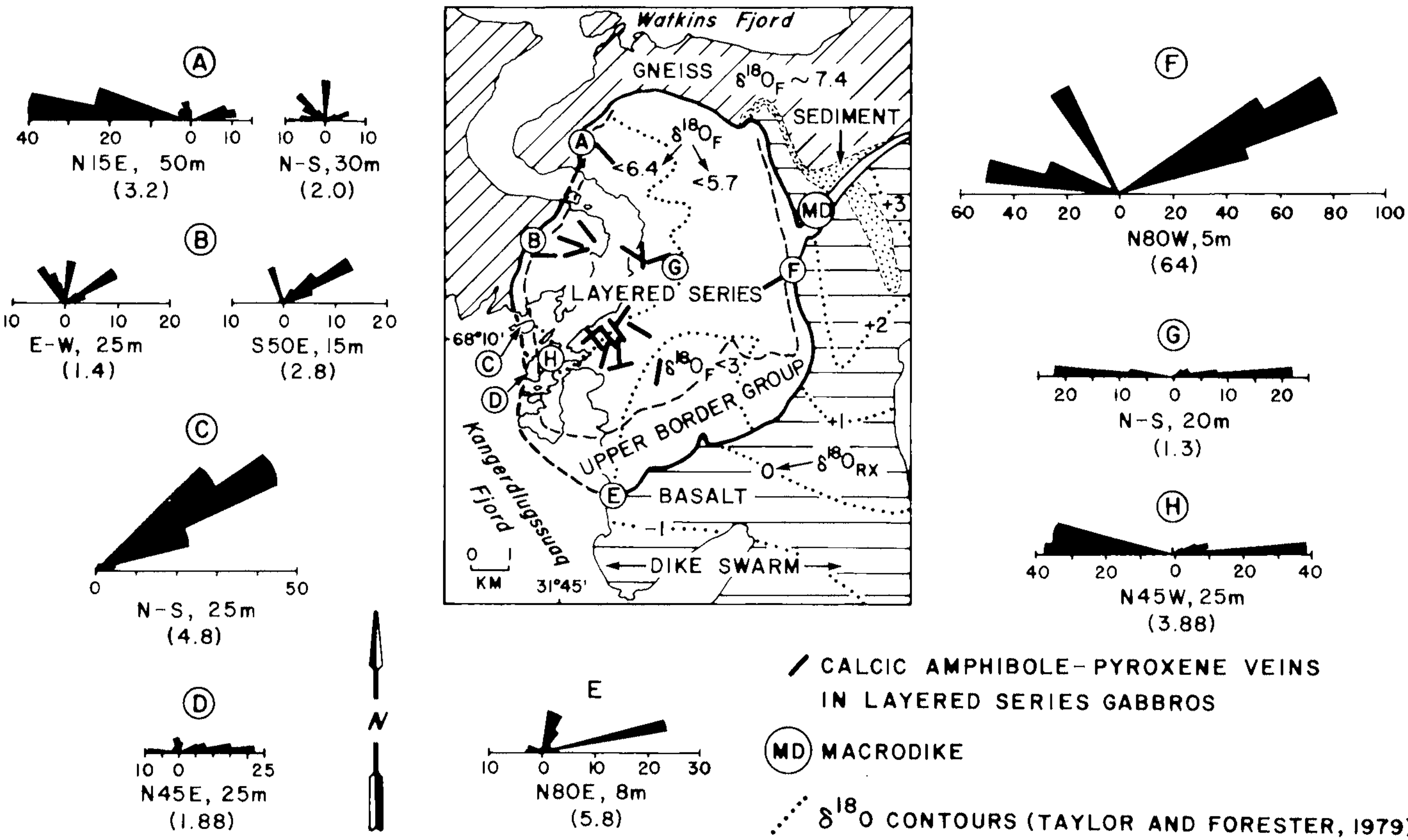


Fig. 18. Generalized geologic map of the Skaergaard intrusion showing the orientations of early calcic amphibole veins in the Marginal Border Group (rose diagrams A through F) and in the Layered Series gabbros (bars). Note that these vein orientations are, in general, either parallel to or normal to the contact of the intrusion with its host rocks. Rose diagrams G and H show orientations of late-stage hornblende + actinolite and chlorite vein sets that parallel the regional east-west dike swarm near the Skaergaard intrusion. Contours of $\delta^{18}O$ for plagioclase feldspar (F) and whole rock (RX) are from Taylor and Forester (1979).

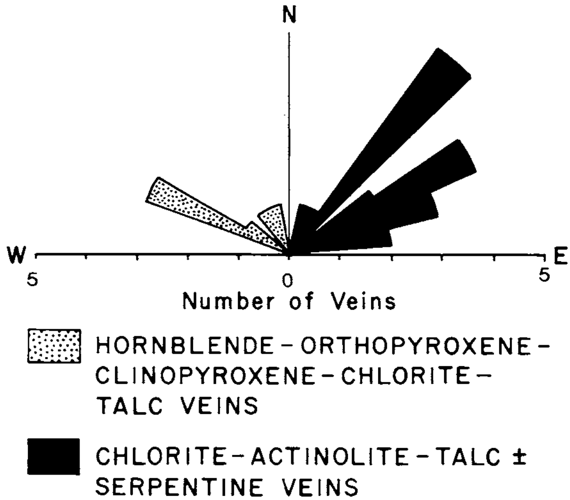


Fig. 19. Rose diagram of early calcic amphibole + pyroxene veins (stippled) and later actinolitic hornblende + chlorite + talc and serpentine veins in the Middle Layered Series of the Kap Edvard Holm complex.

and contraction of the gabbros. Later fracture formation was caused primarily by local stresses associated with the later gabbroic and granophyric intrusions, as well as by regional stresses associated with crustal extension and emplacement of the coast-parallel dike complex. These observations demonstrate that the distribution of porosity in the gabbros changed in time and space as a consequence of variations in the regional and local stress conditions responsible for fracture formation.

Microscopic fracture systems.—The concentration of calcic amphibole alteration near vein margins, with only trace amounts of secondary minerals between veins, appears to be inconsistent with Taylor and Forester's (1979) observation that plagioclase throughout the Skaergaard intrusion is depleted in ^{18}O relative to unaltered magmatic plagioclase. However, close observations of the gabbros away from macroscopic veins reveal mineral-filled microfractures and planar arrays of fluid inclusions (fig. 20; see also figs. 33–35 and 50A of Wager and Brown, 1967; pls. 1B and C of Taylor and Forester, 1979; fig. 2F of Manning and Bird, 1986). These features, together with the occurrence of minor amounts of secondary minerals along grain boundaries, demonstrate that fluid flow occurred along grain boundaries and in microfracture networks as well as in the macroscopic vein systems. The microfracture networks may have provided sufficient permeability in the gabbros between the macroscopic vein systems for the transport and exchange of oxygen isotopes between meteoric hydrothermal solutions and igneous minerals throughout the gabbros studied. Further studies of $\delta^{18}O$ gradients about the macroscopic veins and of the distribution

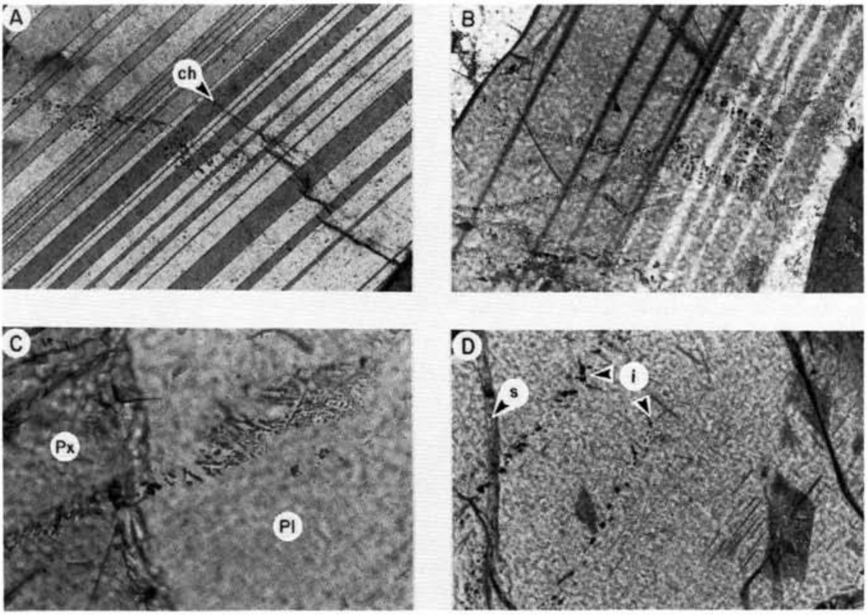


Fig. 20. Photomicrographs of microfractures in igneous minerals. (A) Chlorite (Ch) filled microfracture in plagioclase from the Middle Zone of the Skaergaard intrusion. A plane of irregular-shaped fluid inclusions occurs in the plagioclase just below the label (Ch). Photo is 0.4 mm wide. (B) Annealed microfracture network represented by planes of fluid inclusions in plagioclase from the Middle Layered Series of the Kap Edvard Holm complex. Photo is 0.4 mm wide. (C) Annealed microfracture represented by a plane of fluid inclusions in the Lower Zone c gabbros of the Skaergaard intrusion. Note the apparent offset of the grain boundary between the igneous pyroxene (Px) and plagioclase (Pl) by the microfracture. Photo is 0.2 mm wide. (D) Microfractures in olivine from the southeastern portion of the Kruuse Fjord intrusion. Microfracture marked (s) is filled with serpentine. Planes of oxide inclusions marked (i) in the photo are contiguous with fluid inclusion planes in adjacent plagioclase and probably represent annealed microfractures.

and abundance of microfractures are required to evaluate quantitatively the relation between mineralogic and isotopic alteration of cooling gabbros at temperatures >500° to 600°C.

Distribution of Hydrothermal Alteration and Fracture Sealing

Distribution of alteration assemblages.—The distribution of modally abundant secondary minerals in the Skaergaard intrusion and the Kap Edvard Holm complex are shown in figure 7. In the Skaergaard intrusion calcic amphibole alteration types are primarily restricted to the lower and middle portions of the intrusion, whereas the more extensive epidote + albite alteration is concentrated within and near the later Basistoppen sheet in the upper portions of the intrusion. The distribution of alteration types in the Kap Edvard Holm complex is more complex than that at the Skaergaard intrusion, with alternating calcic amphibole and epidote + albite alteration with increasing stratigraphic height. However, when considered in light of Elsdon's (1969) hypothesis that each of the three layered series at Kap Edvard Holm represents a separate intrusion, there are close similarities in the distribution of modally abundant secondary minerals between the Skaergaard intrusion and the Kap Edvard Holm complex. For example, in the Lower Layered Series, where our sampling is most complete, the lower and middle portions contain calcic amphibole assemblages, and the upper portion contains extensive epidote + albite alteration (fig. 7B). It thus appears that high-temperature water-rock interactions occurred throughout the solidified and cooling intrusions, and that only the upper portions of the intrusions have experienced the more extensive, lower temperature alteration. The concentration of epidote + albite alteration in the upper portions of these intrusions may be a consequence of the emplacement and cooling of later intrusions, such as the Basistoppen sheet in the Skaergaard intrusion and the Middle Layered Series in the Kap Edvard Holm complex.

Correlation of mineralogic and isotopic alteration.—Of the gabbros studied, the distribution of $\delta^{18}O_{plagioclase}$ is known only in the Skaergaard intrusion (Taylor and Forester, 1979). Comparison of this distribution with that of the alteration types summarized in figure 7A allows qualitative correlation of mineralogic and isotopic alteration. The high-temperature calcic amphibole + pyroxene vein assemblages from the Skaergaard intrusion reported by Manning and Bird (1986) occur in or near rocks where $\delta^{18}O_{plagioclase} \geq 5.0$ permil. These altered gabbros occur primarily in the Lower and Middle Zones of the Skaergaard intrusion and are depleted in ^{18}O by ≤ 1.5 permil relative to the unaltered plagioclase (Taylor and Forester, 1979). In contrast, in the Upper Border Group and Basistoppen sheet of the Skaergaard intrusion where low-temperature alteration assemblages are most abundant (Bird, Rogers, and Manning, 1986), $\delta^{18}O_{plagioclase}$ is <4.0 permil, depleted >2.5 permil relative to plagioclase in unaltered gabbros.

Norton and Taylor (1979) calculated a time-integrated, volume-averaged water-rock ratio of 0.52 for the upper part of the Skaergaard intrusion. Minimum water-rock mass ratios required by the ^{18}O depletions near the calcic amphibole + pyroxene and actinolitic hornblende + chlorite + talc assemblages, where $\delta^{18}O_{plagioclase} > 5$ permil, are <0.1 at $>500°$ to $600°C$ (see fig. 27 of Taylor, 1974). Because of the similarity in phase relations, mineral compositions, and textures in all the calcic amphibole-altered gabbros studied here, it is likely that this type of alteration in the Kap Edvard Holm and Kruuse Fjord complexes and in the Miki Fjord macrodike also occurred at low water-rock mass ratios.

Relative water-rock mass ratios are >0.2 at $<500°$ to $600°C$ where $\delta^{18}O_{plagioclase} < 4.0$, which corresponds to modally abundant epidote + albite, hornblende + actinolite, and iron-rich calcic amphibole + pyroxene assemblages in the Skaergaard intrusion. The inferred higher water-rock mass ratios for the lower temperature alteration is consistent with the more extensive metasomatic replacement and fracturing of the gabbros that contain these types of secondary assemblages.

Sealing of high-temperature fractures.—Higher water-rock mass ratios associated with low-temperature alteration, combined with the concentration of these types of alteration in the upper parts of the Skaergaard intrusion and the Kap Edvard Holm complex, suggest that the permeabilities of the high-temperature fracture systems were dramatically reduced at temperatures of ~500° to 600°C. Because of the similar distribution and paragenetic relations of secondary minerals in the gabbros studied, it is likely that the early, high-temperature, calcic amphibole-filled fracture systems were sealed by similar mechanisms. Complete filling of these veins by secondary minerals would prevent both the formation of lower temperature epidote + albite mineral assemblages and more extensive ^{18}O depletions in the gabbros by reducing permeability through mineralogic sealing of the fractures. A possible mechanism for sealing the early fracture systems is considered below.

