Some observations on the structure of the early Proterozoic, Ammassalik mobile belt in the Ammassalik region, South-East Greenland

B. Chadwick and V. N. Vasudev

Ammassalikian deformation appears to have given rise in the first instance to a regional layer cake structure of tectonically interleaved sheets of the early Proterozoic Síportôq supracrustal association and Archaean quartzo-feldspathic orthogneisses, the latter containing locally abundant amphibolite dykes. Younger orthogneisses were emplaced magmatically in parts of the structure. The layer cake structure was progressively modified by fold nappes and later domes with steep intervening cusps. The early Ammassalikian structure is attributed to thrust stacking during ensialic crustal shortening with tectonic instability spreading from north to south. Some of the nappes and upright structures may be buoyancy phenomena which resulted from thermal instabilities generated at depth within the thrust pile.

Introduction

We report here on the structure in two areas of the Ammassalik mobile belt, one northeast and the other southwest of the town of Ammassalik (figs 1, 12), seen on reconnaissance surveys for GGU's 1:500 000 map sheet 14 (Skjoldungen) in 1986 (Kalsbeek & Nielsen, 1987; Chadwick *et al.*, this volume, fig. 1). The northern area (fig. 1) includes the north of Angmagssalik Ø and a tract extending north to include the patchily retrogressed, Archaean granulite facies terrain which is cut by northerly dipping Ammassalikian shear zones and amphibolite dykes. The southern area (fig. 12) is centered on Síportôq, with its southern limit marked by the belt of mylonites north of Kitak (Chadwick *et al.*, this volume). The areas are separated by the intervening tract occupied by the Ammassalik Intrusive Complex and its associated high-grade gneisses (Friend & Nutman, this volume). Both areas include complex modifications of the regional layer cake arrangement of intersheeted, multiphase quartzo-feldspathic orthogneisses and Síportôq supracrustal rocks (Hall *et al.*, this volume - Supracrustals). Whilst some elements of the geometry and tectonic chronology are common to both areas, for convenience they are reviewed independently. The reviews are then integrated to provide a synthesis of the Ammassalikian tectonism. Apart from detailed work on the structure of the Síportôq area by Palmer (1971) which is discussed in this paper, previous work and the basis for the term Ammassalikian have been reviewed by Chadwick *et al.* (this volume).

Our interpretation of the regional structure hinges largely on the assumption that the layer cake arrangement of sheets of multiphase orthogneisses and the Síportôq supracrustal association in both areas was formed by horizontal tectonic interleaving, perhaps with some of the sheets of supracrustal rocks being highly attenuated cores of large isoclinal folds. This assumption is based on the similarity between the Síportôq supracrustal association and early Proterozoic metasedimentary suites elsewhere in Greenland and on isotope data which suggest that most of the orthogneisses are late Archaean and the supracrustal rocks are early Proterozoic (Kalsbeek & Taylor, this volume). We have been unable to prove this tectonic relation from field evidence in either the Síportôq area or the area northeast of Ammassalik. Moreover, no unequivocal evidence of a cover-basement relation between the Síportôq supracrustal rocks and the orthogneisses has been found in these areas. Whilst the isotope data support the view that the regional layer cake structure was formed by tectonic interleaving of sheets of late Archaean orthogneisses and early Proterozoic supracrustal rocks, the relations illustrated in figs 2–5 show that parts of the orthogneisses were emplaced as broadly concordant sheets during or after the tectonic interleaving. On the assumption that the regional layer cake structure is tectonic, it follows that significant parts of the orthogneisses are younger than the multiphase orthogneisses of late Archaean age.

A second important basis for the interpretation of the structures rests on the pattern of deformation of amphi-

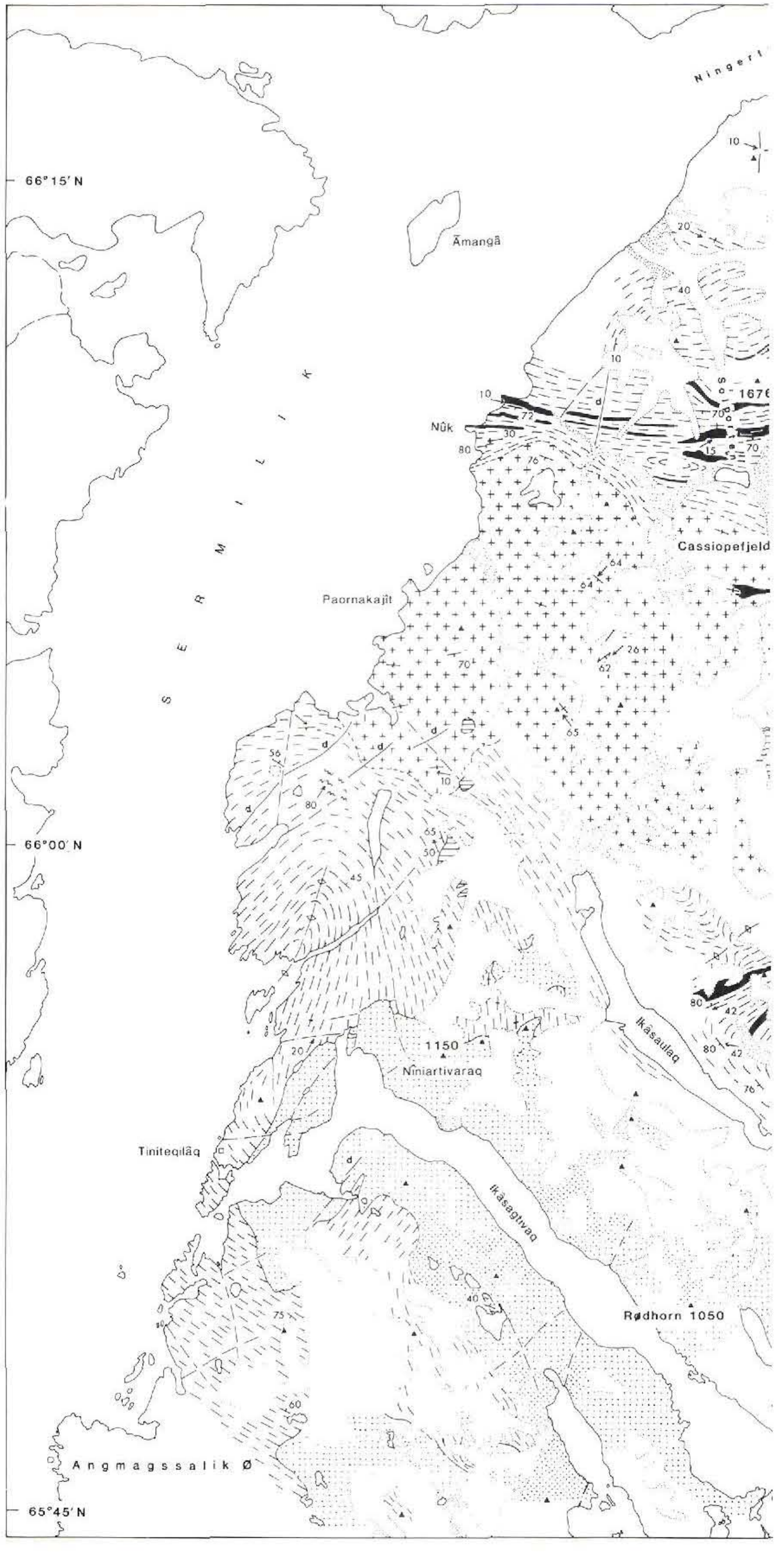
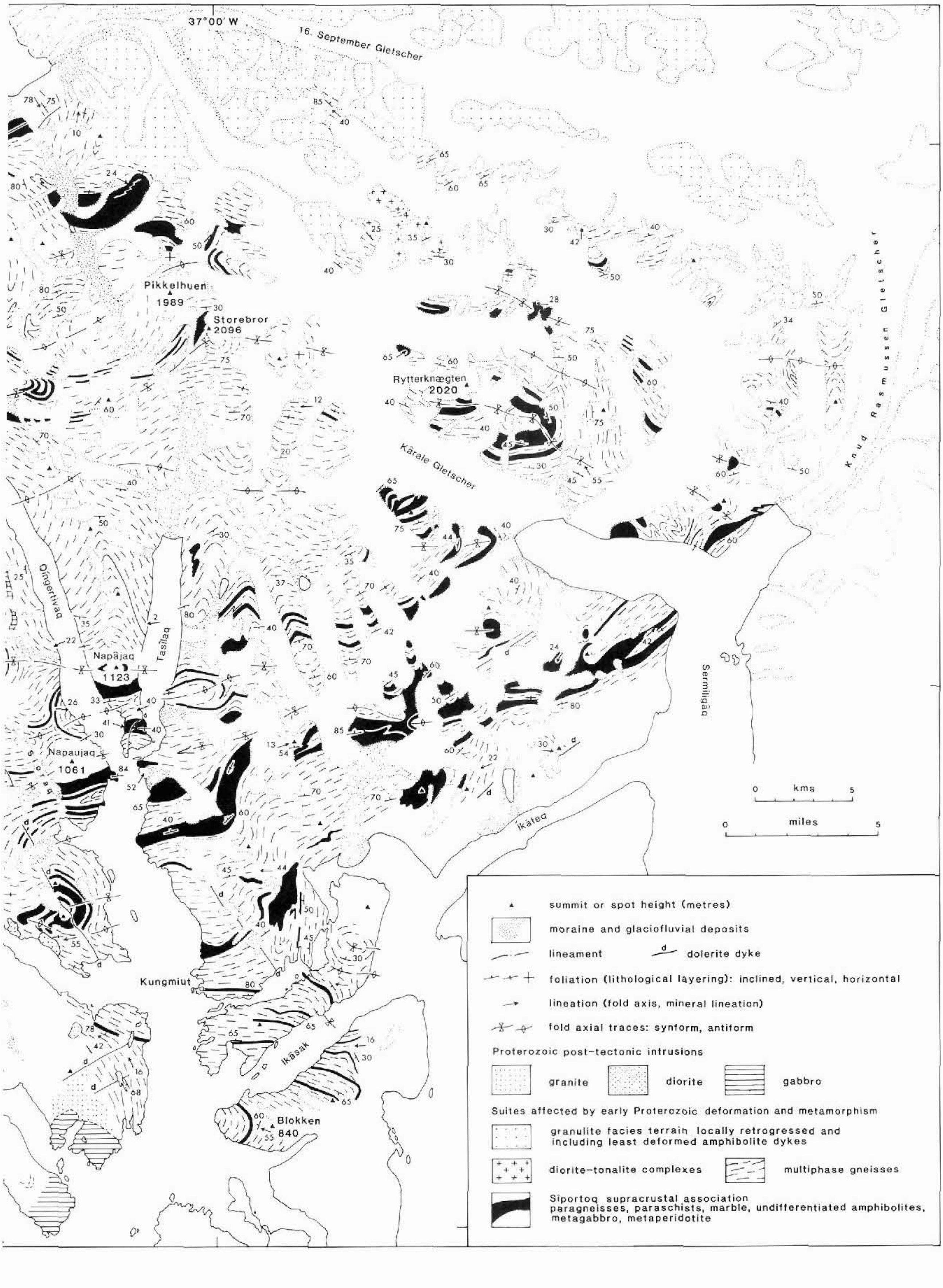


Fig. 1. Geology of the area between the north of Angmagssalik Ø and 16. September Gletscher.



