A Reappraisal of the Mineralogy and Crystallization Features of Los Angeles, a Basaltic Martian Meteorite.

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We have examined the mineralogy, the oxide-silicate phase relations, and the symplectites in a sample of stone 1 of Los Angeles meteorite [1-4]. [2-4] postulated that the symplectites present in Los Angeles consist of the assemblage hedenbergite + fayalite + silica (CaFeSi₂O₆ + Fe₂SiO₄ + SiO₂) as a result of the low pressure breakdown of pyroxferroite: a pyroxenoid (Pxd) with Ca₀.₁₅ Fe₀.₈₅ SiO₃ composition [5]. Implicit in this model is the notion that the bulk of crystallization (~95% crystals) took place at \( \phi \sim 1.0 \) GPa [5, 6]. Alternatively, the reaction could have been pyroxenoid + fayalite + silica = pyroxene + fayalite + silica [5, 6, 7]. This obviates the need for initial high pressures. However, it requires the presence of a SiO₂ polymorph as well as Mg-free olivine and pyroxene in the symplectites.

The texture of the sample studied is dominated by 0.5-2.0 mm anhedral to subhedral grains of pyroxenes (Px) and subhedral to euhedral shocked plagioclase (Plag). The spaces within the Px and Plag grains contain, (a) subhedral titanomagnetite (TiMt) and ilmenite (Ilm) grains, (b) 5 - 15 \( \mu \)m thick Fe-rich olivine (Ol) rims that isolate TiMt from Px and are followed by Ol+Px symplectites (no SiO₂ phase present), (c) pyrrhotite (Fe₀.₉₆ S) inside TiMt and the Ol+Px symplectites, (d) phosphate phase, and (d) alkali-rich (Na, K, Rb) feldspathic glass closely associated with subhedral to euhedral pure SiO₂ grains with a shape occasionally reminiscent of tridymite.

Titanomagnetite has less than 2 wt% Cr₂O₃ and Al₂O₃, and in terms of the components Fe₂TiO₄, MgFe₂O₄, MnFe₂O₄, and Fe₂O₃ its composition varies within the range 60.6-78.9 mol%, 0-1 mol%, 1-2.5 mol%, and 37.5-18.3 mol%, respectively. Peripheral to the titanomagnetite grains are single ilmenite grains with a composition of Hm₁₂₅₋₀₃ ·Gk₁₀₋₀ ·Py₁·₅₋₁·₂ ·Il₉₄·₄₋₉₈·₁ (Fe₂O₃ ·MgTiO₃ ·MnTiO₃ ·FeTiO₃).

Pyroxene compositions, expressed as CaSiO₃-MgSiO₃-FeSiO₃, range from En-rich in the interior to Fs-rich at the rims (Wo₁₃₋₂·₄ ·En₃₁₋₄ ·Fs₃₉₋₈₁). The concentration of non-quadrilateral components is small (total minor oxides <2.5 wt%). Pyroxene grains next to olivine exsolve to pigeonite + augite. Though olivine (Ca₀.₃₄ SiO₄ - Mg₀.₆₆ SiO₄ - Fe₀.₀₁ SiO₄; La₀.₂₋₁ ·Fo₀.₇₋₀.₅ ·Fa₀.₇₋₀.₅) is in contact with both pigeonite and augite, only augite intertwines with olivine to form the characteristic Ol+Px symplectites (Fig. 1a). Despite detailed X-ray maps of the Ol+Aug symplectites, and careful search during microprobe analyses we failed to detect a SiO₂ phase associated with them (Fig. 1b).

Figure 1: (a) BSE image of a typical oxide-silicate cluster [R. NOTE] the Ol around TiMt and in contact with Ilm, sulphide, and Px, (ii) the Px exsolution to Aug (dark gray) and Pig (light gray). (b) Si X-ray map of an Ol+Aug symplectite; SiO₂ would appear as bright red.

The stoichiometric shocked plagioclase grains, with a composition of Ab₁₃·₅ ·Ab₂·₅ ·An₄·₅ , exhibit features of a diaplectic glass and maskelynite [8]. The microprobe analyses of the alkali-rich feldspathic glass suggest that in its present state is probably a mixture of an alkali-rich and a SiO₂ phase, and thus it may be a...
shock related feature. However, both the SiO$_2$ and the alkali-rich phase had to exist prior to the shock as late stage igneous features.

We used the programs QUILF [9] and MELTS [10] to compute the T and f$_{02}$ conditions that may have prevailed during crystallization, and to model the phase relations. The assemblage shown in Figure 1 and the variable Fe$_3$TiO$_4$ content in titanomagnetite (Usp$_{79}$ - Usp$_{61}$), are probably best explained by the reactions:

Px + TiMt = Ol + Ilm (1),
One Px = Pig + Aug (2),
Pig + TiMt = Ol + Aug + Ilm (3),

Reaction 3 is a combination of 1 and 2, and thus becomes operative after pyroxene exsolution.

Figure 2: T and f$_{02}$ crystallization conditions of LA.

We modeled reactions 1 to 3 in the Ca-Mg-Fe-Ti-Si-O system by performing calculations at a constant pressure of 1000 bars (max), and in the range 1000 to 800 °C. We obtained close matches between observed and calculated compositions, except for ilmenite, along a cooling path from 990 °C and FMQ-1.5 to 870 °C and FMQ-0.6 (path A to C in figure 2). Along this path the calculated FeTiO$_3$ content decreases whereas the calculated Fe$_2$O$_3$ content in ilmenite increases. In contrast, the observed ilmenite is characterized by small to negligible Fe$_2$O$_3$ content. This disparity is probably a consequence of the mantling of the titanomagnetite and ilmenite grains by Fe-rich olivine, because then the oxides would have to equilibrate independently of the pyroxenes. In addition, because titanomagnetite is more abundant than ilmenite within each one of these clusters, ilmenite would gain Ti and lose Fe$^{3+}$, because of the equilibrium:

Fe$_7$TiO$_4$ + Fe$_2$O$_3$ = Fe$_8$O$_2$ + FeTiO$_3$ (4)

[12] while the Fe$_3$TiO$_4$ content of titanomagnetite may change little [13] during subsolidus equilibration, notwithstanding Fe-Mg exchange with olivine and between ilmenite and titanomagnetite (arrow in Fig. 2).

Because most of the observed titanomagnetite compositions fall within the range Usp$_{79}$ - Usp$_{61}$ it is permissible that the majority of the observed textures formed in the interval 950 to 900 °C and near FMQ-1.

We conclude that pyroxene crystallization commenced at ≤$1150$ °C whereas between 1050 to 950 °C pyroxenes crystallized together with plagioclase. Crystallization of titanomagnetite probably started at ≥$990$ °C and FMQ-1.5. Subsequently, reaction 1 began producing Ol+Ilm prior to pyroxene exsolution at ≤$905$ °C. Then reaction 2 replaced 1 (Path ABC in Fig. 2).

We argue against the former presence of a Mg-free Pxd and its replacement by the assemblage clinopyroxene + fayalite + silica either directly or indirectly via a Pxd → Px transformation. This conclusion is based upon (a) Px+Pxd+Liq equilibria, (b) the Mg-bearing Px rim compositions and corresponding calculated temperatures (T<950 °C), and (c) the absence of a SiO$_2$ phase in the Ol+Aug symplectites (Fig. 1b), [5, 6, 7, 11].

Finally, oxide-silicate interaction in Martian meteorites has to be carefully evaluated as it bears on the T-f$_{02}$ crystallization conditions, rock magnetism, and the composition of the residual silicate melts.

References: