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ARCHEAN METAMORPHIC SEQUENCE AND SURFACES, KANGERDLUGSSUAQ FJORD,
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Introduction: The characteristics of Archean metamorphic surfaces and fabrics of a mapped sequence of rocks older than ca. 3000 Ma [1] provide information basic to an understanding of the structural evolution and metamorphic history in Kangerdlugssuaq Fjord, east Greenland. This information and the additional results of petrologic and geochemical studies [2] have culminated in an extended chronology (Table 1) of Archean plutonic, metamorphic, and tectonic events for Kangerdlugssuaq Fjord [3,4]. This paper considers the basis for the chronology and especially the nature of the metamorphic fabrics and surfaces in the Archean sequence. The surfaces, which are planar mineral parageneses, may prove to be mappable outside Kangerdlugssuaq Fjord, and if so, they will be helpful in extending the events that they represent to other Archean sequences in east Greenland. The surfaces will become especially important reference planes if the absolute ages of their metamorphic assemblages can be determined in at least one location where strain was low subsequent to their recrystallization. Once an isochron is obtained, the dynamothermal age of the regionally identifiable metamorphic surface is determined everywhere it can be mapped.

Pre-3000 Ma Gneisses: The reconnaissance mapping (1:500,000) over the greater area of Kangerdlugssuaq Fjord [5], and the more detailed mapping (1:20,000) of this study (Fig. 1) along Watkins Fjord indicate that there are two distinct generations of granitoid gneisses. The distinction between the two is mainly structural. The older gneisses are banded migmatitic rocks containing thin biotite-rich and/or hornblende-rich parts veined and fragmented by quartz-feldspar-rich layers. The mafic bands occur as faded, "ghost-like" remnants within the bands and layers of quartz-feldspar. Early folds involving mafic paleosome and quartzofeldspathic neosome are refolded.

Supracrustal Sequence: The supracrustal rocks of this study are in apparent tectonic contact with the older gneisses, and both these rock groups are intruded by the ca. 3000 Ma calc alkaline gneiss suite. The mapped character of the supracrustal sequence is that of very narrow and deformed, elongate belts that are gradationally xenolithic in the ca. 3000 Ma gneisses. Outcrop patterns of belts are partly the result of folding (Fig. 1). Elongate belts of character similar to those of the supracrustal rocks in Kangerdlugssuaq Fjord extend south nearly 300 km to Angmagssalik [5].

Metaclastic rocks are abundant in the belts of the map area. The common types are biotite-bearing quartz-feldspar schists, micaceous quartzites, garnet-biotite schists, and quartz-sillimanite-biotite schists (\pm cordierite \pm garnet). Amphibolites are nearly as abundant as the metaclastic rocks; hornblende and plagioclase are finely banded on a mm scale and locally have gradational relations with garnet-biotite schists. Thin bands of iron-silicate-bearing quartzites or metacherts have persistent interlayered association with the amphibolites. The main iron-silicate in the quartzites is almandine, but hornblende is commonly present, there are subordinate iron-ores, and there is rare occurrence of hypersthene and fayalite.

Ultramafic Rocks: Elongate, pod-like ultramafic bodies of variable dimensions commonly measured in m, but up to 0.5 km long and 100 m thick, are widespread in the supracrustal sequence. Although greatly modified by later deformation, discordant contact relationships with the older gneisses and supracrustal rocks provide evidence that the ultramafic rocks are remnants of elongate dikes/sills. Mapped metamorphic surfaces, structures, and fab-

rics in the supracrust and older gneiss show that intrusion of ultramafic liquid was earlier than regional metamorphism/deformation common to all these rocks. The ultramafic rocks are largely amphibole-bearing peridotites with olivine, orthopyroxene or clinopyroxene (but not both), green hercynitic, brown, and iron-chrome spinels, talc and chlorite.

3000 Ma Gneisses: The younger gneisses from which the 2980±20 Ma Pb-Pb isochron [1] was obtained are polyphase intrusive rocks with compositional range tonalite to grandiorite, adamellite and granite [2]. These gneisses are the most voluminous Archean rocks in the area, and intrude supracrustal belt rocks and migmatitic gneisses. Directional fabrics of the rocks are strong but of variable character, and many rocks are foliated.