37°00' W
16. September Gletscher
Pikkelhuen
1989
Storebror
2096
Rytterknægten
2020
Kârale Gletscher
Knud Rasmussen Gletscher
Qingertivaq
Tasîlaq
Napâjaq
1123
Napaujaq
1061
Sermiligâq
Ikâteq
Kungmiut
Ikâsak
Blokken
840
kms
miles
summit or spot height (metres)
moraine and glaciofluvial deposits
lineament
dolerite dyke
foliation (lithological layering): inclined, vertical, horizontal
lineation (fold axis, mineral lineation)
fold axial traces: synform, antiform
Proterozoic post-tectonic intrusions
granite
diorite
gabbro
Suites affected by early Proterozoic deformation and metamorphism
granulite facies terrain locally retrogressed and including least deformed amphibolite dykes
diorite-tonalite complexes
multiphase gneisses
Siportoq supracrustal association paragneisses, paraschists, marble, undifferentiated amphibolites, metagabbro, metaperidotite

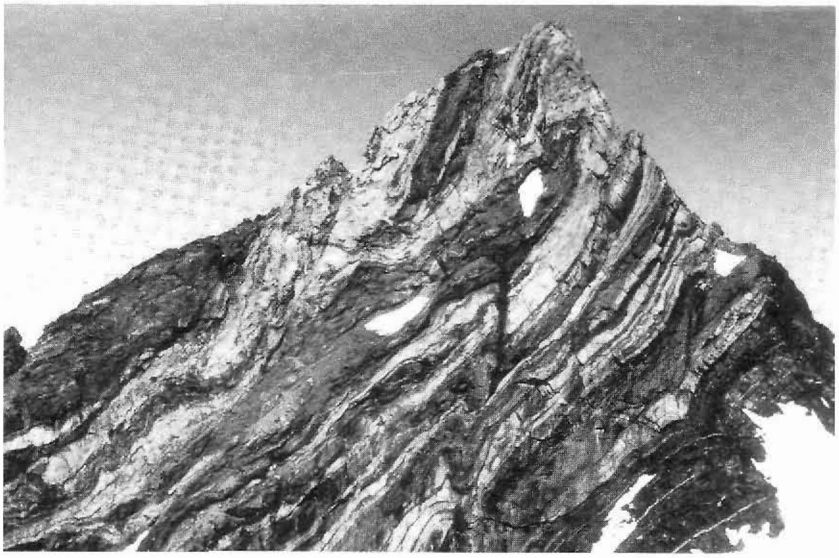


Fig. 2. Intersheeted multiphase orthogneisses (pale) and Síportôq supracrustal rocks (dark) in peak 5 km SE of peak 1676 m in the northern area. Height of cliff is about 150 m.

bolite dykes which appears to be common to both areas. The amphibolite dykes were emplaced into gneisses that had already undergone significant deformation and high-grade metamorphism which in the case of the multiphase orthogneisses and their equivalents in the granulite facies terrain in the north were largely late Archaean. In areas of low Proterozoic strain in the northern area the amphibolite dykes are discordant to foliation which in the orthogneisses is presumed to be late Archaean, the term foliation being used here in the sense of fine-scale lithological layering, including thin seams of pegmatite. This Archaean foliation is generally distinct, although it has been variably modified in areas of more intense Proterozoic deformation. The foliation in the orthogneisses is broadly concordant to contacts with the sheets of supracrustal rocks and their lithological layering which includes bedding in the metasedimentary rocks and primary sheeting in differentiated metagabbroic amphibolites. Contacts of these and other ortho-amphibolites with their metasedimentary hosts are generally parallel to bedding. Schistose fabrics and migmatitic neosome in the supracrustal sheets are parallel to the lithological layering and we assume that these concordant tectonometamorphic phenomena were generated at an early stage, perhaps during the period of tectonic interleaving. Pegmatites at a high angle to contacts with the host orthogneisses commonly give rise to a large-scale, two-dimensional ladder structure in sheets of supracrustal amphibolite (fig. 3). The ladder structure is deformed by early folds, a relation suggesting these pegmatites are also early phenomena.

The timing of the emplacement of the parents of the

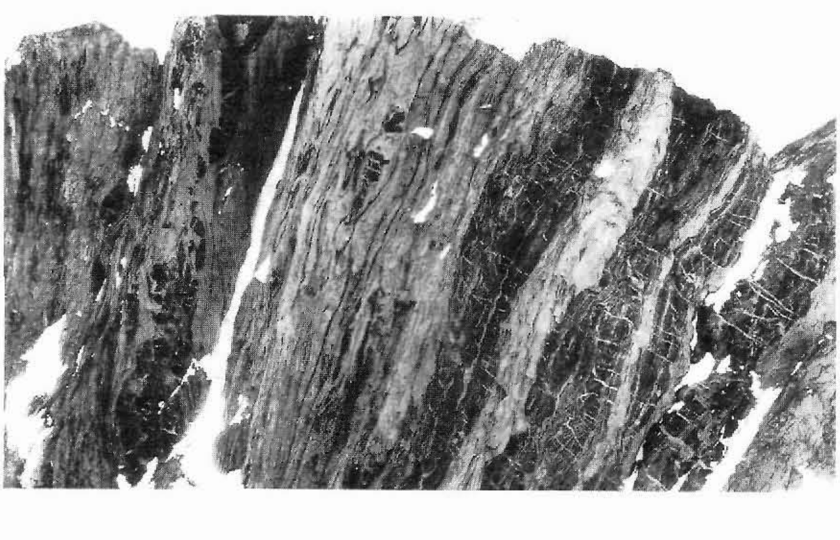


Fig. 3. Two-dimensional ladder structure of high-angle pegmatites in sheets of Síportôq supracrustal amphibolite in multiphase orthogneisses with pods and sheets of amphibolite dykes. Valley side about 10 km east of Napâjaq in the northern area. Height of cliff is about 250 m.