Augites broken by the early fracture systems are recrystallized to hydrothermal clinopyroxene + Fe-Ti oxides at temperatures between 550° to 900°C. With decreasing temperature to ~500° to 600°C, talc + magnetite ± Fe-Mg amphibole replaces olivine within several millimeters of the fractures. Hydrolysis and oxidation of olivine to produce talc + magnetite ± Fe-Mg amphibole releases Mg^{+2} and H_2 to the fluid phase at constant or nearly constant volume (Hemley and others, 1977; Ferry, 1985a) and addition of H_2O and possibly SiO_2 to the altered gabbro. The flux of Mg into the hydrothermal solutions at reaction sites where olivine is hydrolyzing, together with the strong partitioning of Mg into the amphibole relative to the fluid phase (fig. 21), will cause a decrease in the chemical affinity of the amphibole-forming reactions in the vein fluids. This could in turn lead to precipitation of amphiboles within the veins. Because lower temperature phases such as epidote, albite, prehnite, and sphene are absent from most of the early calcic amphibole veins, the fractures must have been sealed shortly after the formation of the talc + magnetite ± Fe-Mg amphibole pseudomorphs of olivine. Local elemental mass transfer associated with the hydrolysis and oxidation of olivine near the high-temperature fractures probably represents the mechanism leading to mineralogic fracture sealing at temperatures of ~500° to 600°C and consequently preservation of the high-temperature alteration assemblages throughout the lower portions of these intrusions.

Controls on the Fe-Mg Content of Vein Amphiboles

Compositional variation in vein-filling calcic amphiboles can be correlated with variations in temperature and bulk-rock composition and mineralogy. Figures 11 and 13 illustrate that the molecular proportions of Mg and Fe^{+2} of fracture-filling calcic amphiboles are closely related to the Mg/Fe^{+2} of the gabbros hosting the veins. The major source of Mg and Fe^{+2} in the bulk gabbro are olivines, pyroxenes, and Fe-Ti oxides, all of which show some degree of alteration near the veins. Molecular Mg/Fe^{+2} ratios for igneous pyroxenes, olivines, average

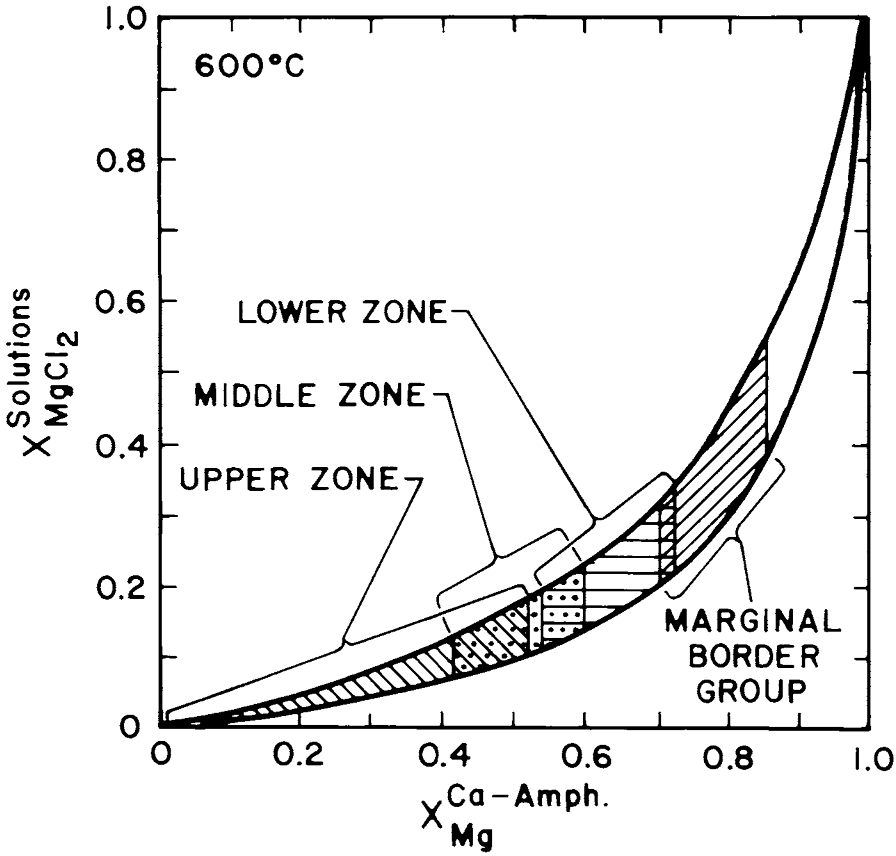


Fig. 21. Relationship of the mole fraction of $MgCl_2$ in an aqueous fluid ($X^{fluid}_{MgCl_2}$) and the mole fraction of Mg in calcic amphiboles (hornblende, X^{amph}_{Mg}) for early calcic amphibole veins in the Skaergaard intrusion. X^{amph}_{Mg} is $n_{Mg}/(n_{Mg} + n_{Fe^{+2}})$ in vein-filling calcic amphibole, and $X^{fluid}_{MgCl_2}$ is $n_{MgCl_2}/(n_{MgCl_2} + n_{FeCl_2})$ in aqueous solution required for equilibrium, where n is number of moles. Diagram modified after Eugster and Ilton (1983) for the approximate range of Fe-Mg partitioning between calcic amphibole and an aqueous solution at 600°C and 1 kb.

gabbro, and vein-filling calcic amphiboles from the Skaergaard intrusion are given in figure 22. A partition coefficient ($K_{Mg\text{-}Fe}$) between the fracture-filling calcic amphiboles and the igneous Fe-Mg silicates or the average gabbros shown in figure 22 can be written as:

$$K_{Mg\text{-}Fe} = \frac{\left(\frac{n_{Mg}}{n_{Fe}}\right)_{amp}}{\left(\frac{n_{Mg}}{n_{Fe}}\right)_{i}} \qquad (3)$$

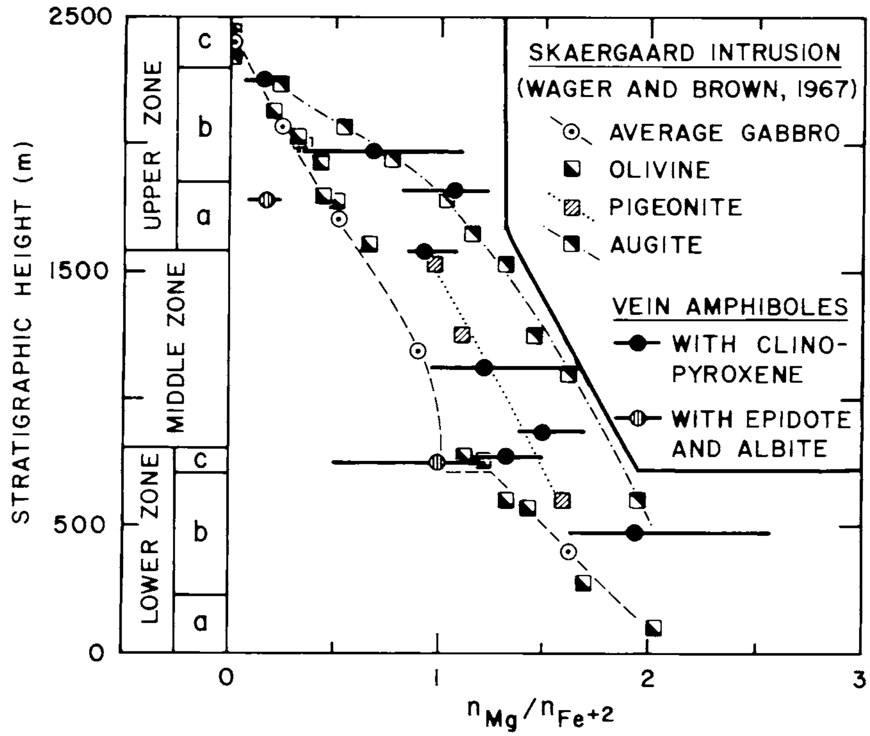


Fig. 22. Molecular Mg/Fe^{+2} of average gabbros, magmatic phases, and vein amphiboles as a function of stratigraphic height in the Skaergaard intrusion. Horizontal bars denote ranges in vein amphibole compositions and solid and hatched circles are averaged compositions.

