GRØNLANDS GEOLOGISKE UNDERSØGELSE

RAPPORT Nr. 97

The Geological Survey of Greenland
Report No. 97

The tholeiitic and komatiitic affinities of the Malene metavolcanic amphibolites from Ivisârtoq, southern West Greenland

by

R. P. Hall

KØBENHAVN 1980

Grønlands Geologiske Undersøgelse

(The Geological Survey of Greenland)

Øster Voldgade 10, DK-1350 Copenhagen K

Reports

GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT Nr. 97

The tholeiitic and komatiitic affinities of the Malene metavolcanic amphibolites from Ivisârtoq, southern West Greenland

by

R. P. Hall

1980

Abstract

The chemistry of a suite of representative samples of the various Malene amphibolite lithologies from Ivisârtoq has been analysed by X-ray fluorescence (XRF) techniques. The major element chemistry of the amphibolites is very variable and is compared to that of amphibolites from other Archaean terrains and to modern basaltic lavas. Pillow-structured and intercalated homogeneous horizons prevail among the amphibolites of Ivisârtoq. These predominant units comprise a suite which ranges chemically from abyssal tholeiite through to basaltic and pyroxenitic komatiite in character, and chromium and nickel contents are in accordance with this classification. The well preserved pillow structures indicate that these rocks originated as subaqueous basic and ultrabasic lavas, and include the first reported ultramafic pillows in the Archaean of southern West Greenland.

Author's address:
Department of Geology,
Portsmouth Polytechnic,
Burnaby Road,
Portsmouth PO1 3QL,
U.K.

Contents

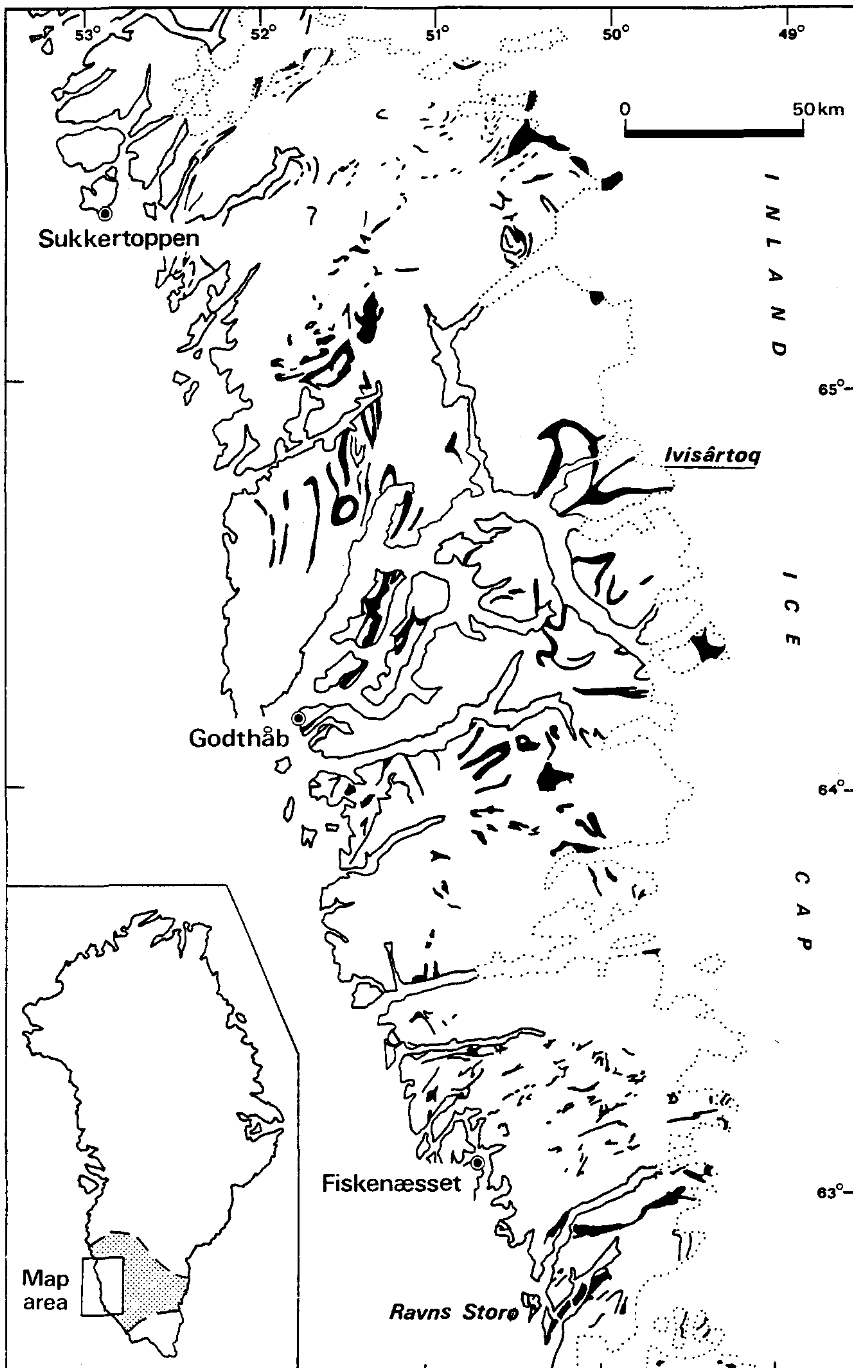

Fig. 1. Sketch map showing the distribution of the major Malene-type supracrustal horizons (black) in the Archaean craton of southern West Greenland (after Allaart *et al.*, 1977; 1978; Bridgwater *et al.*, 1976). The shaded area on the inset map of Greenland depicts the extent of the Archaean craton.

Introduction

Amphibolite horizons are ubiquitous throughout the Archaean craton of Greenland as well as in other Archaean high-grade gneiss terrains. Their chemistry is a significant factor in the understanding of their original magmatic setting and hence of the tectonic environment in which they evolved. The amphibolite belts of West Greenland appear to form a continuous suite from the areas at the southern and northern margins of the Archaean craton into the Malene supracrustal rocks of the central region around Godthåbsfjord (fig. 1). They represent the oldest preserved material in the border regions of the craton (Pidgeon & Hopgood, 1975; Friend, 1975; Rivalenti, 1976) while they are juxtaposed with the older Amîtsoq gneisses which may have formed a basement complex in the Godthåbsfjord region (Allaart *et al.*, 1977; 1978; Bridgwater *et al.*, 1974; Chadwick & Coe, 1976; Hall & Friend, 1979).

Despite their widespread occurrence, the supracrustal rocks are generally highly deformed in the majority of areas and outcrop mainly as horizons of compositionally banded amphibolites and trains of boudins or xenoliths within the younger quartzo-feldspathic gneisses. Consequently the significance of the chemistry of the more deformed horizons is questionable. The majority of amphibolites on Ivisârtoq occur as well preserved pillow-structured and intercalated homogeneous horizons, in which the varying degrees of deformation are easily monitored. These rocks provide the opportunity to study the chemistry of a suite of relatively undeformed amphibolites proximal to the Amîtsoq gneisses, and this report presents the findings on the major element chemistry and chromium and nickel contents of a suite of these rocks. A broader comparison of these amphibolites with those which are remote from the Amîtsoq gneisses in the south of the craton in the Fiskenæsset and Frederikshåb regions (Rivalenti, 1976), and particularly the Ravns Storø belt (fig. 1; Friend, 1975), has been discussed by Friend *et al.* (in press).

Stratigraphy and structure of Ivisârtoq

The Archaean stratigraphy of the Godthåbsfjord region was described by McGregor (1973) and a broader account of the Archaean of West Greenland is presented by Bridgwater *et al.* (1976). The stratigraphy of Ivîsartoq is in accord with that previously established for the region and has been described by Friend & Hall (1977). A simplified geological map of the Ivîsartoq area is presented in fig. 2 and a description of the structural history of the inner Godthåbsfjord region has been given by Hall & Friend (1979).

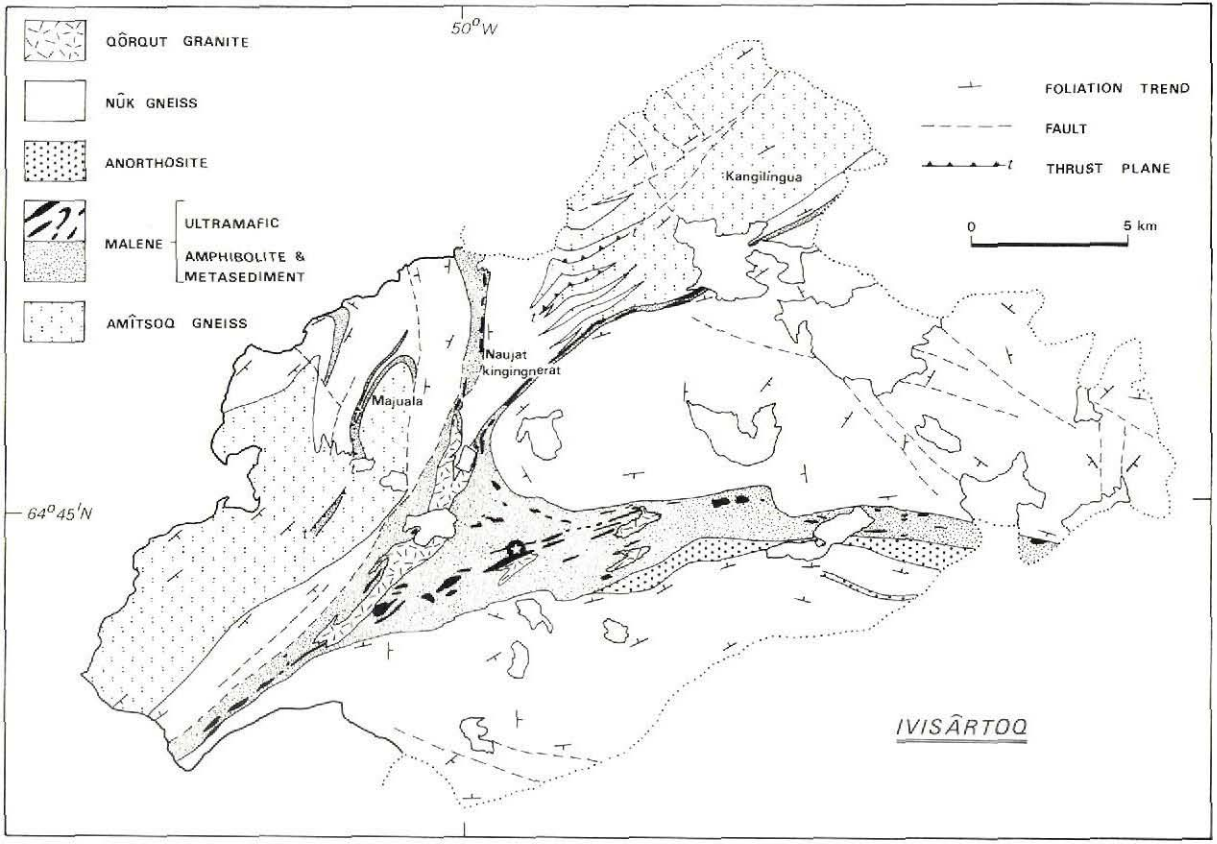

Fig. 2. Geological sketch map of Ivisârtoq. The Amîtsoq gneisses at Kangilíngua occur in the core of a major F2 synformal closure of the two northern amphibolite limbs at Naujat kingingnerat, while those in the west occupy the core of a complementary antiform which closes to the north of Ivisârtoq. The southern limb of the Malene rocks is also the core (now isoclinal) of the F2 synform, refolded about a west-south-west trending anticline. The asterisk indicates the locality of analysed samples presented in Table 1.

The oldest rocks on Ivisârtoq occur as enclaves within the Amîtsoq gneisses (*c*. 3750 m.y., Moorbath *et al.*, 1972). These intensely deformed heterogeneous quartzo-feldspathic banded Amîtsoq gneisses occur in the north-east and west of Ivisârtoq (fig. 2), and the enclaves they contain form a suite of amphibolites, ultrabasics and metasedimentary rocks, including an iron formation, which are related to the Isua supracrustal rocks (*c*. 3760 m.y., Moorbath *et al.*, 1977) and Akilia association (McGregor & Mason, 1977). A swarm of basic dykes, the Ameralik dykes, cut an early fabric (F1) in the Amîtsoq gneisses but were themselves metamorphosed to amphibolite, boudinaged and brought into parallelism with the gneissic fabric during subsequent deformation.

Ivisârtoq is dominated by a major westerly closing V-shaped structure formed by two ridges of Malene supracrustal rocks. These rocks comprise a suite of pillow-structured and homogeneous amphibolites, interpreted as originally water-lain basic lavas, associated with minor gabbroic bodies and intercalated with various types of metasedimentary units (predominantly quartz-biotite schists) and kilometre-scale lenses of coarse-grained ultrabasic (peridotitic) material. This belt of Malene supracrustal rocks has undergone two phases of large scale folding (F2 and F3). The Amîtsoq gneisses at Kangilíngua (fig. 2) occupy the core of a major F2 synform and those in the west of Ivisârtoq the core of the complementary (F2) antiform which closes to the north of Ivisârtoq (fig. 3) (Hall & Friend, 1979). The large F2

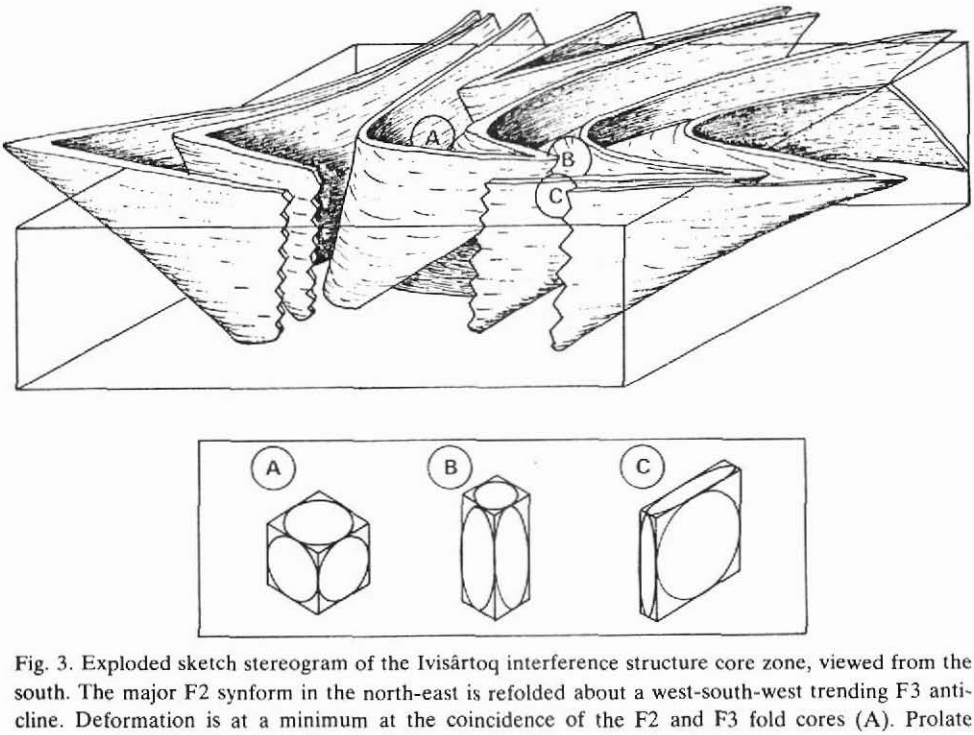

Fig. 3. Exploded sketch stereogram of the Ivisârtoq interference structure core zone, viewed from the south. The major F2 synform in the north-east is refolded about a west-south-west trending F3 anticline. Deformation is at a minimum at the coincidence of the F2 and F3 fold cores (A). Prolate structures are developed where the F2 core enters the southern F3 limb (B) and intense flattening occurs where the limbs coincide (C). The limit of exposure of the structure on Ivisârtoq is indicated by the frame.