Fig. 4. Sheet of orthogneiss in migmatised paragneiss regarded as part of the Síportôq supracrustal association. About 5 km SW of Paornakajît in the northern area.

amphibolite dykes in relation to the presumed tectonic interleaving which gave rise to the regional layer cake structure has been reviewed by Chadwick *et al.* (this volume). The abundance of dykes, albeit in various stages of tectonic disruption, in the orthogneisses compared with their paucity in the sheets of supracrustal rocks suggests the principal period of dyke emplacement may have been earlier than the tectonic interleaving. Whilst dykes are uncommon in the supracrustal sheets, their paucity may be more apparent than real because of the effects of deformation. The presence of dykes in the supracrustal sheets may be interpreted either in terms of dyke emplacement after tectonic interleaving (Wright *et al.*, 1973) or in terms of their emplacement as feeders to differentiated basaltic sills (now metagabbros and related amphibolites) within the supracurstal pile before interleaving. Limited evidence of dykes apparently younger than mafic breccias (figs 6, 7) emplaced along interfaces between sheets of supracrustal rocks and orthogneisses in the Síportôq area suggests dyke injection followed the tectonic interleaving. Amphibolite dykes in the extreme north of the northern area (fig. 1) occupy shear zones which may have formed *c.* 2600 Ma ago (Pedersen & Bridgwater, 1979). We suggest below that these zones may have been reactivated in the Ammassalik mobile belt with

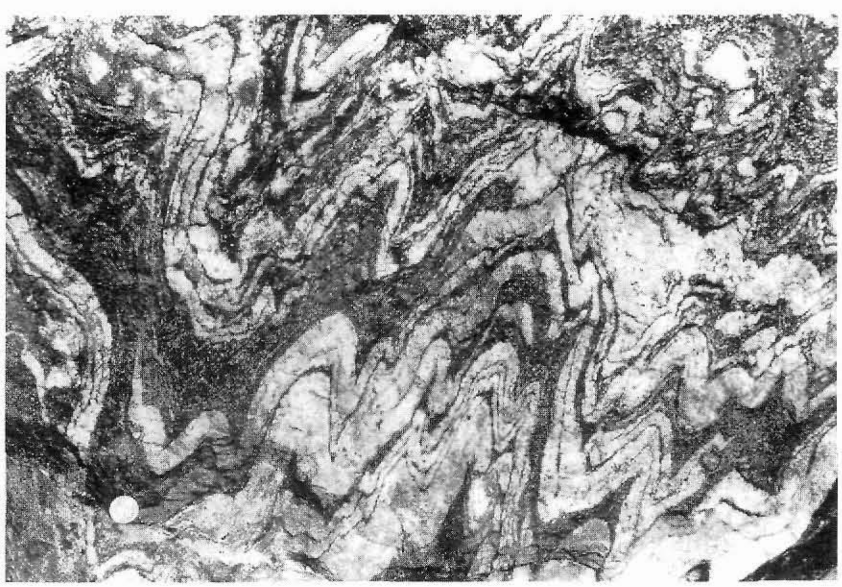


Fig. 5. Granitic seams in Síportôq paragneiss within the sheath fold NW of Tasîlalîk. Síportôq area.

Fig. 6. Brecciated Síportôq metagabbro in matrix of amphibolite. About 4 km east of Arqâjaq, Síportôq area.

dyke emplacement occurring before the reactivation. These relations led Chadwick *et al.* (this volume) to conclude that dyke emplacement may have taken place at various stages prior to and during the early Proterozoic tectonism.

Northern area

In the northern area (fig. 1) there is a progressive change from north to south in the style of deformation of the amphibolite dykes. In the extreme north, in the area of 16. September Gletscher and north of Rytterknægten, the dykes are found principally in shear zones dipping at moderate angles to the north (fig. 8). Limited data collected during helicopter reconnaissance suggest the dykes share the same *L* and *S* fabrics as the shear zones, the shear zone geometry and *L* fabric being consistent with upthrusting from the north. The shear zones are sites of retrogression to amphibolite facies and cut across the patchily retrogressed granulite facies host gneisses. Some dykes that are isoclinally folded appear to have been injected at high angles to the dykes concordant with the shear zones. Further south the dykes are progressively deformed, especially in the form of trains of pods with a chocolate tablet style of boudinage indicative of flattening strains (fig. 9). The flattening strains are strongly heterogeneous as indicated by the variable spacing of the pods of amphibolite and variation in the intensity of the foliation in the host gneisses. The pegmatite ladder-structure in sheets of supracrustal amphibolite (fig. 3) may have developed at the same time as the podding of dykes.

The trains of pods are folded round isoclines whose orientation varies depending on their position on younger regional domes, synforms and related zones where the foliation is steep or vertical. Large-scale isoclines are suggested by the distribution of sheets of supracrustal rocks intersheeted with the multiphase orthogneisses, but individual nappe structures have not been recognised like those in the Síportôq area. Locally, the vergence of small-scale folds of dykes and orthogneisses suggests transport of the isoclines was from north to south (fig. 9).

The isoclines are deformed by regional domes with intervening synformal and steep cusp zones (figs 10,

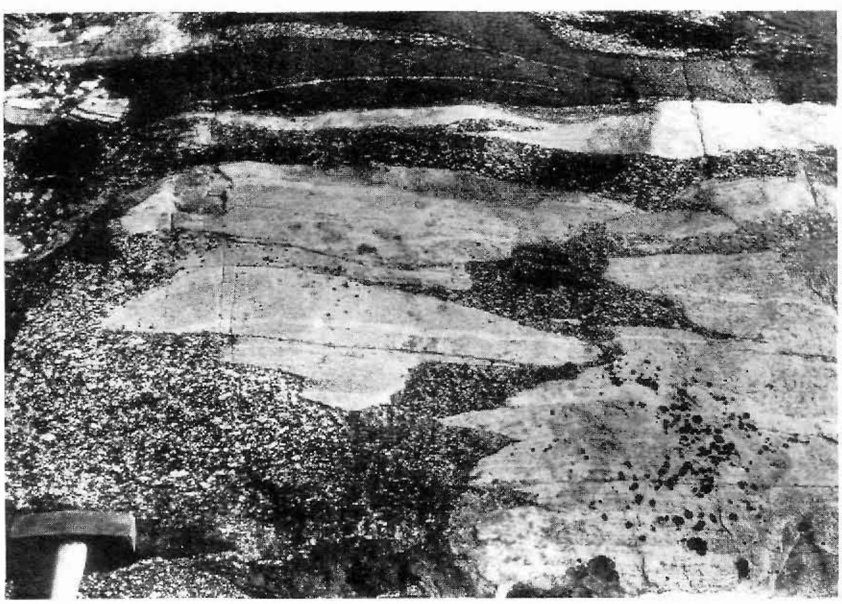


Fig. 7. Brecciated orthogneiss with matrix of amphibolite which appears to be cut by amphibolite dyke (top of photograph). About 3 km NE of Arqâjaq, Síportôq area.

