Mineralogy of ferromagnetic phases

Two distinct textural types were found in the sampled amphibolites of NW Ny Friesland (Fig.SM4-1 a, b). The first type is characterized by typical magmatic textures consisting of relicts of Ti-bearing magnetite and ilmenite (Fig. SM4-1 a) which exhibit features of Ti-Fe oxides that have partly recrystallized during a subsolidus stage (Frost & Lindsley 1991; Haggerty 1991) and by later metamorphic processes. The amphibolite grade of metamorphism is reflected by the presence of tschermakite and/or magnesio-hornblende rims on the primary clinopyroxenes (Fig. SM4-1 b).

The amphibolites, however, are more commonly strongly foliated and the Ti-magnetite has been completely replaced by titanite, while ilmenite is still present as relics. Elongate anatase grains were identified in a few samples while in others large ilmenite grains are found, often containing intergrowths of submicroscopic leucoxene, Ti-oxides, relics of ilmenite and/or a small amount of hematite (Fig. SM4-1 c).

The presence of the above Fe-Ti oxides in such amphibolite facies rocks is taken to indicate increased oxygen fugacity and H_2O activity during their evolution (Xirouchakis & Lindsley 1998, Harlov *et al.* 2006). All of the sampled amphibolites contain complex sulphide aggregates of pyrrhotite, pyrite, chalcopyrite, and sphalerite (Fig. SM4-1 d). The microstructural form of these sulphide aggregates suggests that they are of metamorphic origin. Pyrrhotite within these associations is represented by variously sized mono-mineral aggregates or as small inclusions within pyrite. Ti-free magnetites of metamorphic origin are also present in many of the sulphide aggregates.

Although ferromagnetic minerals in the metacarbonates of NE Ny Friesland (Sorgfjorden area) were not observed microscopically, rock-magnetic experiments on the metacarbonate samples have detected the presence of pyrrhotite and magnetite/maghemite. These ferromagnetic minerals are interpreted as metamorphic products of sulphide transformation (e.g. Kullerud 1986, Rochette 1987, Frost 1991). The Fe-containing association is dominated by texturally varied pyrite grains dispersed within the carbonate matrix (Fig. SM4-2 a). Moreover, numerous small grains of anatase, brookite and rutile pseudomorphing (detrital?) ilmenite or Ti-rich magnetite are also present in many of the metacarbonates.

Carbonates and tillites of W Nordaustlandet (Murchisonfjord area) both contain abundant late diagenetic stage framboidal pyrite aggregates (Fig. SM4-2 b-f). Euhedral pyrite crystals are less

common while rare detrital Ti-oxides grains are almost completely replaced by diagenetic TiO_2 oxides (Fig. SM4-2 b, d, f). As with the Ny Friesland metacarbonates, the ferromagnetic grains in these samples are of submicroscopic size, of low concentrations and were not identified microscopically. Only goethite was observed by optical methods, as a product of the late oxidation of sulphides. Magnetite/maghemite, which again has been identified only in the course of the rock magnetic experiments, may be the product of deep diagenesis (e.g. Kars et al. 2012, Roberts 2015).

