ROCKY CORE MEETS FLUIDS – MODELING METAMORPHIC PHASES ON ICY MOONS. J. S. Semprich1, S. P. Schwenzer1, A. H. Treiman2, 1AstrobiologyOU, The Open University (Milton Keynes, MK7 6AA, julia.semprich@open.ac.uk), 2LPI, USRA, 3600 Bay Area Blvd, Houston, TX 77058.

Introduction: Several observations point towards the interaction between water and the rocky core on icy moons including high heat flux and plume activity on Enceladus [1-3], and the detection of salt-rich particles [4], ammonia and 40Ar [5], H2 [6], and silicon-rich dust grains [7] in its plume. If the rocky core is fractured or unconsolidated [8-10], alteration reactions of silicates, possibly in the form of serpentinization, could be expected at greater depth. Serpentinization releases H2, which can be used by microbial life in redox couples for energy [11], and releases metal cations like Mg2+ that may be essential for metabolism. While changes in water geochemistry at the fluid-rock interface have already been investigated [12, 13], this study aims to model the alteration mineralogy at conditions resembling the deeper crust of icy moons which can identify potential subsurface habitable zones. We use phase equilibria calculations to explore the stability of metamorphic phases as a function of pressure, temperature, and fluid composition.

Methods: As starting bulk composition, we use the section SM51 of the Sutter’s Mill meteorite, which has been classified as a CM chondrite by whole-rock chemistry and isotopic compositions [14]. The measured elemental composition [14] was recalculated to oxides as follows (in wt. %): 29.35 SiO2, 2.53 Al2O3, 0.5 Cr2O3, 29.31 FeO, 22.87 MgO, 2.95 CaO, 1.39 S2. In the calculations H2O and CO2 abundances are varied by 1) H2O from 0-10 wt. % with no CO2; and 2) H2O fixed at 6 wt. % with CO2 varied from 0 to 6 wt. %. Phase equilibria are calculated with the Gibbs free energy minimization software Perple_X 6.9.0 [15] using an internally consistent thermodynamic data set [16] and the following solid solutions: clinopyroxene (Cpx), olivine (Ol), spinel (Spl), and orthopyroxene (Opx) [17]; antigorite (Atg) [18]; chlorite (Chl) [19]; tremolite (Tr), dolomite (Dol), magnesite (Mgs), and pyrrhotite (Po) [16]. Talc (T) is treated as ideal solid solution while calcite (cal), and anorthite (an) occur as pure phases. A generic hybrid molecular fluid equation-of-state solution model [20] is used for the fluid (F), which includes the following species: H2O, CO2, CH4, H2S, SO2, H2, and CO. An arbitrary excess oxygen content of 0 is assumed to account for redox processes. Vesuvianite, andradite, uvarovite, and corundum were excluded from the calculation since they are not expected at the compositions and conditions considered.

Results: Fig. 1 shows the computed stable phases at temperatures of 200-600 °C and pressures of 0-5 kbar for the Sutter’s Mill composition with 6 wt. % H2O and 3 wt. % CO2. Antigorite (serpentine) and talc are stable in the low temperature range of the phase diagram until 300 °C at low pressure and up to 500 °C at 5 kbar. Chlorite and tremolite are abundant hydrous phases at most conditions and are only absent at higher temperatures. Dolomite is the dominant carbonate and only replaced by calcite in the higher temperature, mid pressure range. The spinel composition is predominantly magnetite, while pyrrhotite is the stable sulfide. In Fig. 2, the modal abundances of the major phases and the fluid species at 500 bars and 300 °C (as indicated by the star in Fig. 1) are plotted as a function of increasing water content in the bulk composition. Chlorite is the dominant OH-bearing phase at low water content and is gradually replaced by antigorite at the expense of olivine above ~4.6 wt. % H2O. Below ~4 wt. % bulk H2O, all water is present in OH-bearing minerals without a separate fluid phase. The first free fluid is enriched in H2 but significantly increases in H2O with higher water content in the bulk composition. The effect of higher pressure at 300 °C has also been investigated in the models but changes in the mineral assemblage and modes are not significant and therefore not shown.

Calculations with 6 wt. % H2O and variations in CO2 from 0-6 wt. % (Fig. 3) show a relatively constant...
amount of chlorite, while the proportions of antigorite, tremolite, and olivine decrease with increasing CO$_2$. The amount of talc increases significantly with an increase in CO$_2$ and dolomite is the stable carbonate for most conditions. Magnesite is only present in low modal amounts at the highest CO$_2$ considered (not shown in Fig.3). The fluid phase is enriched in H$_2$ at low CO$_2$ and then dominated by CH$_4$. Modes of spinel, predominantly magnetite, and pyrrhotite are less variable with increasing CO$_2$.

Discussion and conclusions: Serpentine is the main hydrous alteration phase reported in Sutter’s Mill and other CM chondrites and our models match these observations with antigorite being stable above 6-7 wt. % bulk H$_2$O and relatively low CO$_2$. Carbonates in the form of dolomite and calcite are also reported in Sutter’s Mill and CM chondrites, and both are present in our models although calcite is stable at higher temperatures and moderate pressures. In addition to these phases, our results show an abundance of chlorite, which can form at lower bulk H$_2$O than antigorite and is the main hydrous alteration phase that can incorporate Al$_2$O$_3$. While the CM chondrites show a very heterogenous texture and mineralogy with Al$_2$O$_3$ localized in calcium-aluminum-rich inclusions rich in Mg-Al phases [14], our model uses a homogeneous bulk at equilibrium conditions and will therefore favor the formation of chlorite. Several oxides are currently not considered in the calculation, which may slightly influence mineral modes although this effect is reasonably small for the low amounts of MnO and Na$_2$O measured. Ni is found in pentlandite, which has been reported in the Sutter’s Mill meteorite, but is currently not available in the thermodynamic data base and has therefore not been included in our calculations. As a Fe-Ni sulfide, it is expected to influence the proportions of pyrrhotite but will not significantly alter the modeled assemblage of silicates and carbonates presented here. Redox conditions are currently defined by arbitrarily setting the excess oxygen content to 0 but the effect of different redox states should be explored further in the model setup. As expected for serpentinization reaction, the fluid phase is enriched in H$_2$ which was detected in the plume [6], and could potentially provide fuel for life where it has cooled sufficiently for microbes to survive. The addition of CO$_2$ to the bulk composition, however, causes the modeled fluid to be enriched in methane.