Fig. 8. Amphibolite dykes in shear zones cutting patchily retrogressed, granulite facies orthogneisses with inclusions of amphibolite. Shear zones dip north. About 5 km south of 16. September Gletscher in the northern area. Height of cliff about 250 m.

11). The scale of the domes is variable, but their detailed geometry and the reason for the variation in size are not understood. In the central part of the area the trend of the axes of the domes and synforms is approximately E–W, but SE of Kungmiut and Blokken the cusps appear to swing to a NW–SE trend, and west of Qíngertivaq and in Ikâsaulaq the trend of the steep zones may be N–S or NW–SE. Much of the foliation in the gneisses in the area heavily invaded by the post-tectonic Proterozoic gabbro-diorite-granite complexes has a northerly trend and in the Tiniteqilâq–Paornakajît area the regional structure is dominated by a large-scale, tight fold trending and plunging steeply NE. The structural relationships in these areas are not fully understood, but it is conceivable that the orientation of the foliation is a function of divergent trends of steep zones around irregular regional domes. Linear fabrics appear to have developed coaxially with folds in the domes and synformal cusps, but some of these fabrics may be rotated earlier phenomena. Large- and small-scale seams of pegmatite are common in planes parallel to the steep axial surfaces of the dome and synform folds.

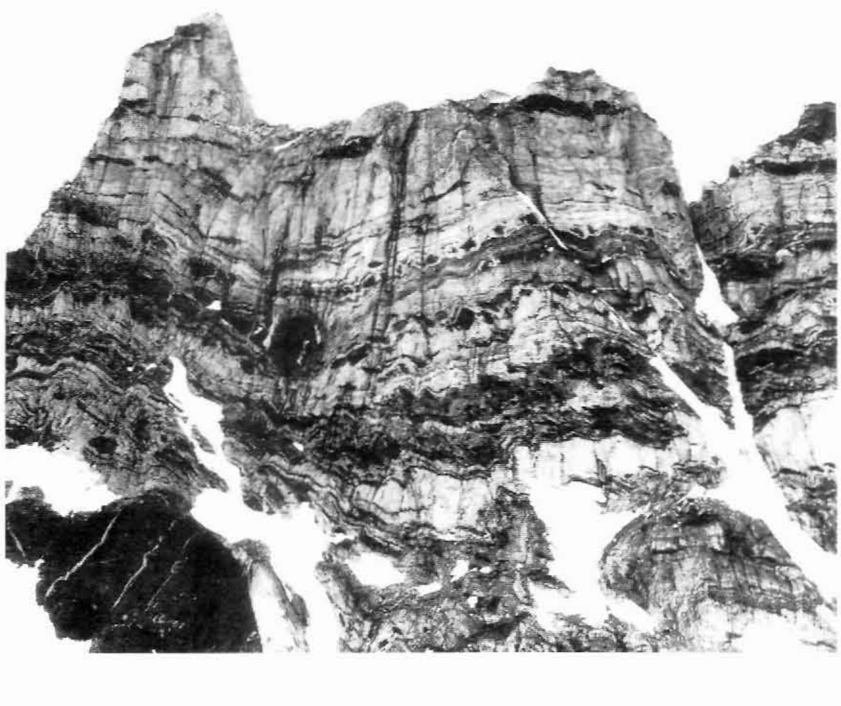


Fig. 9. Podded amphibolite dykes in multiphase orthogneisses. Note asymmetric folds verging to the south (left). About 5 km NE of Rytterknægten in the northern area. Height of cliff face is about 150 m.

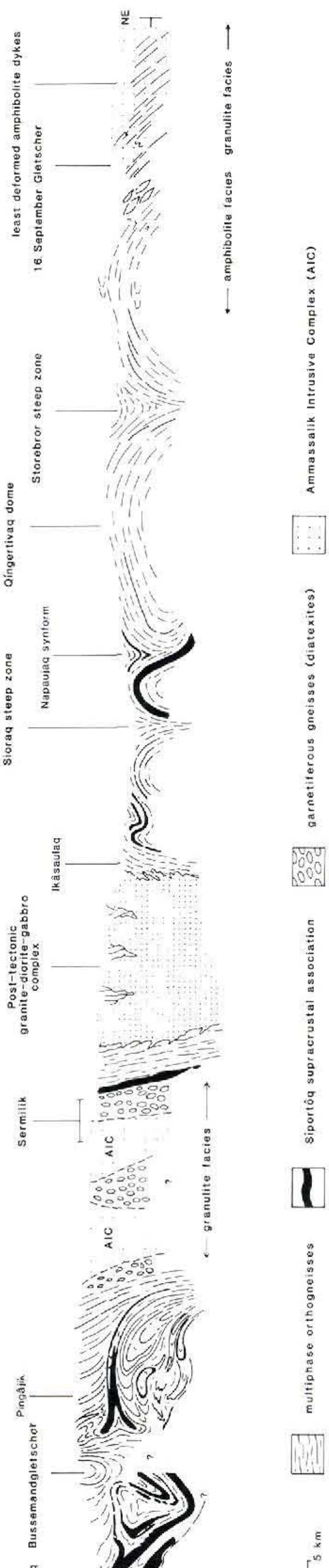


Fig. 10. Composite cross section illustrating the structure in the northern and Síportôq areas. Details of the Ammassalik Intrusive Complex provided by C. R. L. Friend (personal communication, 1986).