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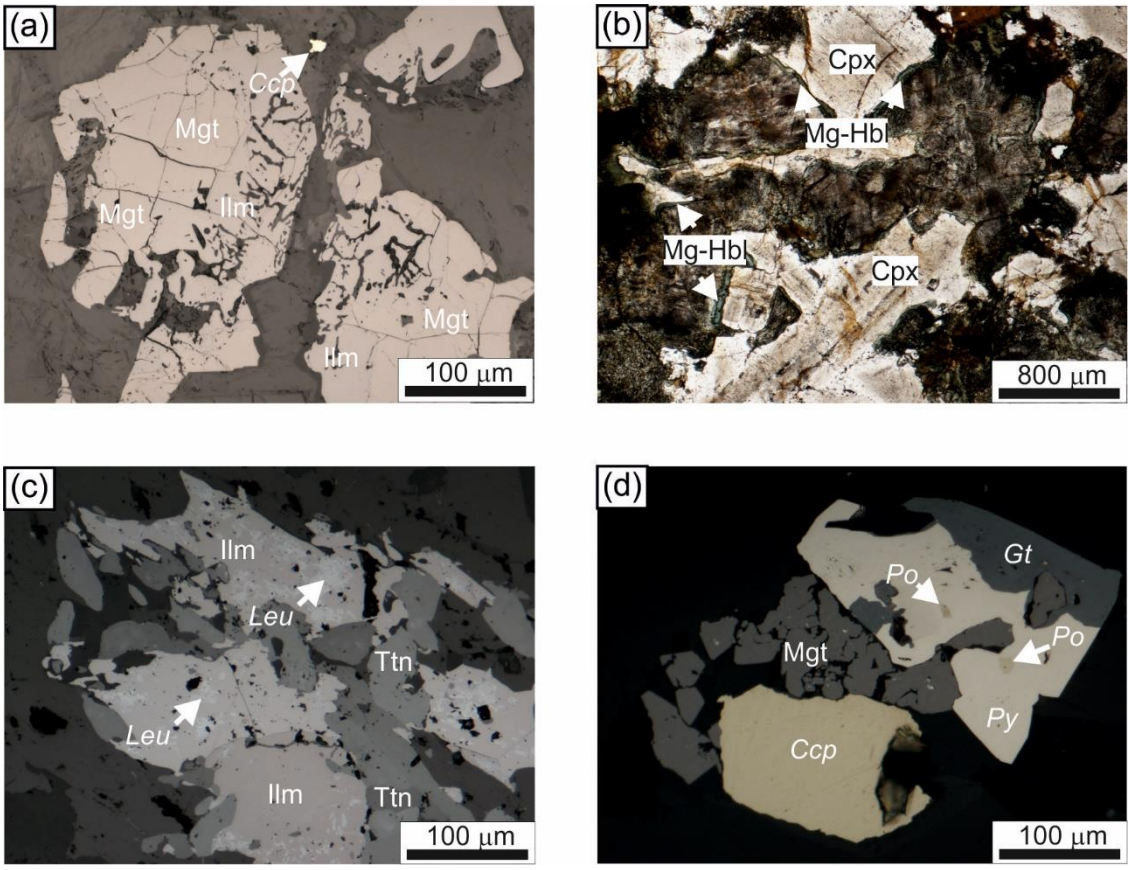

Fig. SM4-1. Oxide and sulphide associations identified within examined amphibolites of Ny Friesland. **(a)** Magnetite and ilmenite association with well-preserved magmatic texture (see irregular inclusions of silicate melts within ilmenite); Fe-Ti oxides associated with small chalcopyrite blebs; sample AMF-4 (site AMF1); reflected light image. **(b)** Clinopyroxene grains are overgrown by metamorphic tschermakite and/or magnesio-hornblende; sample AMF-4 (site AMF1); PPL image. **(c)** Fe-Ti oxides within amphibolite; the ilmenite has broken down into titanite (euhedral grains rimmed ilmenite) and leucoxene (irregular patches within ilmenite grains); sample AMF107 (site AMF6); reflected light image. **(d)** Paragenetic association of Ti-free magnetite, chalcopyrite, and pyrite with small inclusions of pyrrhotite; pyrite is replaced by late goethite; sample AMF107 (site AMF6); reflected light image. Abbreviations: Ccp - chalcopyrite, Cpx- clinopyroxene Gt - goethite, Ilm - ilmenite, Leu - leucoxene, Mg-Hbl- magnesiohornblende, Mgt - magnetite, Po - pyrrhotite, Py - pyrite, Ttn – titanite.