where the subscript i refers to an igneous Fe-Mg silicate (olivine, inverted pigeonite, or augite) or to the average gabbro, and the subscript *amp* refers to vein-filling calcic amphibole. Considering the averaged composition of calcic amphiboles from the early alteration assemblages (solid circles in fig. 22), values of $K_{Mg\text{-}Fe}$ are greater than unity when i = bulk gabbro and olivine, approximately unity for i = inverted pigeonite, and less than unity when i = augite. $K_{Mg\text{-}Fe}$ calculated using averaged compositions of calcic amphiboles from the later epidote + albite-bearing assemblages (hachured circles, fig. 22) are less than unity relative to the host gabbro and its igneous mineralogy. When compared to table 3 it is apparent that vein amphiboles formed at >500° to 600°C are more Mg-rich than amphiboles formed at lower temperatures for the same bulk gabbro composition and mineralogy.

Source and Composition of Hydrothermal Fluids

Stable isotope studies of three gabbros of the North Atlantic Tertiary igneous province, the Skaergaard intrusion, and the intrusive complexes at Mull and the Isle of Skye (fig. 1) demonstrate that the hydrothermal solutions that reacted with these gabbros were low $\delta^{18}O$ meteoric waters (Forester and Taylor, 1976, 1977; Taylor and Forester, 1979). Hydrogen isotope analyses of the Lilloise intrusion (fig. 1) by Sheppard, Brown, and Chambers (1977) indicate that magmatic water was responsible for most of the amphibole alteration within the gabbro and in the contact metamorphosed basalts. The Lilloise amphiboles include pargasite, hastingsite, and kaersutite with Ti contents >0.4 atoms per 23 anhydrous oxygens (Brown, Tocher, and Chambers, 1982) and are distinct from vein amphiboles in the five gabbros studied here (<0.2 Ti atoms per 23 anhydrous oxygens). Similarities in amphibole compositions and mineral assemblages between the Skaergaard intrusion and the Kap Edvard Holm and Kruuse Fjord complexes, the Miki Fjord macrodike and Nordre Aputitêq intrusions suggest that meteoric waters were also a major component of the hydrothermal solutions in all the gabbros studied.

Fluid inclusions in vein quartz within the Skaergaard intrusion and throughout its contact aureole contain low-salinity fluids with <3 wt percent NaCl equivalent (Bird, Rogers, and Manning, 1986; Bird, Manning, and Rose, unpub. data). Vug-filling minerals in metamorphosed basalts at the eastern contact of the Skaergaard intrusion locally include fluorite (Manning and Bird, 1987), as well as halite (<10 μ) and sylvite (2–3 μ). Quartz veins in these rocks contain fluid inclusions with 6 to 10 wt percent NaCl equivalent. These observations suggest that boiling or mixing with a more saline solution such as seawater may have occurred locally.

The inferred low water-rock mass ratios (see above) and the presumably rapid reaction rates at ~500° to 900°C probably led to buffering of hydrothermal fluid compositions by metasomatic exchange reactions with the igneous mineralogy on a grain-size scale. Olivine and pyroxenes are replaced by the greatest volumes of secondary minerals marginal to the calcic amphibole veins, whereas only a minor amount of the vein-margin plagioclase is replaced. This suggests that the fluids were close to local equilibrium with the igneous feldspars in the gabbros during the early stages of hydrothermal alteration. At the lower temperatures (<500°–600°C) associated with epidote + albite- and hornblende + actinolite-alteration, the primary igneous phases are not stable and hydrolyze to form varying amounts of epidote, albite, prehnite, actinolite, and chlorite. Olivine and plagioclase are usually completely replaced by the secondary minerals, whereas augite is only partially replaced. Local equilibrium between vein-filling Ca-Al-silicates and the fluid phase associated with this lower temperature alteration requires that the hydrothermal solutions had a low CO_2 fugacity (<10 bars) and were close to quartz saturation (Bird, Rogers, and Manning, 1986; Rose and Bird, 1987).

Elemental Mass Transfer

Although the quantitative aspects of mass transfer have not been addressed as part of this study, comparison of the type and distribution of observed high-temperature alteration assemblages to similar assemblages in other altered mafic rocks suggests that, with the exception of H_2O addition to the rock, most of the elements mobilized during mineralogic alteration are locally redistributed within the altered gabbros. For example, actinolitic hornblende + chlorite + talc alteration of Mg-rich olivine gabbros of the Skaergaard Lower Zone and of the Kap Edvard Holm complex involves pseudomorphic replacement of olivine by talc + magnetite, releasing Mg to the fluid phase. This Mg could have been used in local metasomatic reactions with plagioclase and the vein fluids to form calcic amphibole and chlorite. Mass transfer calculations for the constant-volume replacement of olivine by talc + magnetite, plagioclase by chlorite or calcic amphibole, and augite by calcic pyroxene + calcic amphibole + ilmenite suggest that, except for H_2O addition to gabbros, and SiO_2 and Mg release from gabbros, very little mass transfer is required to account for the metasomatic alteration zones about the high-temperature veins. Similar results are reported by Ferry (1985a) for the high-temperature alteration of the Isle of Skye gabbros.

The lower temperature episodes of alteration are commonly characterized by extensive metasomatic replacement of host gabbros by modally abundant epidote and prehnite together with albite. Analysis of bulk-rock elemental gains and losses associated with epidote- and/or prehnite-rich alteration of mafic rocks has demonstrated the addition of Ca, Al, and H_2O, removal of alkalis and Mg, and either addition or removal of Fe and Si in this type of alteration (Balsilie, 1937; Watson, 1953; Elsdon, 1982; Marzouki, Kerrick, and Fyfe, 1982). The occurrence of spatially distinct albite-rich domains and epidote ± prehnite-rich domains in the altered gabbros demonstrates that Na- and Ca-metasomatism may have been localized on both outcrop and thin section scales.

CONCLUDING REMARKS

Detailed field and petrographic examination of mineralogic alteration in the five East Greenland gabbros suggests that there are characteristic assemblages of hydrothermal minerals that formed at temperatures ranging from ~900°C to ambient temperatures (~200°–250°C) during the subsolidus cooling histories of these intrusions. Preserved mineral assemblages are analogous to those ranging from the upper amphibolite facies to the zeolite facies in basalts metamorphosed at low pressures (Spear, 1981; Liou, Maruyama, and Cho, 1985).

In the East Greenland gabbros the distribution of the various assemblages of secondary minerals (table 1) is directly related to the nature of permeable structures that permitted hydrothermal solutions to flow through and react with the cooling intrusions. The earliest fracturing of the gabbros was associated with the emplacement of gabbroic pegmatites (Norton, Taylor, and Bird, 1984). Following pegmatite emplacement, near-vertical hydrothermal fracture systems, geometrically related to the shapes of the intrusions, were formed probably by stresses associated with the cooling and contraction of the gabbros. Water-rock reactions in these fractures produced calcic amphibole +

pyroxene assemblages at temperatures between ~500° to 900°C. Actinolitic hornblende + chlorite + talc assemblages may have formed at somewhat lower temperatures, but mineralogic phase relations indicate that veins hosting this assemblage were sealed at temperatures of ~500° to 600°C, similar to the calcic amphibole + pyroxene veins. In olivine-bearing gabbros, hydration and oxidation of magmatic olivine may have been an important reaction leading to the mineralogic sealing of these vein types, precluding overprinting by epidote + albite assemblages. At high temperatures the distribution of vein-filling minerals is dependent on local wall-rock mineralogy. Water to rock mass ratios associated with high temperature alteration were low (<0.1).