synform has wavelength and amplitude with values in the order of 30 km and 40 km respectively and is refolded about an F3 anticline of similar scale which plunges moderately to the south-west. Thus the southern Malene limb of the F3 anticline is also the core, now isoclinal, of the F2 synform (fig. 3).

As the older Amîtsoq gneisses occupy the cores of both the F2 synform and antiform, their pre-F2 folding disposition must have been both above and below the Malene supracrustal rocks, and this indicates an early episode of interleaving by thrusting of the Malene and Amîtsoq rocks. This is born out by the local preservation of relict thrust planes to the south-west of Majuala and west of Kangilíngua (fig. 2), although younger Nûk gneisses (*c.* 2900 m.y., Moorbath & Pankhurst, 1976) have been emplaced as granitic sheets and bodies along these thrust planes and into subsequent developing fold structures. There is no indication of the distances involved during the early thrusting epiode and none to discern whether the Malene supracrustals and Amîtsoq basement gneisses originally occurred in a cover-basement relationship or were juxtaposed tectonically. No evidence of an unconformity exists between these two complexes and no basal conglomerates were identified within the Malene suite although Chadwick & Nutman (1979) believe that they have recognized an unconformity at the west coast, in the small islands to the south of Godthåb (fig. 1).

Amphibolites

The majority of the amphibolites on Ivisârtoq are variably deformed pillow-structured units and presumably orginated as subaqueous basic lavas (fig. 4). These rocks are frequently intercalated with concordant homogeneous amphibolites which are interpreted as flows and sills. The state of deformation of the rocks can be related to their position within the major fold interference structure. The pillows are best preserved at the coincidence of the cores of the principal intersecting F2 synform and F3 antiform (fig. 3). They vary in size from approximately 10 cm to 1 m in length and small and large pillows may occur together (fig. 5). At some localities cuspate bases and flat tops to pillows are preserved indicating

Fig. 4. Undeformed pillow-structured amphibolite showing preserved cuspate bases and flattened tops to pillows which have darker margins and leucocratic rims. Field of view *c.* 80 cm long.

Fig. 5. Variable undeformed pillow structures showing original irregular shape, slightly darker margins and leucocratic rims. More mafic inter-pillow material occurs between some of the pillows. Notebook 17 cm long.

their original orientation (fig. 4). Most of the pillows are composed of either fine-grained, grey amphibolite or grey-green diopside and epidote-bearing amphibolite, surrounded by 2–3 cm marginal zones of darker amphibole-rich material and thin layers of leucocratic material which effectively outline individual pillows. Where the F2 synform core enters the southern limb of the F3 fold the pillows become prolate, plunging steeply west-south-west (fig. 3). They become progressively flattened oblate structures and also compositionally banded where the limbs of the folds coincide (fig. 6). The progressive deformation of pillowed amphibolites into 'striped' and rodded amphibolites has also been noted in the Ravns Storø supracrustal belt (fig. 1; Friend, 1975) and elsewhere throughout the southern

Fig. 6. Compositionally banded 'striped' amphibolites developed by progressive flattening of pillows and the associated development of diposide, epidote and garnet.

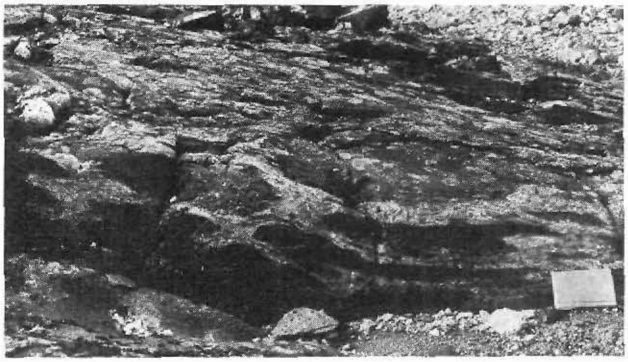

Fig. 7. Fine-grained ultramafic (hornblendite) pillows in an epidote- and diopside-rich matrix. The ultramafic pillows range in size from 20 to 150 cm.

West Greenland Archaean craton (Dawes, 1970; Myers, 1978) and also in similar rocks in Finland (Ehlers, 1976) and Austria (Holland & Norris, 1979). The Ivisârtoq locality forms an excellent example of this deformation and segregation where the transformation can be traced around and related to a single major structure.

Horizons of ultramafic pillows set in a very pale green matrix are intimately associated with the more typical pillowed amphibolite units (fig 7). These ultramafic pillows have the same variability in size as the amphibolitic ones but are composed almost entirely of amphibole, while the matrix is rich in diopside and epidote. The amphibole is dark green, occurring as fine-grained polygonal granoblastic mosaics, and no original igneous textures have been recognized either in the field or in thin section.

However, as relict igneous textures are often preserved in areas of low deformation, and the pillowed units are demonstrably little deformed, it is thought that the fine grain size and monomineralic nature of some of the ultramafic pillows reflect their original character and indicate their recrystallization from a single mineral (pyroxene?) parent. Relict cumulus textures are commonly preserved within units of the Fiskenæsset layered gabbro-anorthosite complex (Myers, 1978) and amygdaloidal textures persist within some of the less magnesian pillows in the Ivisârtoq Malene amphibolites. Hence, the ultramafic pillows probably originated as fine-grained ultramafites (pyroxenites?) which did not possess a cumulus texture.

The shape of the ultramafic pillows is not quite so well formed as that of some of the more typical amphibolite examples. They are clearly ellipsoidal and often have irregular margins but no cuspate bases to pillows were seen, and they seem to occur as pillow agglomerates rather than pillow stacks, having a slightly greater proportion of matrix material (fig 7). These features are thought to represent their original depositional form as water-lain ultramafic lavas, and because of the intimate association of the ultramafic and other well preserved pillowed horizons, it is considered that the varying compositional types of amphibolite essentially reflect the original composition of their igneous precursors. This is the first occurrence of pillow-structured ultramafic rocks to be described from the Archaean complex of southern West Greenland although there are numerous examples of such rocks throughout other Archaean terrains (Arndt *et al.*, 1977; Brooks & Hart, 1972; Naqvi *et al.*, 1978; Nesbitt & Sun, 1976; Nisbet *et al.*, 1977; Viljoen & Viljoen, 1969; Williams, 1972). In these suites of komatiitic rocks characteristic spinifex textures are often associated with the pillow-structured ultramafic rocks, but no such textures have been preserved within the pillowed units of Ivisârtoq. Rivalenti (1976) has described the chemistry of amphibolites, hornblendites and pyroxenites from Fiskenæsset and Frederikshåb regions in the southern part of the Archaean craton of southern West Greenland and has compared these rocks to tholeiites and komatiites. However, the structural control for these southern rocks is less well defined than for those at Ivisârtoq and hence the significance of their chemistry is not so easy to interpret.