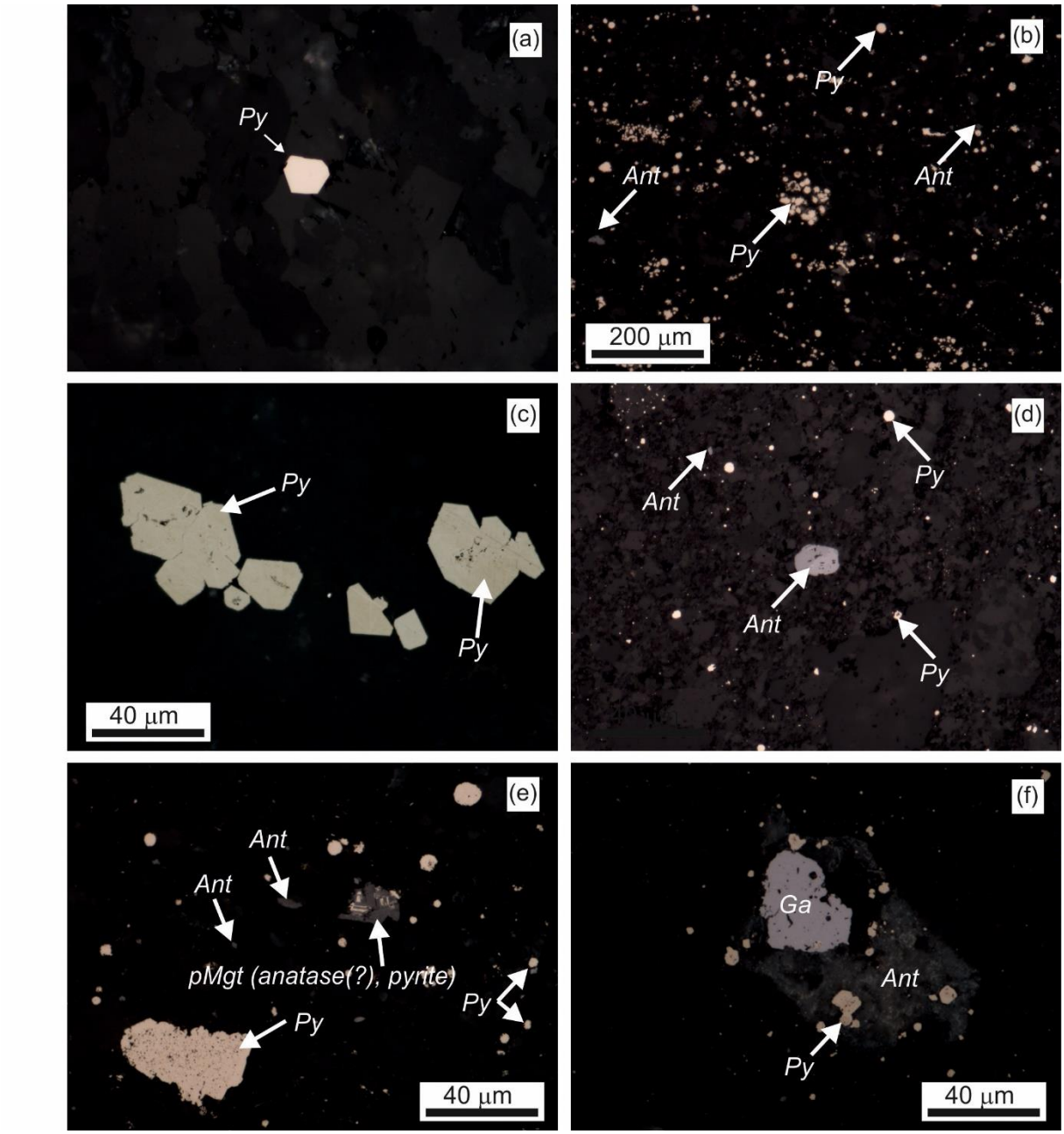

Fig. SM4-2. Oxide and sulphide associations recognized within examined metacarbonates of Ny Fiesland, and carbonates and tillites of Nordaustlandet. All photomicrographs were taken using polarized reflected light, with one nikol in the light path. **(a)** Automorphic grains of metamorphic pyrite (possibly accompanied by metamorphic magnetite and pyrrhotite ?) in strongly recrystalized metacarbonate; sample NFL5405 (site MCARB2 - metacarbonate from Ny Friesland). **(b) N**umerous famboidal pyrite aggregates dispersed within unmetamorphosed limestone with significant admixture of detrital siliciclastic material. Small detrital Fe-Ti oxides breakdown to anatase (intense, white internal reflections visible under crossed nikols); sample NLL 7603 (site CARB1 - carbonate from Murchisonfiorden). **(c)** Euhedral pyrite grains, probably formed as a result of recrystallization of the primary framboidal pyrite. The remnants

of the texture of framboidal pyrite are still preserved and manifest as tiny voids arranged in the center of the euhedral pyrite grains; sample NLL 86046 (site CARB2 - carbonate from Murchisonfiorden). **(d)** Framboidal pyrite and small detrital grains of Fe-Ti oxides completely replaced by anatase; sample DLL13303 (site TILL6 - tillite from Murchisonfiorden). **(e)** Framboidal pyrite of diffrent sizes, and large pyrite aggregates. The derital grain of magnetite is completely replaced by carbonates(calcite) and pyrite. Sample NLL7603 (site CARB1 - carbonate from Murchisonfiorden). **(f)** Galena and recrystallized pyrite grains within carbonate matrix. The tiny intergrowth of TiO2 oxides (anataze) close large galena grains; sample NLL 73306 (site CARB1 - carbonate from Murchisonfiorden). Abreviations: Ant - anatase, Cal - calcite, Ccp - chalkopyrite, Gn - galena, Gt - goethite, Ilm - ilmenite, Py - pyrite, pMgt - pseudomorph after magnetite.