Later, lower temperature (<500°–600°C) alteration includes hornblende + actinolite and epidote-bearing alteration assemblages. The lower temperature alteration types are closely related to fracturing events associated with local secondary intrusions or to the emplacement of the regional mafic dike complex. Low-temperature alteration is characterized by compositional and paragenetic complexity and extensive metasomatic replacement of the gabbros within localized zones of the intrusions. The distribution of vein minerals associated with low-temperature alteration is usually independent of the wall-rock mineralogy. Higher water-rock ratios (>0.2) accompanied the low-temperature alteration.

The combination of higher temperature, faster reaction kinetics, and lower water/rock mass ratios associated with the formation of calcic amphibole + pyroxene and actinolitic hornblende + chlorite + talc veins led to conditions where the types of secondary minerals were determined within microscopic domains that vary on a grain size scale. In these domains fluid compositions were probably controlled by reactions with the local gabbro mineralogy. Compositional variations in the fluid phase with time may have been important in determining phase relations as illustrated in figure 17 and discussed by Mével (1987) for calcic amphibole altered oceanic gabbros from the mid-Atlantic ridge. The more extensive metasomatic alteration of the gabbros and formation of vein mineralogy that is independent of the host-rock mineralogy at <500°–600°C suggest that hydrothermal mobilization and redistribution of chemical components were more efficient during the low-temperature alteration. This may be attributed to greater fluid flux, larger water/rock mass ratios, to decreased stability of primary igneous mineralogy, and to the sensitivity of secondary mineral solubilities to minor variations of temperature and pressure under conditions that are close to the critical point for H_2O (Norton 1979, 1984).

Hydrothermal alteration of the kind described here is not unique to the East Greenland Tertiary igneous province. Fracturing and secondary alteration has been reported in a number of other gabbros worldwide, including the Mull and Cuillin gabbros (Forester and Taylor, 1976, 1977; Ferry, 1985a), the Bushveld complex (Schiffries and Skinner, 1987), the Stillwater complex (Boudreau, Mathez, and McCallum, 1986; B. Waters and L. Caruso, personal commun., 1986 and 1987), the

Artfjället gabbro (Otten, 1983, 1984), ophiolites (for example, Mével, Caby, and Kienast, 1978; Liou and Ernst, 1979; Stern and Elthon, 1979; Girardeau and Mével, 1982; Evarts and Schiffman, 1983; Schiffman and others, 1987), and dredged oceanic gabbros and related ultramafic rocks (Bonatti and others, 1975; Honnorez, Mével, and Montigny, 1984; Prichard and Cann, 1982; Mottl, 1983; Ito and Anderson, 1983; Gallinatti, 1984; Batiza and Vanko, 1985; Kimball, Spear, and Dick, 1985; Stakes and Vanko, 1986; Kelly and Delany, 1987; Mével, 1987). Description and analysis of the well-exposed and relatively simple gabbro-hosted magma-hydrothermal systems of East Greenland provide a basis for interpretation of other hydrothermally altered gabbros that may be structurally and mineralogically more complex.

Deep drilling in geothermal systems in the rift valleys of Iceland and the Salton Trough, Calif. commonly encounter temperatures of 300° to 350°C at depths between 2 to 2.5 km. Numerical modeling of these types of hydrothermal systems (Norton and Knight, 1977; Norton and Taylor, 1979; Elders and others, 1984) shows that fracture permeabilities of $\sim 10^{-12}$ to 10^{-13} cm^2 in solidified cooling intrusions are essential for the convective transport of thermal energy leading to the development of 300° to 350°C isotherms within several kilometers of the Earth's surface. It is apparent from this and from the present study that the development of fracture systems and subsequent water-rock reactions critically affect the evolution of magma-hydrothermal systems associated with upper crustal gabbroic intrusions. Evidence from the East Greenland gabbros suggests that fracture permeability changed spatially and temporally throughout the intrusions' cooling histories as older fractures sealed with secondary minerals and new fractures were formed. The evolution of a steady state spreading system from a continental rift environment, such as is recorded in the East Greenland Tertiary province and the present-day North Atlantic ridge spreading center, must encompass an increase in the extent of structural disruption and multiple magma injection associated with the development of oceanic magma-hydrothermal systems. This is locally demonstrated by the increasing complexity of secondary mineral parageneses with increasing structural and magmatic complexity of the East Greenland gabbros.

ACKNOWLEDGMENTS

This research benefited from our association with S. Adalsteinsson, T. I. H. Anderson, S. Bernstein, C. K. Brooks, L. Caruso, S. Forsstedt, R. Gannicott, A. Gaines, H. Hreggvidsdottir, T. N. Irvine, C. Lesher, A. R. McBirney, H. R. Naslund, T. F. D. Nielsen, T. Nielsen, A. Noe-Nygaard, D. Norton, E. Padovani, W. L. E. Penno, M. T. Rosing, D. Rumble III, H. P. Taylor, Jr., and B. Waters. This study was made possible by combined logistics with Platinova Resources Ltd. (Canada), C. K. Brooks (Univ. of Copenhagen), the Geodetic Institute (Denmark), and the Geological Survey of Greenland during field seasons in 1981, 1982, 1984, 1986 and 1987. The manuscript was substantially improved by the perceptive reviews of C. K. Brooks, L. Caruso, J. Ferry, T. F. D. Nielsen, and A. B. Thompson. Research was supported by National Science Foundation (NSF-EAR 82-15120, NSF-EAR 84-18129 and NSF-EAR 86-06256 to DKB). CEM thanks the Corning Glass Corporation, the McGee Trust, the Geological Society of America, and the Shell Companies for their support.

References

Abbott, D., and Deer, W. A., 1972, Geological investigations in East Greenland, Pt. X. The gabbro cumulates of the Kap Edvard Holm lower layered series: Medd. om Grønland, v. 190, 42 p.

Balsillie, D., 1932, The Ballantrae igneous complex, south Ayrshire: Geol. Mag., v. 69, p. 107–131.

Batiza, R., and Vanko, D. A., 1985, Petrologic evolution of large failed rifts in the eastern Pacific: petrology of volcanic and plutonic rocks from the Mathematician Ridge area and the Guadalupe trough: Jour. Petrology, v. 26, p. 564–602.

Beckinsdale, R. D., Brooks, C. K., and Rex, D. C., 1970, K-Ar ages for the Tertiary of East Greenland: Geol. Soc. Denmark Bull., v. 20, p. 27–37.

Berman, R. G., Engi, M., Greenwood, H. J., and Brown, T. H., 1986, Derivation of internally consistent thermodynamic data by the technique of mathematical programming: A review with application to the system MgO-SiO_2-H_2O: Jour. Petrology, v. 27, p. 1331–1364.

Bird, D. K., and Helgeson, H. C., 1981, Chemical interaction of aqueous electrolyte solutions with epidote-feldspar mineral assemblages in geologic systems. II. Equilibrium constraints in metamorphic/geothermal processes: Am. Jour. Sci., v. 281, p. 576–614.