Other lithologies associated with the major pillow-structured and homogeneous amphibolite horizons include metagabbroic bodies, metre-wide amphibolite dykes and a series of metasedimentary units and large ultrabasic bodies. A few of the metagabbroic bodies retain relict igneous textures although the rocks are now in amphibolite facies. The basic dykes which cut the amphibolite horizons are homogeneous fine-grained amphibolite, and these rocks are relatively rare. Minor garnet amphibolite horizions also occur locally and are interpreted as metamorphosed gabbroic sills although the field data were insufficient to determine the relationships between these and the other amphibolite types.

Two samples of quartz-rich cummingtonite schists which occur closely associated with the pillowed horizons were also analysed. The origin of these rocks is uncertain but they possibly represent either more acid agglomerate lavas or deuterically altered lavas or lava-sediment mixtures. However, these rocks are relatively rare on Ivisârtoq although similar rocks are more abundant in the Ravns Storø supracrustal belt (Friend, 1975). Their chemistry does not correspond to any recent igneous or sedimentary rocks.

Major element geochemistry

The geochemistry of the amphibolites was analysed by XRF techniques using homogenised powder pellets, as described by Norrish & Chappell (1967), with a Philips 1410 X-ray spectrometer in the Department of Geology, Portsmouth Polytechnic. The data retrieval

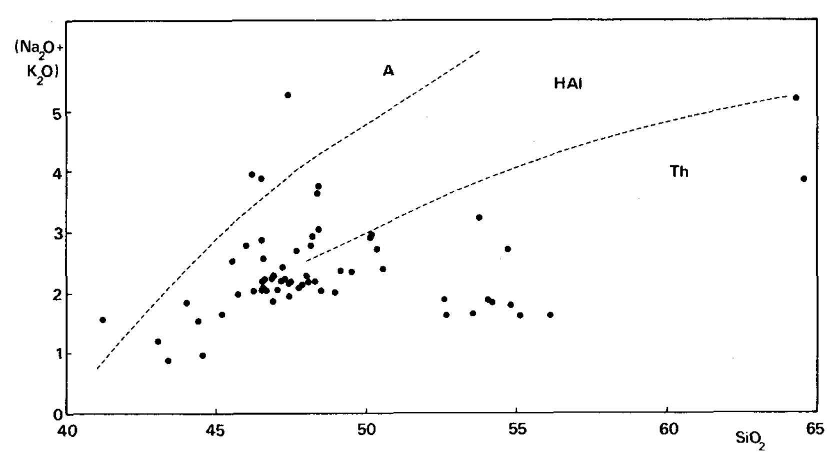

Fig. 8. Plot of (Na_2O + K_2O) versus SiO_2 for Ivisârtoq Malene amphibolites showing fields of alkali (A), high-alumina (HAl) and tholeiitic basalts (Th) (after Irvine & Barager, 1971; Kuno, 1966).

Table 1. Representative analyses from one horizon of metavolcanic amphibolites

wt%	200887 (k)	207623 (k)	207625 (k)	207627 (t)	207626 (t)	207616 (k)	207629 (t)	207628 (t)	207619 (k)	207618 (t)	200891 (t)	200889 (t)
SiO_2	44.52	43.41	46.49	45.99	47.99	46.61	47.70	47.39	47.14	49.54	54.78	56.08
Al_2O_3	8.65	8.23	9.37	12.14	13.31	10.28	14.46	14.01	13.34	13.35	13.00	13.11
Fe_2O_3 ★	12.87	12.47	12.35	12.43	12.03	14.35	12.04	13.13	12.61	11.99	8.15	6.94
MgO	21.78	19.65	17.05	16.20	12.57	11.93	11.35	10.22	10.22	9.51	7.20	5.18
CaO	10.49	14.70	11.96	9.65	10.98	13.74	10.79	11.80	13.52	12.35	14.31	16.30
Na_2O	0.77	0.76	2.03	2.00	2.07	2.00	2.44	2.11	2.02	2.25	1.74	1.58
K_2O	0.19	0.10	0.02	0.78	0.21	0.23	0.24	0.05	0.16	0.11	0.06	0.03
TiO_2	0.38	0.35	0.55	0.59	0.60	0.57	0.66	0.97	0.69	0.62	0.49	0.52
MnO	0.24	0.22	0.23	0.21	0.22	0.29	0.28	0.23	0.29	0.26	0.20	0.19
P_2O_5	0.10	0.11	n.d.	0.01	0.02	0.01	0.03	0.07	0.02	0.02	0.07	0.07
ppm												
Cr	2467	2217	1765	878	480	811	347	246	1104	954	947	940
Ni	723	618	556	330	187	322	131	186	310	297	358	189
CIPW norm												
Q	-	-	-	-	-	-	-	-	-	-	8.36	12.02
or	1.12	-	0.12	4.61	1.24	1.36	1.42	0.30	0.95	0.65	0.36	0.18
ab	6.52	-	12.18	13.11	17.52	11.30	20.65	17.85	15.64	19.04	14.72	13.37
an	19.59	18.75	16.40	21.84	26.41	18.39	27.79	28.61	26.86	26.00	27.48	28.59
lc	-	0.46	-	-	-	-	-	-	-	-	-	-
ne	-	3.48	2.71	2.06	-	3.05	-	-	0.79	-	-	-
di	25.39	36.50	34.41	20.83	22.53	40.36	20.65	23.94	32.57	28.56	34.89	42.16
hy	3.22	-	-	-	8.04	-	2.74	7.87	-	11.86	10.20	0.04
ol	38.60	33.00	28.77	31.93	18.77	19.26	21.08	14.70	17.34	8.37	-	-
cs	-	2.41	-	-	-	-	-	-	-	-	-	-
mt	3.58	3.47	4.34	3.47	3.35	4.00	3.35	3.65	3.51	3.34	2.26	1.93
il	0.72	0.67	1.05	1.12	1.14	1.08	1.25	1.84	1.31	1.18	0.93	0.99
ap	0.23	0.26	-	0.02	0.05	0.02	0.07	0.16	0.05	0.05	0.16	0.16

★All Fe reported as Fe_2O_3.
(t) and (k) indicate samples with tholeiitic and komatiitic affinities respectively.

techniques and programs of Brown *et al.* (1973) were used for data reduction, and six USGS standard samples (AGV1, BCR1, DTS1, GSP1, G2 and PCC1) were analysed concurrently as an accuracy check. The values obtained for these samples show a good overall correspondence to those quoted by Flanagan (1973) (details available on request).

A representative suite of analyses of amphibolites is presented in Table 1 arranged in order of decreasing MgO. These twelve samples are from a single traverse of well preserved pillow-structured and associated homogeneous flow amphibolites to the south of the core zone of the major interference structure (fig 2). They illustrate that the intercalated units of originally extruded basic lava types form a chemically variable suite. Because of the good preservation of these rocks, the effects of metamorphic differentiation and metasomatism are thought to be at a minimum; the more highly deformed and banded amphibolites (fig. 6) have not been examined. All iron is presented as Fe_2O_3; FeO was not analysed since the oxidation state of the iron in the amphibolites bears no relation to that of their igneous precursors. An FeO value was adopted for the CIPW norm calculation based on an average Fe^{2+}/Total Fe ratio of 0.808 in basaltic rocks (Engel *et al.*, 1965; Manson, 1967). This is an obvious source of inaccuracy in the norm calculation and, therefore, a corresponding error margin is necessary in the examination of the norms.