Significance of Fsp-Stage and Fgn-Stage Folds: Archean surfaces folded by Fsp-stage folds are 1) Sbgn migmatitic banding in the older gneisses; 2) Suml compositional banding generally at a high angle to and frequently transposed by 3) Scl metamorphic cleavage in the ultramafic rocks; 4) Ssp metamorphic foliation and nearly parallel compositional banding in the supracrustal rocks. Fsp-stage folds are not found in the 3000 Ma gneisses (Table 1). Strong deformation during and following intrusion of the younger gneisses developed in them penetrative fabrics Sgn and nearly parallel trends with Ssp, Scl, and Sbgn surfaces of the intruded rocks. Nevertheless, evidence is preserved for angular intrusive discordance just at the contacts between intrusive and intruded rocks. The gneisses with Sgn fabrics are folded by only the Fgn-stage folds which also affect the Fsp-stage folds and all the Fsp-folded metamorphic and migmatitic surfaces (Table 1).

The Sbgn Surface and its Relation to Ssp: Of earliest generation in this region may be the Sbgn surface of migmatitic banding. Biotite-rich and/or hornblende-rich bands now only mm thick are clearly fragmentary remnants of some pre-existing, presumably supracrustal rocks, and constitute the paleosome. The Sbgn and Ssp surfaces are both affected by Fsp-stage and Fgn-stage folds. However, on northwest Kraemers Island the Ssp and Sbgn surfaces of supracrustal belt biotite-garnet schist and migmatite gneiss, respectively, are discordant: here, near their contact, discrete and streamlined, lenticular bodies of schist are enclosed by gneiss and their respective surfaces share Fgn-stage folds. The interpretation is that the discordance is tectonic and that the lenticular schist bodies are tectonic slivers formed as a result of thrust faulting during the later stages in the development of a fold nappe. According to such a model the Sbgn surface must be older than tectonic juxtaposition but the relative age of it with respect to the surface Ssp cannot be determined.

The Ssp Surface in Supracrustal Belt Rocks: The prominent penetrative fabric Ssp in the supracrustal belt rocks consists of planar orientations of the minerals biotite, hornblende, platy quartz, and feldspar. The Ssp schistosity is parallel or subparallel to compositional banding which consists of alternating layers of quartz, or quartz-feldspar, or feldspar and segregations of a variety of Fe-Mg-Al-silicates and sillimanite. Because they have essentially the same orientation, and there is no consistent evidence for transposition of one by the other, schistosity and compositional banding are not distinguished and both are referred to as Ssp foliation. The parallel growth of planar minerals and their segregation into roughly parallel bands were in response to syntectonic recrystallization possibly along axial planar surfaces at an earlier stage. Subsequently, minerals of Ssp-stage fabrics were folded about Fsp-stage hinges earlier than or during tectonic juxtaposition with the migmatite gneisses. Maximum metamorphism associated with the Ssp surface in pelitic and semipelitic rocks is constrained only in

terms of the divariant association of sillimanite-biotite-quartz above the breakdown temperature of muscovite-quartz (upper amphibolite facies). This is because the assemblages of the supracrustal rocks are polymetamorphic and recrystallization following development of Ssp assemblages overlapped their stability field while preserving Ssp assemblages and fabrics.

Scl and other Surfaces in Ultramafic Rocks: Observations from many locations indicate that there are three kinds of fabrics recognizable in the ultramafic rocks: 1) compositional layering Suml in which occasional iron-chrome-oxide-rich bands alternate with olivine-richer and pyroxene-richer bands that are frequently several cm to tens of cm thick; 2) metamorphic cleavage Scl which transposes and frequently obliterates the earlier compositional layering; 3) reaction selvages Surs which conform generally to the pod-like shape of the bodies and are several cm to tens of cm thick separating the ultramafic rocks from the adjacent gneisses and gneiss-intruded contact with supracrustal rocks. The evidence is good that the order given here is also the order in which the fabrics were acquired. Field evidence from northwest Kraemers Island suggests that perfectly parallel Scl cleavage and Ssp foliation are equivalent in ultramafic and supracrustal rocks, respectively, and are later than the discordant contact between the two rock types. Assemblages which form the Scl surface correspond regionally to metamorphism in the T-P field of tremolite-chlorite peridotite [6]. However, the assemblages are polymetamorphic and post-Scl assemblages Surs are at higher grade.