Bird, D. K., Rogers, R. D., and Manning, C. E., 1986, Mineralized fracture systems of the Skaergaard intrusion: Medd. om Grønland, Geosci., v. 16, 68 p.

Bird, D. K., Rosing, M. T., Manning, C. E., and Rose, N. M., 1985, Geologic field studies of the Miki Fjord area, East Greenland: Geol. Soc. Denmark Bull., v. 34, p. 219–236.

Bird, D. K., Schiffman, P., Elders, W. A., Williams, A. E., and McDowell, S. D., 1984, Calc-silicate mineralization in active geothermal systems: Econ. Geology, v. 79, p. 671–695.

Bonatti, E., Honnorez, J., Kirst, P., and Radicati, F., 1975, Metagabbros from the Mid-Atlantic ridge at 06°N: contact-hydrothermal-dynamic metamorphism beneath the axial valley: Jour. Geology, v. 83, p. 61–78.

Boudreau, A. E., Mathez, E. A., and McCallum, I. S., 1986, Halogen geochemistry of the Stillwater and Bushveld complexes: evidence for transport of the platinum-group elements of Cl-rich fluids: Jour. Petrology, v. 27, p. 967–986.

Bridgwater, D., Davies, F. B., Gill, R. C. O., Gorman, B. E., Myers, J. S., Pedersen, S., and Taylor, P., 1978, Precambrian and Tertiary geology between Kangerdlugssuaq and Angmagssalik, East Greenland: Rapp. Grønlands Geol. Unders., v. 83, 17 p.

Brooks, C. K., 1979, Geomorphological observations at Kangerdlugssuaq, East Greenland: Medd. om Grønland, Geosci., v. 1, 21 p.

——— 1980, Episodic volcanism, epeirogenesis and the formation of the North Atlantic ocean: Paleogeography Paleoclimatology Paleoecology, v. 30, p. 229–242.

Brooks, C. K., and Gleadow, A. J. W., 1977, A fission-track age for the Skaergaard intrusion and the age of the East Greenland basalts: Geology, v. 5, p. 539–540.

Brooks, C. K., and Nielsen, T. F. D., 1978, Early stages in the differentiation of the Skaergaard magma as revealed by a closely related suite of dike rocks: Lithos, v. 11, p. 1–14.

——— 1982a, The Phanerozoic development of the Kangerdlugssuaq area, East Greenland: Medd. om. Grønland, Geosci., v. 9, 30 p.

——— 1982b, The East Greenland continental margin: a transition between oceanic and continental magmatism: Geol. Soc. London Jour., v. 139, p. 265–275.

Brown, P. E., and Becker, S. M., 1986, Fractionation, hybridisation and magma-mixing in the Kialineq centre East Greenland: Contr. Mineralogy Petrology, v. 92, p. 57–70.

Brown, P. E., Chambers, A. D., and Becker, S. M., 1987, A large soft-sediment fold in the Lilloise intrusion, East Greenland, *in* Parsons, I., ed., Origins of Igneous Layering: Dordrecht, D. Reidel, p. 125–143.

Brown, P. E., and Farmer, D. G., 1972, Size-graded layering in the Imilik gabbro: Geol. Mag., v. 108, p. 465–475.
Brown, P. E., Tocher, F. E., and Chambers, A. D., 1982, Amphiboles in the Lilloise intrusion, East Greenland: Mineralog. Mag., v. 45, p. 47–54.
Brown, P. E., van Breeman, O., Noble, R. H., and Macintyre, R. M., 1977, Mid-Tertiary igneous activity in East Greenland—the Kialineq complex: Contr. Mineralogy Petrology, v. 64, p. 109–122.
Chernosky, J. V., Day, H. W., and Caruso, L. J., 1985, Equilibria in the system MgO-SiO_2-H_2O: experimental determination of the stability of Mg-anthophyllite: Am. Mineralogist, v. 70, p. 223–236.
Day, H. W., Chernosky, J. V., and Kumin, H. J., 1985, Equilibria in the system MgO-SiO_2-H_2O: a thermodynamic analysis: Am. Mineralogist, v. 70, p. 237–248.
Deer, W. A., 1976, Tertiary igneous rocks between Scoresby Sund and Kap Gustav Holm, East Greenland, *in* Escher, A. and Watt, W. S., eds., Geology of Greenland: Copenhagen, Geol. Survey of Greenland, p. 405–429.
Deer, W. A., and Abbott, D., 1965, Clinopyroxenes of gabbro cumulates of the Kap Edvard Holm complex, East Greenland: Mineralog. Mag., v. 34, p. 177–193.
Delany, J. M., and Helgeson, H. C., 1978, Calculation of the thermodynamic consequences of dehydration in subducting oceanic crust to 100 kb and >800°C: Am. Jour. Sci., v. 278, p. 638–686.
Douglas, J. A. V., 1964, Geologic investigations in East Greenland, Pt. VII. The Basistoppen sheet, a differentiated basic intrusion into the upper part of the Skaergaard complex, East Greenland: Medd. om. Grønland, v. 164, 66 p.
Elders, W. A., Bird, D. K., Williams, W. E., and Schiffman, P., 1984, Hydrothermal flow regime and magmatic heat source of the Cerro Prieto geothermal field of Baja California, Mexico: Geothermics, v. 13, p. 27–37.
Elsdon, R., 1969, The structure and intrusive mechanism of the Kap Edvard Holm layered gabbro complex, East Greenland: Geol. Mag., v. 106, p. 45–56.
——— 1971, Crystallization history of the upper layered series, Kap Edvard Holm, East Greenland: Jour. Petrology, v. 12, p. 499–521.
——— 1982, Autometasomatic alteration of gabbro, Kap Edvard Holm intrusive complex, East Greenland: Mineralog. Mag., v. 45, p. 219–225.
Escher, A. and Watt, W. S., eds., 1976, Geology of Greenland: Copenhagen, Geol. Survey of Greenland, 603 p.
Eugster, H. P., and Ilton, E. S., 1983, Mg-Fe fractionation in metamorphic environments, *in* Saxena, S. K., ed., Kinetics and equilibrium in mineral reactions: New York, Springer-Verlag, Adv. in Phys. Geochemistry, v. 3, p. 115–140.
Evarts, R. C., and Schiffman, P., 1983, Submarine hydrothermal metamorphism of the Del Puerto ophiolite, California: Am. Jour. Sci., v. 283, p. 289–340.
Ferry, J. M., 1985a, Hydrothermal alteration of Tertiary igneous rocks from the Isle of Skye, northwest Scotland. I. Gabbros: Contr. Mineralogy Petrology, v. 91, p. 264–282.
———1985b, Hydrothermal alteration of Tertiary igneous rocks from the Isle of Skye, northwest Scotland. II. Granites: Contr. Mineralogy Petrology, v. 91, p. 283–304.
Ferry, J. M., Mutti, L. J., and Zuccala, G. J., 1987, Contact metamorphism/hydrothermal alteration of Tertiary basalts from the Isle of Skye, northwest Scotland: Contr. Mineralogy Petrology, v. 95, p. 166–181.
Forester, R. W., and Taylor, H. P., Jr., 1976, ^{18}O-depleted igneous rocks from the Tertiary complex of the Isle of Mull, Scotland: Earth Planetary Sci. Letters, v. 32, p. 11–17.
——— 1977, $^{18}O/^{16}O$, D/H, and $^{13}C/^{12}C$ studies of the Tertiary igneous complex of Skye, Scotland: Am. Jour. Sci., v. 277, p. 136–177.
Gallinatti, B. C., 1984, Initiation and collapse of active circulation in a hydrothermal system at the mid-Atlantic ridge, 23°N: Jour. Geophys. Research, v. 89, p. 3275–3289.
Girardeau, J., and Mével, C., 1982, Amphibolitized sheared gabbros from ophiolites as indicators of the evolution of the oceanic crust: Bay of Islands, Newfoundland: Earth Planetary Sci. Letters, v. 61, p. 151–165.
Gleadow, A. J. W., and Brooks, C. K., 1979, Fission track dating, thermal histories and tectonics of igneous intrusions in East Greenland: Contr. Mineralogy Petrology, v. 71, p. 45–60.
Hawthorne, F. C., 1981, The crystal chemistry of the amphiboles: Canadian Mineralogist, v. 21, p. 173–480.