Fig. 11. Synform deforming podded amphibolite dyke in multiphase orthogneiss. West face of Napaujaq, 1061 m, in the northern area. Height of cliff is about 500 m.

Síportôq area

The structure of the Síportôq area (fig. 12) was investigated in detail by Palmer (1971). He concluded that the sheets of orthogneisses and supracrustal rocks had been interleaved by thrusting, with emplacement of lenses of ultrabasic rocks taking place at an early stage along thrust contacts. Palmer rejected the possibility that the interleaved sheets of metasedimentary rocks are isoclinal fold cores on the grounds that there are no symmetrical repetitions of the stratigraphy in individual sheets. He argued that amphibolite dykes of Kitak type (Wright *et al.*, 1973) were emplaced into the orthogneisses and metasedimentary rocks after the tectonic interleaving. He subdivided the post-dyke deformation into two principal phases, namely, DN_1 which is characterised by regional isoclinal folds, and DN_2 which is represented by mainly upright folds trending NW which deform the DN_1 isoclines.

Although little isotopic information is available from the Síportôq area so far, we assume that tectonic interleaving together with the emplacement of younger phases of orthogneisses gave rise to the regional layer cake structure. A number of field relations, including the persistent thin screens and pods of supracrustal rocks within the orthogneisses (fig. 12), suggest the former were intruded by a significant proportion of the latter. We also regard the strings of ultrabasic lenses as tectonically disrupted sheets, not as intrusions along thrust contacts as suggested by Palmer (1971). The fact that these strings of ultrabasic lenses occur within the orthogneisses close to contacts with sheets of supracrustal rocks suggests they may be parts of differentiated sills disrupted by injection of the precursors of the

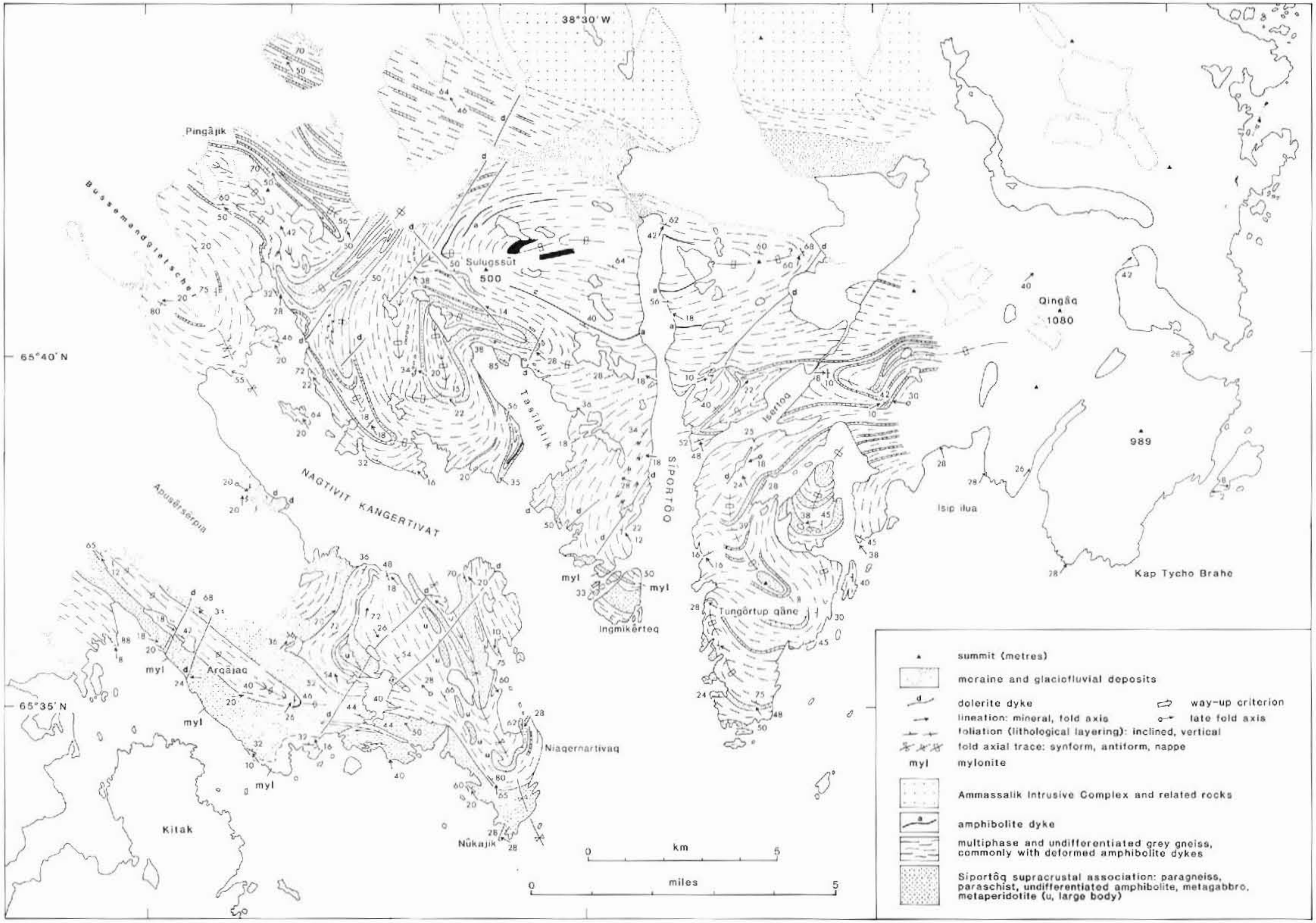


Fig. 12. Geology of the Síportôq area. Lineations in the unornamented ground in the east provided by A. P. Nutman and A. E. Wright (personal communication, 1986).

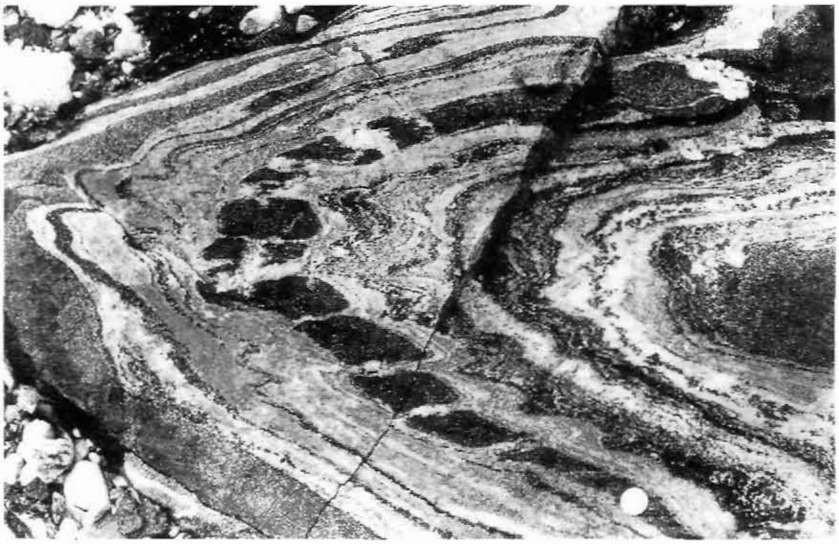


Fig. 13. Outcrop of deformed amphibolite dyke in multiphase orthogneiss with older isoclinal fold (top of photograph). North coast of Tasîlalik, Síportôq area.

orthogneisses. Like Palmer (1971), we found no symmetrical relations to suggest that individual sheets of supracrustal rocks or the associated sheets of orthogneisses are isoclinal fold cores.

The Síportôq area is dominated by fold nappes, some with complex involutions (fig. 10), which can be defined relatively easily using the persistent sheets of metasedimentary rocks and amphibolites intercalated with the orthogneisses: persistent amphibolite dykes within the orthogneisses are also valuable markers. These nappes are equivalent to the DN_1 isoclines of Palmer (1971). They deform amphibolite dykes that were podded in a chocolate tablet form of boudinage before the period of nappe development, the heterogeneous flattening strains and their timing being comparable with those in the northern area. Outcrops of folded multiphase orthogneisses and disrupted amphibolite dykes near Tasîlalîk include small isoclines which may also be older than the nappes (fig. 13). The regional nappe geometry suggests transport from the north, but the sheath fold and its coaxial stretching lineation at the head of Tasîlalîk suggest a component of displacement with a NW–SE trend.

The axial surfaces of the nappes north of Nagtivit kangertivat are arched over an asymmetric antiform trending NW through Tasîlalîk: this arch is a DN_2 structure of Palmer (1971). On the north of the arch the nappes are steepened and attenuated into a zone where the foliation and lithological layering have a regular steep dip to the northeast (fig. 10). This steep zone is the site of intense shearing, although the nature of the strains is not clear. Epidotisation and bleaching of the gneisses also appear to be characteristic of the zone. It is bounded to the northeast by garnetiferous paragneisses and the late- or post-tectonic intrusions of the Ammassalik Intrusive Complex. A strong ribbing and mineral lineation coaxial with folds of all scales associated with the nappes is also found on the foliation in the steep zone. The lineation has a variable plunge, although north of Nagtivit kangertivat it is generally 30°–40°NW.

The steepening and attenuation of the nappes in the steep zone may be interpreted in two ways. First, the zone may be closely related to the generation of the nappes because the regional outcrop and the cross section (fig. 10) suggest the zone itself may have a step-like form with a décollement above the nappe pile on the north of Nagtivit kangertivat (fig. 10, in which the extent of the décollement is exaggerated because of the composite nature of the section). On the other hand, assuming no regional tilting has taken place since the zone was formed, the orientation of the linear fabric and the curvature of the nappe axial traces suggest the zone may have accommodated displacements younger than the nappe deformation. These movements may have been related to the emplacement of the Ammassalik Intrusive Complex.

East of Síportôq the structure appears to be compatible with that to the west. Two major nappes are suggested by the distribution of persistent thin sheets of supracrustal rocks extending across Isertoq and through Tungôrtup qâne, both nappes apparently becoming attenuated as they are traced northeast. The nappe in the Isertoq area forms part of a synform in the high ground in the northeast. The axial trace of this nappe appears to cross Síportôq to curve into an area of low-angle parasitic isoclines in orthogneisses in the peninsula east of Tasîlalik. The extension of this closure southwards on the peninsula curves sharply against the small zone of supracrustal rocks on Ingmíkêrteq and the islands and mainland to the west. The metasedimentary gneisses and quartz-phyllonites which are intensely sheared on the north side of the supracrustal outcrop lie at the junction of the convergence. The axial trace of the other closure appears to pass east of Tungôrtup qâne to reappear in the peninsula south of the summit. This curvature appears to be an effect of younger folding on an upright open structure (DN_2 of Palmer, 1971) trending northwest through Tungôrtup qâne.

Linear fabrics east of Isertoq plunge northeast compared with northwesterly plunges west of Síportôq (fig. 12). This variation suggests the nappe axes are curved, a relation suggested most clearly by the nappe closure through Sulugssût (fig. 12). The curvature may be related to lateral spreading (axial stretching) of the evolving nappes. Their arching, which is clearly revealed by the curving axial traces above the sheath fold in Tasîlalîk (figs 10, 12), may be an effect of antiformal stacking of the evolving nappe pile.

Southwest of Nagtivit kangertivat the structure is well displayed by the thick zone of supracrustal rocks on the southwest of the peninsula and by seams of amphibolite and paragneisses and elongate pods of ultramafic rocks northwest of Niaqernartivaq. The supracrustal outcrop on the southwest of the peninsula (Arqâjaq) is cored by an isocline of orthogneisses. No details of this structure are available because it was seen only on helicopter reconnaissance, but the southeastern part of the closure is a neutral structure plunging northeast, and further northwest the geometry appears to be antiformal with a curving hinge line. Mylonites and ultramylonites concordant with foliation in the paragneisses, amphibolites and multiphase orthogneisses are common in coastal outcrops bording Arqâjaq. The mylonites are folded by structures coaxial with the regional fold (nappe?) on the southwest of the peninsula. This relation suggests the mylonitisation occurred relatively early. Local coarse crenulations of the intense *S* fabric are developed especially in the supracrustal amphibolites. Fabrics in the orthogneisses south of the junction dip northeast broadly concordant with those in the supracrustal rocks to the north.