The Sgn Surface: The penetrative foliation Sgn in the ca. 3000 Ma gneisses consists of flattened-elongated quartz-feldspar, parallel biotite flakes, and elongated hornblende. The assemblages are consistent with subsolidus recrystallization above the stability of muscovite+quartz but below the stability of biotite+quartz and hornblende+quartz in rocks of compositional range tonalite to granite. Sgn fabrics are discordant with and later than Scl, Ssp, and Sbgc cleavages and foliations.

Post-Sgn Effects: Porphyroblastic minerals of supracrustal rocks incorporate minerals of the Ssp surface and overlap their stability fields. Locally the porphyroblastic minerals have measured alignment in outcrop parallel with Fgn axes and transpose Ssp foliation in the hinge areas of Fgn folds. The porphyroblastic assemblages of ultramafic rocks are those of previously described Surs selvage assemblages. Preferred orientations of the porphyroblastic assemblages aren't obvious, but the Surs selvage surfaces have boudinage elongation parallel to Fgn axes. In the 3000 Ma gneisses, annealed mylonitic flaser structure emphasized by coarse feldspar augen also has elongation parallel to Fgn axes locally transposing Sgn foliation through Fgn fold hinges. None of the post-Sgn effects just described is penetrative. Ssp, Scl, and post-Sgn porphyroblastic assemblages together constitute polymetamorphic assemblages which at maximum grade are represented by 1) chlorite = orthopyroxene + olivine + green spinel + vapor [7] in peridotites, and by 2) biotite + sillimanite + quartz = cordierite + garnet + K-feldspar + vapor/liquid [8] in metapelites.

Summary and Conclusions: An effective method of documenting isotopically disturbed rocks older than the ca. 3000 Ma Pb-Pb isochron obtained for the voluminous calc alkaline gneisses in Kangerdlugssuaq Fjord is to map the metamorphic surfaces and fabrics of all the Archean rocks. A key to an understanding of Archean chronological relations (Table 1) is the recognition of Fsp-stage folding that is earlier than formation of the metamorphic surface Sgn in the ca. 3000 Ma gneisses. Important features of the earlier metamorphism are the well preserved, and predominant Ssp and Scl metamorphic surfaces which record a high grade dynamothermal event older than intrusion of

the ca. 3000 Ma gneisses. The interpretation here is that the final high grade metamorphic event overlapped with the heating associated with emplacement and continuing deformation (Fgn) of the youngest gneisses. The Sgn fabric in those gneisses is interpreted to be the result of synkinematic crystallization and/or subsolidus flow at temperatures above about 600°C [9,10] in a recumbent tectonic regime [11,12]. Flow fabrics equivalent to Sgn are absent in the supracrustal, ultramafic, and older gneissic rocks because stress as a component of lithostatic pressure effected pervasive movement in only the hot plastic or semi-liquid calc alkaline nappes.

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Table 1. Chronology of Archean events in Kangerdlugssuaq Fjord

7. Isoclinal upright Fgn folding of the ca. 3000 Ma calc alkaline gneiss suite, Ssp, Scl, Sbg surfaces; local transposition of Sgn and Ssp foliation through Fgn hinges during final high grade equilibration of Archean rocks.
6. Extended period of intrusion, sheet-like pulses of calc alkaline mantle-derived magma invade tectonically interlayered supracrust and migmatitic gneisses. Planar and linear penetrative Sgn fabrics by synkinematic or sub-solidus flow of plutonic rocks forming flattened-aligned quartz, feldspar, and biotite+hornblende.
5. Fold nappes form resulting at some early stage in tight recumbent Fsp-stage folds of Ssp and Sbg surfaces; at a later stage there is thrusting and tectonic interleaving of the recumbent folded sequence.
4. Syntectonic regional metamorphism of intermediate baric type forms penetrative Ssp foliation (supracrust) and Scl cleavage (ultramafic rocks).
3. Intrusion of ultramafic magma forming elongate dikes in supracrust and migmatitic gneisses; crystal settling-differentiation of magma forms Suml compositional layers (iron-chrome-oxides, olivine, and pyroxenes).
2. Deposition of supracrustal rocks apparently on granitoid basement gneisses. Accumulation of sedimentary debris with very aluminous interlayers (to 25 wt % Al₂O₃) was apparently in a basin of moderate depth with nearby volcanic source which periodically erupted basic magma; associated chemical precipitation of silica forms chert beds with localized iron-oxides-sulfides.
1. Intrusion of granitoid magma into biotite and hornblende-bearing layered and presumably metamorphosed rocks results in secondary migmatitic layers in which there is alternating quartz-feldspar and hornblende/biotite identifiable now as the surface Sbg.