Overall, the amphibolites are chemically comparable to modern low-K tholeiitic basalts although many of them also have some important differences. Some of the major tholeiitic affinities are demonstrated in figs 8–11 by the discriminatory diagrams proposed by Kuno (1966), Irvine & Baragar (1971) and Miyashiro (1975) in terms of the relative concentrations of Si, Al, Na, K, Fe and Mg.

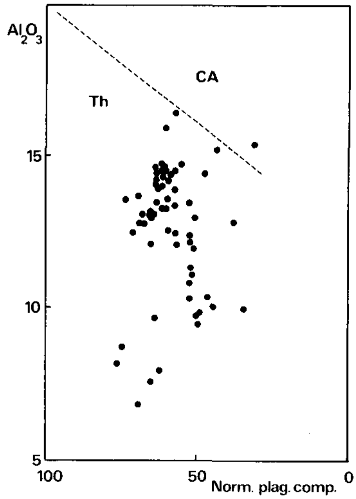

Fig. 9. Plot of Al_2O_3 versus normative plagioclase composition (100 × An/(An + Ab + 5/3Ne)) for Ivisârtoq Malene amphibolites showing fields of calc-alkali (CA) and tholeiitic basalts (Th) (after Irvine & Baragar, 1971).

In the plot of $(Na_2O + K_2O)/SiO_2$ (fig. 8) all but five of the analysed samples fall within a field ranging between high-alumina and tholeiitic basalt types although most have low Na_2O values (*c.* 2%), negligible K_2O and none has greater than 17% Al_2O_3. Two of the samples which plot in the alkali basalt field are relatively Na-rich metagabbros (*c.* 3% and 5% Na_2O) while two others are amphibolites which have anomalous high K_2O values (*c.* 1.8%).

The normative plagioclase composition (fig. 9) has been calculated as 100 × An/(An + Ab + 5/3Ne) (Irvine & Baragar, 1971). All of the samples except for one metagabbro have ratios of normative plagioclase composition to alumina content similar to modern tholeiitic rocks although only four samples have alumina values greater than 15% compared to typical tholeiitic values of 15–17% (Engel *et al.*, 1965; Manson, 1967). Two of these are metagabbros, the third a basic dyke which cuts a coarse-grained cumulate-texture leucogabbro, and the fourth is one of the two analysed quartz-cummingtonite schists (SiO_2 *c.* 64.5%) the last named probably represent more acid lavas, although their alkali contents are rather low (Na_2O *c.* 3.5%; K_2O *c.* 0.25% and 2%), or agglomeratic layers or deuterically altered lava-sediment mixtures.

The range in ratios of alkalis with respect to Fe and Mg is distinctly tholeiitic in character (fig. 10) as are those from the Fiskenæsset and Frederikshåb regions described by Friend (1975) and Rivalenti (1976). The two leucocratic schist samples plot in the calc-alkaline field on the AFM diagram, and apart from these two samples, all the amphibolites have a Fe/Mg ratio similar to that of abyssal tholeiites (fig. 11).

Despite the chemical similarities to modern tholeiitic lavas, many of the pillowed and associated homogeneous amphibolites also show some importance differences compared to these rocks in that they are relatively rich in MgO (10–20%) and CaO (12–17%), and poor in Al_2O_3 (6–12%), K_2O (0–0.9%) and TiO_2 (0.4–0.9%) (Engel *et al.*, 1965; Manson, 1967). They resemble more closely the komatiites which are widespread in other Archaean terrains (Arndt *et al.*, 1977; Brooks & Hart, 1972; Naqvi *et al.*, 1978; Nesbitt & Sun, 1976; Nisbet *et al.*, 1977; Viljoen & Viljoen, 1969; Williams, 1972). The amphibolites from Ivisârtoq which are considered to be komatiitic satisfy the chemical definitions of Brooks &

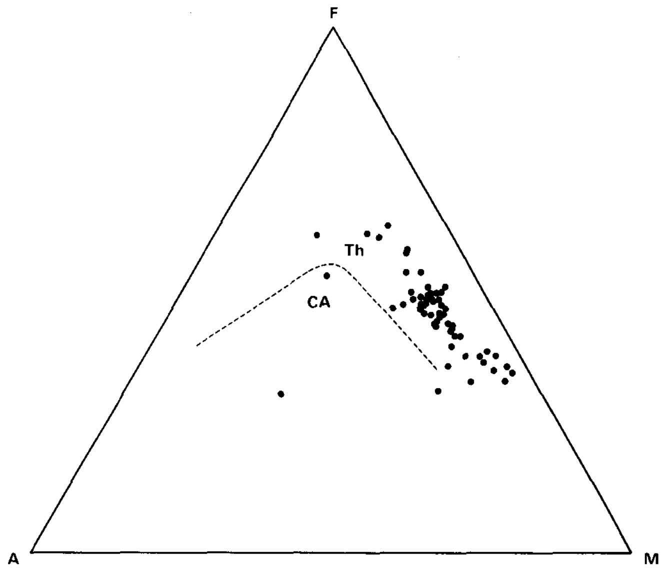

Fig. 10. AFM diagram showing the tholeiitic character of the Ivisârtoq Malene amphibolites. The line separating tholeiitic (Th) and calc-alkaline (CA) fields is from Irvine & Baragar (1971).

Hart (1974) and Arndt *et al.* (1977) having SiO_2<53%, Al_2O_3<14%, K_2O<0.9%, TiO_2<0.9%, MgO<9%, FeO*/MgO<1.5% and CaO/Al_2O_3>0.9% although there is a continuum from the komatiitic to the tholeiitic types. Viljoen & Viljoen (1969) originally proposed a ratio of CaO/Al_2O_3 greater than unity to be one of the most characteristic chemical features of komatiites but many authors have since described rocks with ratios of approximately 0.9 as komatiitic (Arndt *et al.*, 1977; Nisbet *et al.*, 1977); the significance of this ratio with respect to magmatic and metamorphic processes has been discussed by Cawthorn & Strong (1974), Cox (1978), Nesbit & Sun (1976) and Williams (1972).

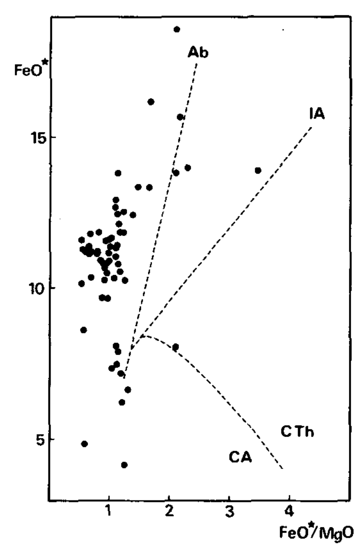

Fig. 11. Plot of FeO* versus (FeO*/MgO) showing the relationship of Ivisârtoq Malene amphibolites to the trends of abyssal tholeiites (Ab), island arc (IA) and continental tholeiites (CTh), and calc-alkali rocks (CA) (after Miyashiro, 1975). FeO* = total iron as FeO.

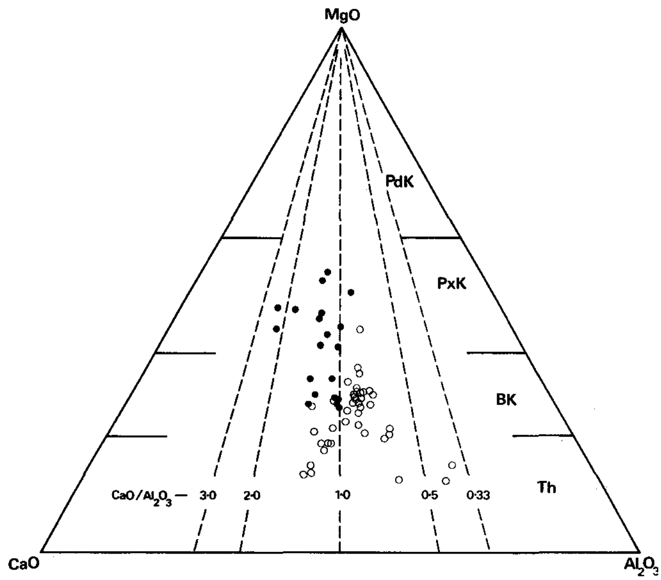

Fig. 12. Plot of MgO : CaO : Al_2O_3 for all analysed Malene amphibolites from Ivisârtoq showing fields of tholeiitic basalt (Th), and basaltic (BK), pyroxenitic (PxK) and peridotitic komatiites (PdK) (after Arndt *et al.*, 1977). The pillowed and associated homogeneous amphibolites have $Al_2O_3/(MgO + CaO + Al_2O_3)$ values less than 0.42. Filled circles : komatiitic amphibolites; open circles : tholeiitic and high-magnesian tholeiitic amphibolites.

One important factor stipulated by various authors in identifying komatiites is the textural evidence for the rocks having crystallized from a liquid, and their most common features are the quenched spinifex texture of skeletal olivine and pyroxene and their general occurrence as pillow horizons and flows. Although the Ivisârtoq amphibolites do not possess relict spinifex textures, they do occur predominantly as well preserved pillows and intimately associated flow horizons. The metagabbros and amphibolite dykes have not been considered in this context.

Approximately half of the analysed samples of amphibolite have a CaO/Al_2O_3 ratio greater than unity (fig. 12). These rocks vary in chemical character from tholeiitic basalts (MgO *c.* 6%) to basaltic (MgO *c.* 12%) and pyroxenitic komatiites (MgO *c.* 18%) with respect to CaO, Al_2O_3 and MgO. TiO_2 is less than 0.9% in the majority of samples and tends to decrease with increasing CaO/Al_2O_3 ratio (fig. 13), while the Mg-rich samples also tend

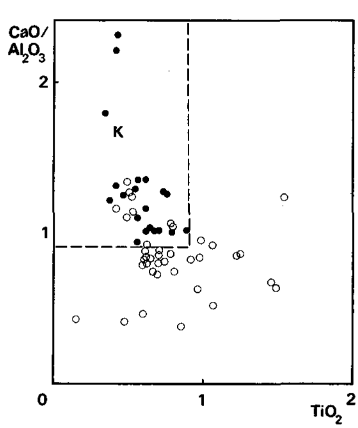

Fig. 13. Plot of (CaO/Al_2O_3) versus TiO_2 for Malene amphibolites from Ivisârtoq showing field of komatiites (K) based on values recommended by Brooks & Hart (1974) and Arndt *et al.* (1977). Symbols as for fig. 12.

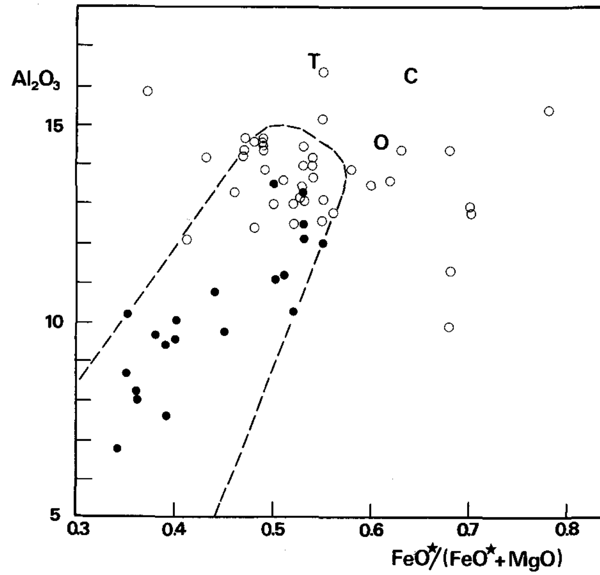

Fig. 14. Plot of Al_2O_3 versus FeO*/(FeO* + MgO) for the Ivisârtoq Malene amphibolites where FeO* = all Fe as FeO. Dashed line encloses field of komatiites from Canada, Australia, India, Rhodesia and South Africa (Arndt *et al.*, 1977). Symbols as for fig 12. T: average oceanic tholeiite of Engel *et al.* (1965); O and C: average oceanic and continental tholeiites respectively of Manson (1967).

to be those poor in Al_2O_3 (fig. 14). No peridotitic komatiites (MgO *c.* 30%) have been identified on Ivisârtoq although they frequently occur in other Archaean terrains. However, the distinctive chemical character of some of the pillowed and homogeneous amphibolites closely resembles that of komatiitic rather than tholeiitic suites.

There is only a weak correlation between the tholeiitic and komatiitic amphibolites and their normative compositions. Almost half of the originally extrusive amphibolites are komatiitic and of these a large proportion (65%) are nepheline normative although none can be considered to be alkalic with respect to Na_2O, K_2O, Al_2O_3 and SiO_2 (figs. 9, 10). Some of the metagabbros, amphibolite dykes and Si-rich amphibolites are also nepheline normative while most of the 'tholeiitic' amphibolites are hypersthene normative. While true tholeiites are by definition hypersthene normative, a normative classification is not rigorously adhered to because of the absence of meaningful FeO content data.

While the effects of metamorphism on the chemistry cannot be ignored particularly with reference to CaO and Al_2O_3 (Nesbitt & Sun, 1976; Williams, 1972), it is considered that the chemical continuum from tholeiitic to komatiitic types within a single pile of well preserved pillow-structured amphibolites primarily reflects the original composition of these rocks. The only possible evidence of metasomatic change within these undeformed rocks is the development of diopside and epidote in the low-MgO (*c.* 6%) pillowed amphibolites and it remains uncertain to what extent metamorphic processes and the original chemistry are each responsible for this development. These rocks also have CaO/Al_2O_3 greater than 1 and CaO/TiO_2 and Al_2O_3/TiO_2 ratios both greater than chondritic values implying that both Ca and Al must have been relatively enriched in these more silicic lavas. In this respect they differ from both the Barberton komatiites discussed by Nesbitt & Sun (1976), some of which are Ca enriched and some Al depleted and from their mid-ocean ridge basalts which are both Ca and Al depleted. The low-MgO tholeiites from the Lawlers greenstone sequence (Nesbitt & Sun, 1976) also differ from the low-MgO Ivisârtoq amphibolites in that these rocks are depleted in both Ca and Al.

The association of ultrabasic komatiites with more felsic tholeiites is a common feature in several Archaean terrains (Arndt *et al.,* 1977; Brooks & Hart, 1972; Viljoen & Viljoen, 1969; Williams, 1972) and although the more acidic pillows from Ivisârtoq in no way resemble andesites or rhyolites, there is an intricate intercalation of ultrabasic, basic and intermediate pillowed and flow horizons of amphibolites in this area.

Nickel and chromium

Both nickel and chromium contents were determined by XRF analysis using the techniques and programs of Brown *et al.* (1973). The chemical continuum between tholeiitic and komatiitic affinities defined by the major element chemistry of the Ivisârtoq amphibolites is corroborated by their Ni and Cr values. Most of the amphibolites have Ni contents similar to, or slightly higher, than those of abyssal tholeiites (fig. 15), that is between 50 and 300 ppm (Prinz, 1967; Miyashiro & Shido, 1975). However, those rocks which are considered to have a komatiitic major element chemistry have been differentiated on the Ni: (FeO*MgO) diagram and tend to have much higher Ni values (100–1200 ppm) as well as lower FeO*MgO ratios although there is a clear overlap of values between the two groups.