Helgeson, H. C., and Aagaard, P., 1985, Activity/composition relations among silicates and aqueous solutions. I. Thermodynamics of intrasite mixing and substitutional order/disorder in minerals: Am. Jour. Sci., v. 285, p. 769–844.
Helgeson, H. C., Delany, J. M., Nesbitt, H. W., and Bird, D. K., 1978, Summary and critique of the thermodynamic properties of rock-forming minerals: Am. Jour. Sci., v. 278-A, 229 p.
Helgeson, H. C., and Kirkham, D. H., 1974, Theoretical prediction of the thermodynamic behavior of aqueous electrolytes at high pressures and temperatures: I. Summary of the thermodynamic properties of the solvent: Am. Jour. Sci., v. 274, p. 1089–1198.
Hemley, J. J., Montoya, J. W., Shaw, D. R., and Luce, R. W., 1977, Mineral equilibria in the MgO-SiO_2-H_2O system: II talc-antigorite-forsterite-anthophyllite-enstatite stability relations and some geologic implications in the system: Am. Jour. Sci., v. 277, p. 353–383.
Holdaway, 1972, Thermal stability of aluminum-iron epidote as a function of f_{O_2} and iron content: Contr. Mineralogy Petrology, v. 36, p. 307–340.
Honnorez, J., Mével, C., and Montigny, R., 1984, Geotectonic significance of gneissic amphibolites from the Vema fracture zone, equatorial Mid-Atlantic ridge: Jour. Geophys. Research, v. 89, p. 11,379–11,400.
Hreggvidsdottir, H., ms, 1987, The greenschist to amphibolite facies transition in the Nesjavellir hydrothermal system, southwest Iceland: M.S. thesis, Stanford Univ., 61 p.
Ito, E., and Anderson, A. T., 1983, Submarine metamorphism of gabbros from the Mid-Cayman rise: petrographic and mineralogic constraints on hydrothermal processes at slow spreading ridges: Contr. Mineralogy Petrology, v. 82, p. 371–388.
Kays, M. A., McBirney, A. R., and Goles, G. G., 1981, Xenoliths of gneisses and the conformable, clot-like granophyres in the Marginal Border Group, Skaergaard intrusion, East Greenland: Contr. Mineralogy Petrology, v. 76, p. 265–284.
Kays, M. A., and McBirney, A. R., 1982, Origin of the picrite blocks in the Marginal Border Group of the Skaergaard intrusion, East Greenland: Geochim. et Cosmochim. Acta, v. 46, p. 23–30.
Kelly, D. S., and Delaney, J. R., 1987, Two-phase separation and fracturing in mid-ocean ridge gabbros at temperatures greater than 700°C: Earth Planetary Sci. Letters, v. 83, p. 53–66.
Kempe, D. R. C., and Deer, W. A., 1970, The petrogenesis of the Kangerdlugssuaq alkaline intrusion, East Greenland: Medd. om Grønland, v. 190, 95 p.
Kimball, K. L., Spear, F. S., and Dick, H. J. B., 1985, High temperature alteration of Abyssal ultramafics from the Islas Orcadas Fracture Zone, South Atlantic: Contr. Mineralogy Petrology, v. 91, p. 307–320.
Kretz, R., 1982, Transfer and exchange equilibria in a portion of the pyroxene quadrilateral as deduced from natural and experimental data: Geochim. et Cosmochim. Acta, v. 46, p. 411–421.
Larsen, H. C., 1978, Offshore continuation of East Greenland dike swarm and associated coastal flexure: Nature, v. 274, p. 220–223.
——— 1980, Geological perspectives of the East Greenland continental margin: Geol. Soc. Denmark Bull., v. 29, p. 77–101.
——— 1984, Geology of the East Greenland shelf, *in* Spencer, A. M., et al., eds., Petroleum Geology of the North European Margin: London, Norwegian Petroleum Soc., p. 329–339.
Leake, B. E., 1978, Nomenclature of amphiboles: Canadian Mineralogist, v. 16, p. 501–520.
Lindsley, D. H., 1983, Pyroxene thermometry: Am. Mineralogist, v. 68, p. 477–493.
Lindsley, D. H., and Anderson, D. J., 1983, A two pyroxene thermometer, *in* Proc. 13th Lunar and Planetary Sci. Conf., pt. 2: Jour. Geophys. Research, v. 88 (suppl.), p. A887–A906.
Liou, J. G., 1973, Synthesis and stability relations of epidote, $Ca_2Al_2FeSi_3O_{12}(OH)$: Jour. Petrology, v. 14, p. 381–413.
Liou, J. G., and Ernst, W. G., 1979, Oceanic ridge metamorphism of the East Taiwan Ophiolite: Contr. Mineralogy Petrology, v. 68, p. 335–348.
Liou, J. G., Maruyama, S., and Cho, M., 1985, Phase equilibria and mineral paragenesis in low-grade metamorphism: Mineralog. Mag., v. 49, p. 321–333.
Manning, C. E., and Bird, D. K., 1986, Hydrothermal clinopyroxenes of the Skaergaard intrusion: Contr. Mineralogy Petrology, v. 92, p. 437–447.
——— 1987, Wollastonite + fluorite in metabasalt host rocks of the Skaergaard intrusion: implications for metamorphic fluid composition: Geol. Soc. America Abs. with Programs, v. 19, no. 7, p. 759.

Marzouki, F., Kerrich, R., and Fyfe, W. S., 1979, Epidotisation of diorites at Al Haddah, Saudi Arabia: Fluid influx into cooling plutons: Contr. Mineralogy Petrology, v. 68, p. 281–284.

McKenzie, W. F., and Helgeson, H. C., 1984, Estimation of the dielectric constant of H_2O from experimental solubilities of quartz, and calculation of the thermodynamic properties of aqueous species to 900°C at 2 kb: Geochim. et Cosmochim. Acta, v. 11, p. 2167–2177.

Mével, C., 1987, Evolution of oceanic gabbros from DSDP Leg 82: influence of the fluid phase on metamorphic crystallizations: Earth Planetary Sci. Letters, v. 83, p. 67–79.

Mével, C., Caby, R., and Kienast, J.-R., 1978, Amphibolite facies conditions in the oceanic crust: example of amphibolitized flaser-gabbro and amphibolites from the Chenaillet ophiolite massif (Haute Alpes, France): Earth Planetary Sci. Letters, v. 39, p. 98–108.

Morse, S. A., Lindsley, D. H., and Williams, R. J., 1980, Concerning intensive parameters in the Skaergaard intrusion: Am. Jour. Sci., v. 280-A, p. 159–170.