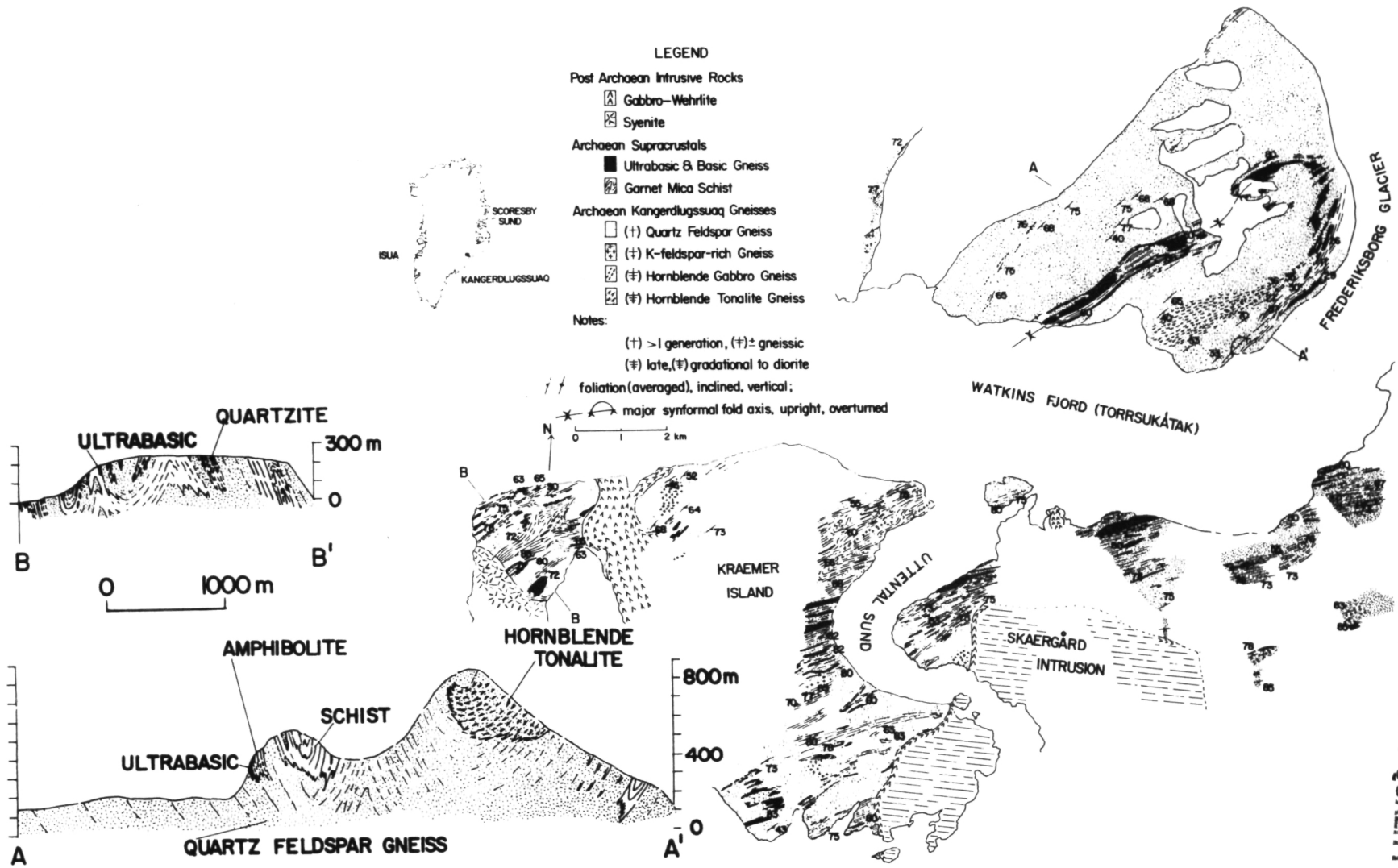


Fig. 1. Geology of the inner part of Kangerdlugssuaq Fjord in the Watkins Fjord area.