The behaviour of chromium in the Ivisârtoq amphibolites is analogous to that of nickel, as

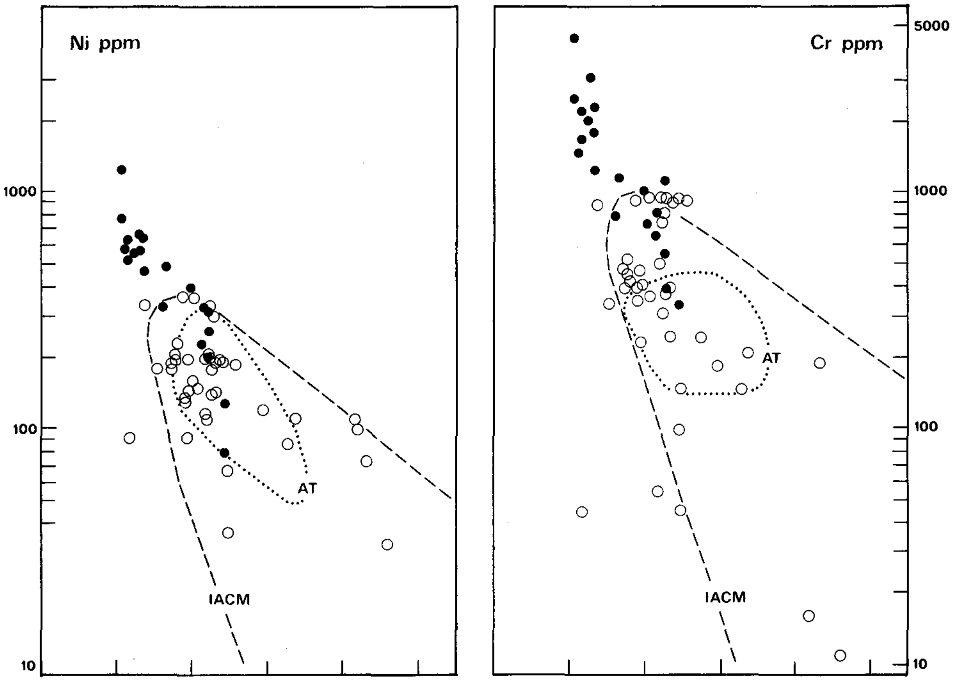

Fig. 15. Ni and Cr (ppm) concentrations in Malene komatiitic (dots) and tholeiitic amphibolites (open circles) from Ivisârtoq. Fields of abyssal tholeiites (AT) and island arc and continental margin rocks (IACM) after Miyashiro & Shido (1975). FeO* is total Fe as FeO.

it is in more recent volcanic rocks (fig. 15). There is a wide range of Cr values, many approximating to those of abyssal and island arc tholeiites (150–1000 ppm), and the low-MgO (*c.* 6%) 'tholeiitic' pillows retain Cr values in the order of 900 ppm. The komatiitic rocks have Cr contents ranging from 340 to 4400 ppm and once again the overlap in values reflects the gradation from tholeiitic to komatiitic affinities in these rocks. The high Ni and Cr values are similar to those reported in several komatiitic suites (Arndt *et al.,* 1977; Naqvi *et al.,* 1978; Nesbitt & Sun, 1976; Nisbet *et al.*, 1977; Williams, 1972) and have been suggested as parameters for identifying such rocks by Arndt *et al.,* (1977). Therefore, it seems that the range in Ni and Cr contents of some of the Ivisârtoq amphibolites endorses their classification as komatiites.

Concluding remarks

The significance of the variable assemblage of interleaved pyroxenitic and basaltic komatiites with tholeiitic supracrustal rocks on Ivisârtoq with respect to their formative igneous province and processes in the Archaean remains problematical (Brooks & Hart, 1974). The chemistry of similar complex supracrustal suites has been used to interpret igneous mechanisms in the mantle (Cawthorn & Strong, 1974; Cox, 1978) and comparison has been made with numerous different analogues of modern tectonic environments including sea floor (Glikson, 1971; Gale, 1973), island arcs (Brooks & Hart, 1972), primitive crust (Viljoen & Viljoen, 1969) and crustal rifting (Cox, 1978; Nisbet *et al.,* 1977). Brooks & Hart (1974) have concluded that for a steep geothermal gradient, high rate of convection and thin lithospheric plates in the Archaean, spreading ridges, island arcs and isolated mantle plumes may all favour the formation of komatiites although Wells (1979) has argued for a relatively thick crust during the Archaean in West Greenland. Therefore, the chemical considerations alone are insufficient to define a formative igneous province of the Ivisârtoq amphibolites.

The field relations are inconclusive as to the relationship between the Malene supracrustal rocks and the older (3750 m.y.) Amîtsoq gneiss basement. Chadwick & Nutman (1979) believe that they have recognized an original unconformable contact between the two suites at the west coast while most field relationships clearly indicate a tectonic origin for their juxtaposition, interpreted as an early phase of interleaving by thrusting (Bridgwater *et al.,* 1974; Hall & Friend, 1979). No older basement gneisses have been recognized in the Fiskenæsset and Frederikshåb regions to the south and only a few enclaves of possibly older gneisses were identified incorporated within younger (*c.* 2900 m.y.) agmatitic gneisses in the eastern Sukkertoppen region (Hall, 1978), whereas the Malene supracrustal rocks occur variably deformed throughout these regions as the oldest recognizable rocks. The simplest model which can be inferred for the formation of the Malene rocks from this arrangement is that the southern and northern regions formed oceanic areas and the central, Godthåbsfjord region a continental one during the deposition of the Malene lavas, sediments and incorporated ultrabasic bodies. However, the chemical data are so far inconclusive as to the environment of formation of the amphibolites and supply only a little weight to the above simple model.

Acknowledgements

I thank C. R. L. Friend, D. J. Hughes and G. M. Power for help and comments throughout these investigations.

References

Allaart, J. H., Jensen, S. B., McGregor, V. R. & Walton, B. J. 1977: Reconnaissance mapping for the 1:500 000 map sheet in the Godthåb–Isua region, southern West Greenland. *Rapp. Grønlands geol. Unders.* **85,** 50–54.

Allaart, J. H., Friend, C. R. L., Hall, R. P., Jensen, S. B. & Roberts, I. W. N. 1978: Continued 1:500 000 reconnaissance mapping in the Precambrian of the Sukkertoppen region, southern West Greenland. *Rapp. Grønlands geol. Unders.* **90,** 50–54.

Arndt, N. T., Naldrett, A. J. & Pyke, D. R. 1977: Komatiitic and iron-rich tholeiitic lavas of Munro township, north-east Ontario. *J. Petrol.* **18,** 319–369.

Bridgwater, D., McGregor, V. R. & Myers, J. S. 1974: A horizontal tectonic regime in the Archaean of Greenland and its implications for early crustal thickening. *Precambrian Res.* **1,** 179–197.

Bridgwater, D., Keto, L., McGregor, V. R. & Myers, J. S. 1976: Archaean gneiss complex of Greenland. *In* Escher, A. & Watt, W. S. (edit.) *Geology of Greenland,* 18–75. Copenhagen: Geol. Surv. Greenland.

Brooks, C. & Hart, S. R. 1972: An extrusive basaltic komatiite from a Canadian Archaean meta-volcanic belt. *Can. J. Earth Sci.* **9,** 1250–1253.

Brooks, C. & Hart, S. R. 1974: On the significance of komatiite. *Geology* **2,** 107–110.

