THE FORMATION OF METALLIC IRON IN MAFIC MAGMAS: THE ROLE OF CARBON (CLUES FROM NATIVE IRON IN DISKO ISLAND BASALTS) Cyrena Anne Goodrich, Cornell University, Ithaca, N. Y. 14853. (Present address: Institute of Meteoritics, Department of Geology, University of New Mexico, Albuquerque, NM. 87131)

The native iron occurrences in the Tertiary basalts of Disko Island, West Greenland, provide a terrestrial example of formation of metal in a carbon-bearing, mafic silicate melt. The iron assemblages record changing conditions of fO₂, T, and composition within basaltic magma. Petrologic and field studies of the Disko iron, reported here, have led to a better understanding of the physical and chemical processes involved in formation of the metal. The details of these processes are potentially important for understanding the role of C in mafic magmas, both terrestrial and extraterrestrial (e.g., ureilite parent magmas (1)). In addition, they may help us understand the processes of metal-silicate fractionation during early stages of planetary formation.

It has been generally accepted that the Disko native iron-bearing rocks are the products of interaction between mantle-derived picritic to tholeiitic magmas and carbonaceous components of the Cretaceous-Tertiary sediments through which the magmas erupted (2). Assimilated carbon is thought to have reduced iron oxide components of the magma to form native iron (e.g., Fe₃C). Carbon presently occurs in all the native iron-bearing rocks in plagioclase-graphite-spinel xenoliths, thought to be thermally metamorphosed shale inclusions (3,4). The Uivfaq iron is the most well-known of the Disko iron occurrences. Enormous masses of iron (weighing up to 22 tons), apparently weathered out of basalt, were found along the Uivfaq shore in the 19th century (5). I have surveyed a large collection of Uivfaq iron samples from the Steenstrup collection of the Mineralogical Museum of Copenhagen and the Cornell University collection. I have studied 12 of these samples in detail. One of the 12 is a boulder, ~12 cm in diameter and weighing ~5 kg, which has a rim of fine-grained basalt and is probably the whole of an iron mass that weathered out of basalt.

The Uivfaq samples are assemblages of iron and cohenite (Fe₃C), with inclusions of silicates, sulfides, (principally troilite) and oxides (principally wustite). The silicate inclusions are reduced assemblages containing several minerals previously reported only from Ti-rich lunar mare basalts and meteorites: chromian ulvospinel, Fe-rich pyroxene (pyroxferroite?), and phosphoran pyroxene and olivine (6).

Two types of metal, distinguished on the basis of bulk C-content (and consequent textures) occur among the samples surveyed. High-carbon samples contain 3.8 - 4.0 wt.% C. They have eutectic textures of iron and cohenite (Fig. 1) similar to those typical of commercial white cast irons. Eutectic cohenite crystals in the Uivfaq iron are up to 15 mm in length, which is 2-3 orders of magnitude larger than in commercial alloys and indicates considerably longer cooling times for the Uivfaq iron. The high-carbon iron occurs in approximately spherical bodies, up to 15 mm in diameter (Fig. 1), within basalt, and appears to have been immiscible iron-carbon liquid "droplets" within basaltic liquid. Low-carbon samples contain 1.5-2.0 wt.% C. They have textures similar to those typical of commercial hypereutectoid steels. Gamma-iron grains (~1 mm) occur in an equigranular texture (Fig. 2). Cohenite occurs in all the morphologies of proeutectoid cohenite (cohenite that exsolves from gamma-iron in the temperature interval 1148 - 727°C that commonly form in steels. The dominant proeutectoid cohenite morphology is grain boundary cohenite (Fig. 2).

Low-carbon iron is far more abundant than high-carbon iron and forms the large iron masses. Textural evidence indicates that the large masses formed as cumulates of mm-sized iron grains. Near the top of the 5 kg boulder isolated iron grains occur within the basalt matrix. Toward the boulder the iron grains become progressively more compact, and in the densest parts of the boulder trapped silicate occurs as isolated intergranular inclusions. The varying proportions of interstitial silicate in the other low-carbon samples suggest that they represent various parts of other cumulate boulders. This textural evidence is supported by the results of a Stoke's law calculation, which show that at 1150°C, 3.7 cm is the maximum diameter of an iron mass that could be carried upward by a basaltic magma. The presence of small (100-700 μm), spherical, intragranular inclusions that appear to have been immiscible liquids within the low-carbon iron grains indicates that the low-carbon iron was also originally iron-carbon liquid within basaltic liquid. Phase relations within both types of metal indicate that they crystallized in approximately equilibrium crystallization sequences from iron-carbon liquids with their present bulk carbon contents.

These iron-carbon liquids formed by a reduction process within basaltic liquid. Consideration of equilibria in the system Fe-C-O (7) shows that at magmatic temperatures iron oxide components of a mafic magma would be reduced by assimilated carbon. At these temperatures, effectively all of the Ni, Co, and Cu in the volume of magma affected by the reduction would also be reduced and concentrated into the metal. Ni, Co, and Cu occur as minor elements in the Uivfaq iron in relative proportions consistent with derivation from a basaltic magma. The metallic iron produced by reduction would have immediately absorbed carbon (the abundance of graphitic xenoliths in the iron-bearing rocks indicates that there was...
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excess carbon in the magma) up to the solubility limit of carbon in iron (3.9 wt.% at 1200°C) and formed an immiscible Fe (Ni, Co, Cu, F)-C liquid. Direct crystallization of this liquid produced the high-carbon samples. The sizes of these samples suggest that the immiscible liquid formed as isolated 1-15 mm droplets. Carbon geobarometry indicates that the reduction took place at a pressure less than 1 kb (8, 9).

Low-carbon iron could have formed from high-carbon iron-carbon liquid by an oxidation reaction in a restricted range of fO2 below the iron-wustite (IW) reaction curve. This process would have been similar to the commercial process of "decarburizing" white cast iron to produce steels. If excess C is not present (graphite in the magma would be naturally separated from iron due to density differences) and/or the fO2 is raised, C in the metal would be oxidized and removed from the metal as CO and CO2. If the system is open with respect to gas exchange (i.e., the rise in fO2 is externally induced) then the reaction occurs without net reduction of the magma. The decarburization reaction C (in iron) + O2 = CO or CO2 is exothermic, and produced enough heat locally to raise the temperature of the low-carbon metal to at least its melting point (1400°C). The low-carbon liquid existed as mm-sized droplets which crystallized as single gamma-iron grains. The P content of the metal and of the silicate inclusions can be used as an indicator of fO2 near the IW buffer because the P2O5-P buffer is close to IW (10). Experimental work by Newsom and Drake (11) indicates that the partitioning of P between metal and silicate is a sensitive function of fO2. Their equations indicate that the low-carbon metal equilibrated at an fO2 close to IW, while the high-carbon metal equilibrated at lower fO2.

I suggest a two-stage geologic model for the formation of the iron. The reduction process could have occurred in a magma chamber, at a depth of 3 km or less, within the sediments. Upon movement of the iron-bearing magma upward from the magma chamber, the fO2 rose, and low-carbon iron was produced. The iron was carried upward as mm-sized grains. Some of it accumulated to form large masses at the base of a small, subvolcanic intrusion at a depth of at least 0.6 km.

The Uivaq iron samples provide evidence of two processes which could be important in carbon-bearing terrestrial and extraterrestrial mafic magmas. In a closed system, carbon can cause self-reduction of a magma at low pressures. In an open system, oxidation of carbon could cause local heating of a magma to anomalously high temperatures.