Mottl, M. J., 1983, Metabasalts, axial hot springs, and the structure of hydrothermal systems at mid-ocean ridges: Geol. Soc. America Bull., v. 94, p. 161–180.

Myers, J. S., 1980, Structure of the coastal dyke swarm and associated plutonic intrusions of East Greenland: Earth Planetary Sci. Letters, v. 46, p. 401–418.

Naslund, H. R., 1986, Disequilibrium partial melting and rheomorphic layer formation in the contact aureole of the Basistoppen sill, East Greenland: Contr. Mineralogy Petrology, v. 93, p. 359–367.

Naslund, H. R., Hughes, J. M., and Birnie, R. W., 1983, Ilvaite, an alteration product replacing olivine in the Skaergaard intrusion: Am. Mineralogist, v. 68, p. 1004–1008.

Nielsen, T. F. D., 1975, Possible mechanism of continental breakup in the North Atlantic: Nature, v. 253, p. 182–184.

——— 1978, The Tertiary dike swarms of the Kangerdlugssuaq area, East Greenland. An example of magmatic development during continental break-up: Contr. Mineralogy Petrology, v. 67, p. 63–78.

Nielsen, T. F. D., Soper, N. J., Brooks, C. K., Faller, A. M., Higgins, A. C., and Matthews, D. W., 1981, The pre-basaltic sediments and the lower basalts at Kangerdlugssuaq, East Greenland: their stratigraphy, lithology, palaeomagnetism and petrology: Medd. om Grønland, Geosci., v. 6, 25 p.

Norton, D., 1979, Transport phenomena in hydrothermal systems: the redistribution of chemical components around cooling magmas: Bull. Minéralogie, v. 102, p. 471–486.

——— 1984, Theory of hydrothermal systems: Ann. Rev. Earth Planetary Sci., v. 12, p. 155–177.

Norton, D., and Knight, J. E., 1977, Transport phenomena in hydrothermal systems: cooling plutons: Am. Jour. Sci., v. 277, p. 937–981.

Norton, D., and Taylor, H. P., Jr., 1979, Quantitative simulation of the hydrothermal systems of crystallizing magmas on the basis of transport theory and oxygen isotope data: an analysis of the Skaergaard intrusion: Jour. Petrology, v. 20, p. 421–486.

Norton, D., Taylor, H. P., Jr., and Bird, D. K., 1984, The geometry and high temperature brittle deformation of the Skaergaard intrusion: Jour. Geophy. Research, v. 89, p. 10,178–10,192.

Otten, M. T., ms, 1983, The magmatic and subsolidus evolution of the Artfjället gabbro, central Swedish Caledonides: Ph.D. thesis, Univ. Utrecht (Netherlands), 185 p.

——— 1984, The origin of brown hornblende in the Artfjället gabbro and dolerites: Contr. Mineralogy Petrology, v. 86, p. 189–199.

Pankhurst, R. J., Beckinsdale, R. D., and Brooks, C. K., 1976, Strontium and oxygen isotopic evidence relating to the petrogenesis of the Kangerdlugssuaq alkaline intrusion, East Greenland: Contr. Mineralogy Petrology, v. 54, p. 17–42.

Perchuk, L. L., 1969, The effect of temperature and pressure on the equilibrium of natural iron-magnesium minerals: Internat. Geology Rev., v. 11, p. 875–901.

Prichard, H. M., and Cann, J. R., 1982, Petrology and Mineralogy of Dredged gabbro from Gettysburg Bank, eastern Atlantic: Contr. Mineralogy Petrology, v. 79, p. 46–55.

Rex, D. C., Gledhill, A. R., Brooks, C. K., and Steenfelt, A., 1979, A Rb-Sr whole rock age of 55 ± 7 m.y. from the Nualik plutonic centre, East Greenland: Rapp. Grønlands Geol. Unders., v. 95, p. 102–105.

Robinson, P., 1980, The compositional space of terrestrial pyroxenes—internal and external limits, *in* Prewitt, C. T., ed., Pyroxenes: Mineral Soc. America Reviews in Mineralogy, v. 7, p. 419–494.

Rogers, R. D., and Bird, D. K., 1987, Fracture propagation associated with dike emplacement at the Skaergaard intrusion, East Greenland: Jour. Structural Geology, v. 9, p. 71–86.
Rose, N. M., and Bird, D. K., 1987, Prehnite-epidote phase relations in the Nordre Aputitêq and Kruuse Fjord layered gabbros, East Greenland: Jour. Petrology, v. 28, p. 1193–1218.
Schiffman, P., Smith, B. M., Varga, R. J., and Moores, E. M., 1987, Geometry, conditions and timing of off-axis hydrothermal metamorphism and ore-deposition in the Solea graben: Nature, v. 325, p. 423–425.
Schiffries, C. M., and Skinner, B. J., 1987, The Bushveld hydrothermal system: field and petrologic evidence: Am. Jour. Sci., v. 287, p. 566–595.
Sheppard, S. M. F., Brown, P. E., and Chambers, A. D., 1977, The Lilloise intrusion, East Greenland: hydrogen isotope evidence for the efflux of magmatic water into the contact metamorphic aureole: Contr. Mineralogy Petrology, v. 63, p. 129–147.
Spear, F. S., 1981, An experimental study of hornblende stability and compositional variability in amphibolite: Am. Jour. Sci., v. 281, p. 697–734.
Stakes, D., and Vanko, D. A., 1986, Multistage hydrothermal alteration of gabbroic rocks from the failed Mathematician Ridge: Earth Planetary Sci. Letters, v. 79, p. 75–92.
Stern, C., and Elthon, D., 1979, Vertical variations in the effects of hydrothermal metamorphism in Chilean ophiolites: their implications for ocean floor metamorphism: Tectonophysics, v. 55, p. 179–213.
Tagiri, M., 1977, Fe-Mg partition and miscibility gap between coexisting amphiboles from the southern Abakuma plateau, Japan: Contr. Mineralogy Petrology, v. 62, p. 271–281.
Talwani, M., and Eldholm, O., 1977, Evolution of the Norwegian-Greenland Sea: Geol. Soc. America Bull., v. 88, p. 969–999.
Taylor, H. P., Jr., 1974, The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition: Econ. Geology, v. 69, p. 843–883.
Taylor, H. P., Jr., and Forester, R. W., 1979, An oxygen isotope study of the Skaergaard intrusion and its country rocks: a description of a 55-m.y. old fossil hydrothermal system: Jour. Petrology, v. 20, p. 355–419.
Wager, L. R., 1934, Geological investigations in East Greenland, Pt. I. General geology from Angmagsalik to Kap Dalton: Medd. om Grønland, v. 105, 46 p.
——— 1947, Geological investigations in East Greenland, Pt. IV. The stratigraphy and tectonics of Knud Rasmussens Land and the Kangerdlugssuak region: Medd. om Grønland, v. 5, 64 p.
Wager, L. R., and Deer, W. A., 1938, A dyke swarm and crustal flexure in East Greenland: Geol. Mag., v. 75, p. 39–46.
——— 1939, Geological investigations in East Greenland, Pt. III. The petrology of the Skaergaard intrusion, Kangerdlugssuak region: Medd. om Grønland, v. 134, 352 p.
Wager, L. R., and Brown, G. M., 1967, Layered Igneous Rocks: San Francisco, W. H. Freeman, 588 p.
Watson, K. D., 1953, Prehnitization of albitite: Am. Mineralogist., v. 38, p. 197–206.