Introduction: The forsterite-bearing Type B CAIs (FoBs) are rare but important members of the CV chondrite CAI’s suite because of (1) their intermediate chemistry and mineralogy between the ‘classic’ CAIs and forsterite-rich AOA’s and (2) high proportion of FUN CAIs among them [1]. The characteristic feature of most FoBs is the pronounced enrichment of the external Al-melilite mantles in heavy Si and Mg isotopes compared to the Fo-Sp-Cpx interiors that is typically attributed to the evaporative loss of Si and Mg from molten CAIs [1]. Recently we described [2,3] a new FoB from Allende, SJ101, that shows neither petrographic nor isotopic [4,5] evidence for Si and Mg evaporation. Here we present the results of thermodynamic modeling of condensation of the SJ101 precursors and speculate about nebular history of SJ101.

Petrology & Chemistry: SJ101 consists of three major structural units (Fig. 1): (1) light patches of sector-zoned, poikilitic Al-rich clinopyroxene (Cpx) with numerous inclusions of small spinel grains and aggregates and subordinate amounts of Mg-rich melilite (Mel) and anorthite (An) (Sp-Cpx lithology), (2) dark sinuous bands of Al-rich clinopyroxene with large (up to ~300×60 μm) poikilitically enclosed euhedral forsterite (Fo) crystals (Fo-Cpx lithology), and (3) the external Cpx-Sp-An rim overlying the entire inclusion. The two major lithologies are always separated by a transition zone of clinopyroxene poikilitically enclosing both forsterite and spinel. The patches of the Sp-Cpx lithology exhibit significant textural and mineralogical variability that is size-dependent. Small patches typically consist of Cpx and spinel with minor remnants of melilite and/or its alteration products. Large patches contain Mel-An-rich cores with either equigranular-ophitic-subophitic or ‘lacy’ textures reminiscent of those in Type B or C CAIs, respectively. All silicates poikilitically enclose numerous spinel grains of identical habit. Both melilitie and anorthite gradually disappear toward the boundary with the Fo-Cpx lithology. Neither the evaporation mantle of Al-rich melilitie typical of other FoBs nor the Wark-Lovering rim is present.

Being a rather typical FoB mineralogically and chemically (Fig. 2), texturally SJ101 differs from other FoBs in displaying the nearly complete segregation of forsterite from spinel which occur only in the Fo-Cpx and Sp-Cpx lithologies, respectively. The complex, convoluted internal structure of SJ101 suggests that the coarse-grained Sp-An-Mel-Cpx cores and Fo-Cpx lithology represent the precursor materials of FoBs, proto-CAIs and Fo-rich accretionary rims. While the inferred chemistry and mineralogy of the Fo-rich rims are fairly typical, the high Åk content in SJ101 melilite (78.7-82.3 mol. %) implies that the SJ101 proto-CAIs represent a new type of CAIs that has not been sampled before.

Condensation Origin of SJ101 Precursors: The Group II REE pattern [9], slightly negative δ29Si and δ25Mg values, and nearly solar ratios of the major elements in the bulk SJ101 suggest that its precursors, proto-CAIs and Fo-rich rims, could have formed by a non-equilibrium condensation in a closed system of...
solar composition somewhat depleted in a super-refractory evaporation residue.

Such a scenario was explored by thermodynamic modeling \cite{10} of equilibrium and non-equilibrium (CWPI-type) condensation in the system of solar composition at different pressures. Reasonable fits between the bulk chemical composition of the Fo-Cpx lithology and the amount of Fe-Ni metal in it were found at nebular pressures of (6-9)×10^{-5} bar. For the discussion below we have chosen 9×10^{-5} bar because at this pressure metal and forsterite start to condense nearly simultaneously.

Matching the chemical compositions of the SJ101 lithologies and condensates formed in a system of solar composition at 9×10^{-5} bar requires some deviations from equilibrium condensation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Chemical compositions of the SJ101 lithologies and other FoBs. Black labeled squares show chemical compositions of the bulk SJ101 (B), Sp-Cpx (S) and Fo-Cpx (F) lithologies as well as their ‘lacy’ (L) and coarse-grained (C) cores. Black numbered circles – FoBs. Numbers are the same as in Fig. 2. The bulk composition of equilibrium condensate is shown by the dashed line. The blue and red lines show the chemical compositions of the total condensate and reactive solids, respectively.}
\end{figure}

The condensation paths that pass through or near the bulk compositions of the whole SJ101 and its lithologies (Fig. 3) were calculated by assuming a gradual isolation of hibonite (isolation degree of 0.01 rel. % per K), perovskite (0.05 %/K), spinel (12 %/K), and melilite (0.05 %/K) during condensation of a system of solar composition depleted in Ti by 10 %, consistent with the TiO_2 concentration in the SJ101 bulk. Shown for comparison is the equilibrium condensation path of a system of solar composition. It has to be noted that neither the selected set of isolated minerals nor values of isolation degrees are unique; isolation of either hibonite or spinel alone, or both, also allows reasonable fits to the compositions of the SJ101 lithologies to be made. Varying the values of isolation degrees for this mineral set within ~30 % can still yield acceptable fits to the SJ101 chemical compositions.

The bulk compositions of the ‘lacy’ and coarse-grained proto-CAIs and the whole SJ101 are matched by the chemical compositions of condensates at 1380.4 K, 1373.3 K, and 1372.8 K, respectively (blue line). These condensates have to consist of ~15 wt. % inert refractory phases and 85 % reactive solids. The inert refractory condensate, on average, contains 82.5 wt. % spinel, 14.1 % gehlenitic melilite, 2.5 % hibonite, and 0.9 % perovskite. The reactive solids mainly consist of 87-96 wt. % clinopyroxene (~13 wt. % TiO_2, ~18 % Al_2O_3), ~4 % spinel, and up to 9 % forsterite (~0.14 wt. % FeO, ~0.5 % CaO). At 1371.1 K the chemical composition of the Fo-Cpx lithology approaches the composition of the reactive solids (red line) which consist of 65.7 wt. % Cpx, 28.3 % Fo, 2.6 % spinel, and 3.4 % Ni-rich metal. Upon further cooling, ongoing condensation of forsterite and metal rapidly increases their contents in the reactive solids to ~40 and 10 wt. %, respectively, at 1369 K and, eventually, ~57 and 30 % at 1338 K. The contents of spinel and clinopyroxene decrease accordingly, although their absolute amounts remain essentially unchanged. At 1337 K the Ca-tschermak (CaAl_2SiO_6) component of clinopyroxene begins to react with the gaseous SiO to form anorthite.

\textbf{Nebular History of SJ101:} (1) nearly complete vaporization of primary dust except for a very small amount of Ti- and HREE-rich super-refractory residue, (2) relatively fast cooling and condensation of the gaseous phase produces hibonite-perovskite-spinel aggregates coated by melilite mantles (a-la fine-grained spinel-rich CAIs), (3) much slower cooling allowing small particles and melilite mantles to react with the residual gas to form clinopyroxene, (4) a flash heating event that melts large refractory objects to form proto-CAIs, (5) condensation of clinopyroxene, spinel, forsterite and metal and accretion of Fo-rich rims on proto-CAIs as system slowly cools down to ~1371 K, (6) another flash heating event of a lower magnitude melts the Fo-rich rims around proto-CAIs allowing many proto-CAIs to stick together, (7) rapid cooling down to ~1337 K leads to corrosion of clinopyroxene and spinel in the SJ101 external rim by anorthite. (8) Soon after SJ101 has to be removed from its nebular source region.