The large-scale antiformal fold (nappe?) in the Arqâjaq area appears to be folded further to the southeast about a tight, regional fold whose axial trace extends northwest from Niaqernartivaq (DN_2 structure of Palmer, 1971). The area immediately east of Apusêrsêrpia was not examined in detail but there appears to be a link between the main outcrop of the supracrustal gneisses and those northwest of Niaqernartivaq through a fold closure plunging north. However, the relationships are not fully understood and require further investigation.

Synthesis

A synthesis of the regional structure may be approached in the first instance from the geometrical pattern and its chronology in the northern area (fig. 1). These suggest that tectonic instability began with patchy retrogression of the granulite facies terrain. This was followed by shear zones which dip north in areas least affected by later deformation. After the initial displacements, basic dykes (now amphibolites) were emplaced within and outside the shear zones. This emplacement was followed by reactivation of the zones (Chadwick *et al.*, this volume). The geometry of the shear zones and their deformed dykes indicate crustal shortening with upthrusting from the north. The upthrusting is assumed to have been related to overriding of thrust sheets from north to south with consequent thickening to the south.

Flattening strains presumed to have been related to this overthrusting gave rise to podding (chocolate tablet boudinage) and folding of dykes. Progressive deformation deformed the shear zones and dykes further south in low-angle isoclines and nappes, although individual nappes have not been recognised in the northern area. The generation of nappe structures is believed to have taken place beneath a carapace of thrust slices emplaced from the north and related to the shear zones. Increasing thickening and consequent heating at deeper levels may account for the generation of buoyancy forces that led to development of the regional domes, synformal cusps and straight zones which deform the isoclines in the northern area. Alternatively, the domes and related structures may be related to lateral spreading of younger nappes.

A similar pattern of structures is seen in the Síportôq area, but early shear zones which characterise the extreme north of the northern area are not preserved, the earliest recognisable deformation of the amphibolite dykes in the Síportôq area being that of flattening broadly parallel to the foliation in the host gneisses. The flattened (podded) amphibolites and their host rocks, including the supracrustal association, were folded by nappes with southwesterly vergence. The form of the nappes (figs 10, 12) indicates displacement from northeast to southwest, although significant regional displacements believed to be related to lateral spreading (axial stretching) to the northwest and northeast are indicated respectively by the sheath fold and coaxial linear fabric in the northeast. These displacement directions are compatible with those indicated by the nappes and shear zones and their fabrics in the orthogneiss terrain south of Kitak (Escher *et al.*, this volume). The nappes were deformed by steep or upright structures that include the northwest-trending structure extending through the Niaqernartivaq peninsula. The steep zone that intervenes between the Ammassalik Intrusive Complex in the north and the pile of nappes in the Síportôq area may be related either to the nappes or it may have accommodated younger displacements. Other upright structures include the gentle arch between the head of Tasîlalîk and Síportôq and the steep zone and fold through Bussemandgletscher. Local small-scale, open or gentle folds which deform the linear fabric may be related to these steep structures or they may be associated with a younger phase whose large-scale effects have not been recognised.

The tectonic sequence which followed the generation of the regional layer cake structure in both areas is attributed to ensialic crustal shortening and concomitant diapirism manifested in the first instance as overthrusting from north to south. Our evidence from the northern area is limited, but we favour migration of tectonic instability from north to south with piggy-back transport and propagation of thrusts into the footwall block comparable with processes common in other mobile belts. The geometry of the nappe pile north of Nagtivit kangertivat (fig. 10) may be that of an antiformal stack which would imply that nappes younger than the thrusts were also propagated sequentially in the footwall block, i.e. instability migrated from north to south. As a consequence of crustal thickening by overthrusting, further shortening and generation of buoyancy forces at depth led to development of nappes, the principal transport direction having been from north to south. Interference between evolving nappes in the Síportôq region gave rise to a complex geometry, especially evident in the form of the antiformal system north of Nagtivit kangertivat. Similar complications almost certainly exist in the northern area where progressive reaction to buoyancy forces gave rise to domes and synforms. In the Síportôq area later structures may have accommodated displacements which steepened and attenuated parts of the nappe pile. Emplacement of the Ammassalik Intrusive Complex with concomitant granulite facies metamorphism may have been related to these later events.

The range of structures that are superimposed on the regional layer cake arrangement of sheets of orthogneisses and supracrustal rocks in both areas are regarded as effects of progressive Ammassalikian deformation (Chadwick *et al.*, this volume, Table 1). The layer cake structure is assumed to have formed by tectonic interleaving on thrusts during the earliest period of Ammassalikian tectonism, although field relations suggest injection of concordant sheets of orthogneisses was also important as an intersheeting process. Tectonic interleaving implies that substantial crustal shortening had already taken place before the overthrusting on northerly dipping shear zones which are preserved in the patchily retrogressed, late Archaean granulite facies terrain in the north. The thrusting represented by these shear zones indicates a further period of crustal shortening which was followed by a period of nappe development, a phase that gave rise to characteristic fold nappes in the Síportôq area. Their structure suggests that these fold nappes developed in a highly ductile environment which may be attributable to density variations in hot, relatively deep crustal levels, the instability and gravitational spreading associated with the density variations being comparable with that in centrifuge models of Ramberg (1980). The regional upright structures, including the domes in the north, may represent additional buoyancy phenomena that were generated with negligible shortening. These relations suggest that the Ammassalikian tectonism was characterised by periods of not only significant crustal shortening, but also pervasive ductile deformation related to buoyancy phenomena.