Brown, G. C., Hughes, D. J. & Esson, J. 1973: New X.R.F. retrieval techniques and their application to U.S.G.S. standard rocks. *Chem. Geol.* **11,** 223–229.

Cawthorn, R. G. & Strong, D. F. 1974: The petrogenesis of komatiites and related rocks as evidence for a layered upper mantle. *Earth Planet. Sci. Lett.* **23,** 369–375.

Chadwick, B. & Coe, K. 1976: New evidence relating to Archaean events in southern West Greenland. *In* Windley, B. F. (edit.) *The early history of the Earth,* 203–211. London, John Wiley.

Chadwick, B. & Nutman, A. 1979: Archaean structural evolution in the north-west of the Buksefjorden region, southern West Greenland. *Precambrian Res.* **9,** 199–226.

Cox, K. G. 1978: Komatiites and other high-magnesia lavas: some problems. *Phil. Trans. R. Soc. Lond.* **A 288,** 599–609.

Dawes, P. R. 1970: Bedrock geology of the nunataks and semi-nunataks in the Frederikshåbs Isblink area of southern West Greenland. *Rapp. Grønlands geol. Unders.* **29,** 60 pp.

Ehlers, C. 1976: Homogeneous deformation in Precambrian supracrustal rocks of Kumlinge area, South-west Finland. *Precambrian Res.* **3,** 481–504.

Engel, A. E. J., Engel, C. G. & Havens, R. G. 1965: Chemical characteristics of oceanic basalts and the upper mantle. *Bull. geol. Soc. Amer.* **76,** 719–734.

Flanagan, F. J. 1973: 1972 values for international geochemical reference samples. *Geochim. cosmochim. Acta* **37,** 1189–1200.

Friend, C. R. L. 1975: The geology and geochemistry of the Pre-ketilidian basement complex in the Ravns Storø area, Fiskenæsset region, southern West Greenland. Unpubl. Ph.D. thesis, Univ. London, 254 pp.

Friend, C. R. L. & Hall, R. P. 1977: Field work in the Ivisârtoq area, inner Godthåbsfjord, southern West Greenland. *Rapp. Grønlands geol. Unders.* **85,** 54–60.

Friend, C. R. L., Hall, R. P. & Hughes, D. J. in press: The geochemistry of the mid-Archaean (Malene) metavolcanics from Ivisârtoq and Ravns Storø, southern West Greenland. Submitted to *Spec. Publ. geol. Soc. Aust.*

Gale, G. H. 1973: Palaeozoic basaltic komatiite and ocean floor basalts from north-eastern Newfoundland. *Earth Planet. Sci. Lett.* **18,** 22–28.

Glikson, A. Y. 1971: Primitive Archaean element distribution patterns: chemical evidence and geotectonic significance. *Earth Planet. Sci. Lett.* **12,** 309–320.

Hall, R. P. 1978: An occurrence of ironstone enclaves east of Sukkertoppen, southern West Greenland. *Rapp. Grønlands geol. Unders.* **90,** 57–60.

Hall, R. P. & Friend, C. R. L. 1979: Structural evolution of the Archaean rocks in Ivisârtoq and the neighbouring inner Godthåbsfjord region, southern West Greenland. *Geology* **7,** 311–315.

Holland, T. J. B. & Norris, R. J. 1979: Deformed pillow lavas from the central Hohe Tauerne, Austria, and their bearing on the origin of epidote-banded greenstones. *Earth Planet. Sci. Lett.* **43,** 397–405.

Irvine, T. N. & Baragar, W. R. A. 1971: A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* **8,** 523–548.

Kuno, H. 1966: Lateral variation of basalt magma types across continental margins and island arcs. *Bull. volcan.* **29,** 195–222.

Manson, V. 1967: Geochemistry of basaltic rocks: major elements. *In* Hess, H. H. & Poldervaart, A. (edit.) *Basalts,* 215–269. London: John Wiley.

McGregor, V. R. 1973: The early Precambrian gneisses of the Godthåb district, West Greenland. *Phil. Trans. R. Soc. Lond.* **A 273,** 343–358.

McGregor, V. R. & Mason, B. 1977: Petrogenesis and geochemistry of metabasaltic and metasedimentary enclaves in the Amîtsoq gneisses, West Greenland. *Amer. Miner.* **62,** 887–904.

Miyashiro, A. 1975: Classification, characteristics and origin of ophiolites. *J. Geol.* **83,** 249–281.

Miyashiro, A. & Shido, F. 1975: Tholeiitic and calc-alkalic series in relation to the behaviours of titanium, vanadium, chromium and nickel. *Amer. J. Sci.* **275,** 265–277.

Moorbath, S. & Pankhurst, R. J. 1976: Further rubidium-strontium age and isotope evidence for the nature of the late Archaean plutonic event in West Greenland. *Nature* **262,** 124–126.

Moorbath, S., O'Nions, R. K., Pankhurst, R. J., Gale, N. H. & McGregor, V. R. 1972: Further rubidium-strontium age determinations of the very early Precambrian rocks of the Godthåb district, West Greenland. *Nature Phys. Sci.* **240,** 78–82.

Moorbath, S., Allaart, J. H., Bridgwater, D. & McGregor, V. R. 1977: Rb–Sr ages of early Archaean supracrustal rocks and Amîtsoq gneisses at Isua. *Nature* **270,** 43–45.

Myers, J. S. 1978: Formation of banded gneisses by deformation of igneous rocks. *Precambrian Res.* **6,** 43–64.

Naqvi, S. M., Viswanathan, S. & Viswanatha, M. N. 1978: Geology and geochemistry of the Holenarasipur schist belt and its place in the evolutionary history of the Indian peninsula. *In* Windley, B. F. & Naqvi, S. M. (edit.) *Archaean geochemistry,* 109–126. Oxford: Elsevier.

Nesbitt, R. W. & Sun, S.-S. 1976: Geochemistry of Archaean spinifex-textured peridotites and magnesian and low magnesian tholeiites. *Earth Planet. Sci. Lett.* **31,** 433–453.

Nisbet, E. G., Bickle, M. J. & Martin. A. 1977: The mafic and ultramafic lavas of the Belingwe greenstone belt, Rhodesia. *J. Petrol.* **18,** 521–566.

Norrish, K. & Chappell, B. W. 1967: X-ray fluorescence spectrography. *In* Zussman, J. (edit.) *Physical methods in determinative mineralogy,* 161–214. London: Academic Press.

Pidgeon, R. T. & Hopgood, A. M. 1975: Geochronology of Archaean gneisses and tonalites from north of the Frederikshåbs Isblink, S. W. Greenland. *Geochim. cosmochim. Acta 39,* 1333–1346.

Prinz, M. 1967: Geochemistry of basaltic rocks: trace elements. *In* Hess, H. H. & Poldervaart, A. (edit.) *Basalts,* 271–323. London: John Wiley.

Rivalenti, G. 1976: Geochemistry of metavolcanic amphibolites from South-West Greenland. *In* Windley, B. F. (edit.) *The early history of the Earth,* 213–223. London: John Wiley.

Viljoen, M. J. & Viljoen, R. P. 1969: The geology and geochemistry of the lower ultramafic unit of the Onverwacht Group and a proposed new class of igneous rock. *Spec. Publ. geol. Soc. S. Africa* **2,** 55–86.

Wells, P. R. A. 1979: Chemical and thermal evolution of Archaean sialic crust, southern West Greenland. *J. Petrol.* **20,** 187–226.

Williams, D. A. C. 1972: Archaean ultramafic, mafic and associated rocks, Mt Monger, Western Australia. *J. geol. Soc. Aust.* **19,** 163–188.

ISSN 0418–6559
AiO Tryk as, Odense