
Supplementary information

Meteoritic evidence for a Ceres-sized water-rich carbonaceous chondrite parent asteroid

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Supplemental Material for:

Meteoritic Evidence for a Ceres-sized Water-rich Carbonaceous Chondrite Parent Asteroid

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Supplementary Table 1. Average compositions of minerals in AhS 202 from EMP analyses by wt% oxide and ion calculation

	Amphibole		Serpentine 1		Serpentine 2		Clinochlore		Magnetite*		Diopside		Olivine		Phosphate**	
	avg (24)	std dev	avg (11)	std dev	avg (12)	std dev	avg (22)	std dev	avg (47)	std dev	avg (4)	std dev	avg (37)	std dev	(1)	
SiO2	57.5	0.6	40.8	1.4	37.2	1.4	35.3	1.1	0.15	0.17	54.3	0.8	37.3	0.5	3.1	
TiO2	0.03	0.03	bdl		bdl		bdl		0.45	0.07	bdl		bdl		0.12	
Al2O3	0.32	0.13	2.94	0.45	3.11	0.33	10.8	0.6	0.02	0.01	0.26	0.18	bdl		0.08	
Cr2O3	0.05	0.02	0.38	0.26	0.35	0.07	0.75	0.26	0.67	0.71	0.23	0.08	0.03	0.01	1.30	
V2O3	na		na		na		na		bdl		na		na		na	
FeO	4.2	0.3	8.0	0.7	6.4	0.5	7.3	0.4	30.1	0.5	3.9	0.2	28.6	0.3	14.0	
Fe2O3									66.9	1.1						
NiO	0.06	0.04	0.11	0.05	0.10	0.02	0.12	0.03	0.16	0.06	0.04	0.02	0.12	0.02	0.11	
MnO	0.18	0.04	0.11	0.03	0.07	0.02	0.06	0.02	0.11	0.03	0.20	0.01	1.33	0.09	0.03	
MgO	22.5	0.4	33.4	1.7	30.3	1.4	31.9	0.8	0.42	0.24	17.5	0.7	33.8	0.5	0.43	
CaO	12.5	0.6	0.09	0.07	0.16	0.14	0.20	0.08	0.15	0.21	23.0	1.1	0.05	0.10	42.3	
Na2O	0.80	0.34	0.17	0.13	0.35	0.18	0.10	0.06	na		0.14	0.03	bdl		bdl	
K2O	bdl		bdl		bdl		0.17	0.14	na		bdl		na		bdl	
F	bdl		bdl		bdl		bdl		na		na		na		bdl	
Cl	bdl		0.03	0.01	0.05	0.01	bdl		na		na		na		0.01	
P2O5	bdl		bdl		bdl		bdl		na		bdl		na		30.7	
SO3	bdl		0.08	0.10	0.07	0.03	bdl		na		bdl		na		0.18	
Total	98.2	0.7	86.2	3.9	78.1	3.3	86.8	1.6	99.1	0.6	99.6	1.0	101.3	0.7	92.3	
Mg#	90.6		88.2		89.4		88.6				88.9		67.8			
Wo											45.7					
ions normalization method	13 cations†		9 anions		9 anions		36 anions		4 oxygen		24 oxygen		24 oxygen			
Si	7.862		1.920	} 2.000	1.634	} 1.800	6.760	} 8.000	0.006	} 1.990	7.968	} 8.000	5.957	} 5.960	} 12.100	
Ti	0.003				0.161		1.240		0.013							
Al	0.051		0.080				1.193		0.001		0.032					
Al			0.083	} 2.800		} 2.269		} 11.710		} 1.010	0.013	} 8.020		} 12.100		
Fe3+	0.326								1.948							
Cr			0.014		0.012		0.114		0.020		0.026		0.003			
Fe2+	0.149		0.316		0.234		1.166		0.974		0.477		3.822			
Mg	4.576		2.352		1.984		9.104		0.024		3.816					
Mn	0.021		0.005		0.003		0.009		0.004		0.024		8.054			
Ca	1.837		0.004		0.007		0.041		0.006		3.615		0.009			
K				} 0.016		} 0.029	0.040	} 0.037				} 0.040				
Na	0.212						0.037									
P																
Ni																
OH***	2.000		4.409		6.458		16.600				0.015					

*Magnetite analyses re-calculated under the assumption that molar Fe²⁺/Fe³⁺ = 2/3.Detection limits: F - 0.04; Na₂O - 0.02; K₂O - 0.01; CaO - 0.01; SO₃ - 0.03; Cl - 0.004; P₂O₅ - 0.03; TiO₂ - 0.02; NiO 0.02.

bdl = below detection limit; na = not analyzed.

**Small phosphate inclusion in magnetite. This analysis includes significant overlap with surrounding magnetite, therefore calculation of a cation mineral formula is not appropriate.

*** For serpentines and chlorite, cations calculated assuming wt.% H₂O = 100-(analytical total from EMPA).

†Amphibole recalculated using method of Locock (2014). See Table S2 for complete calculation.

Supplementary Table 2. Compositions in wt.% of amphiboles from EMP analyses

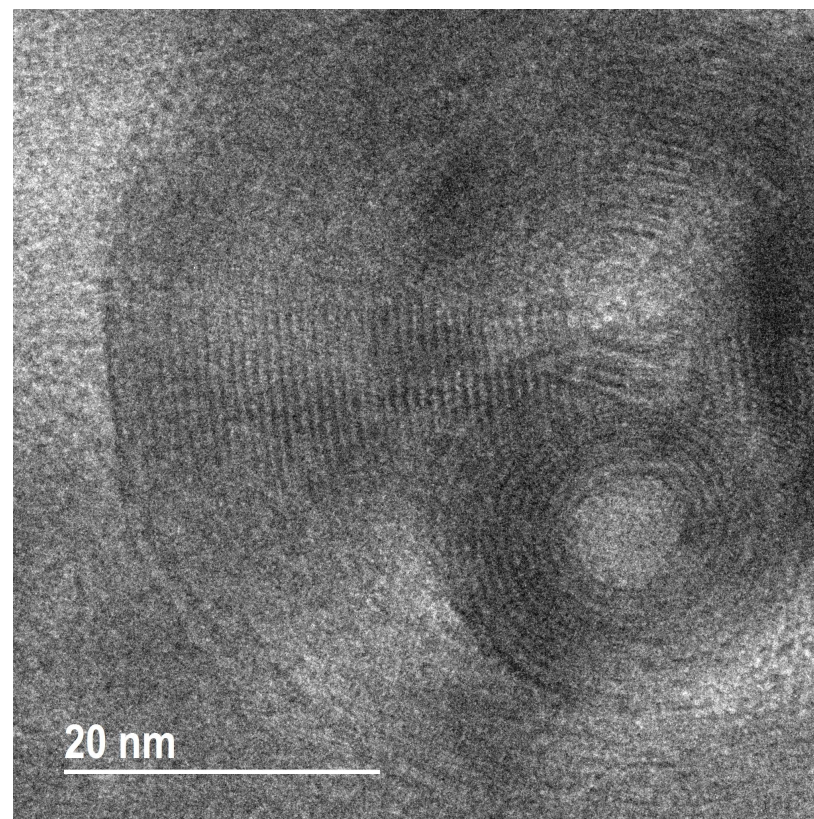
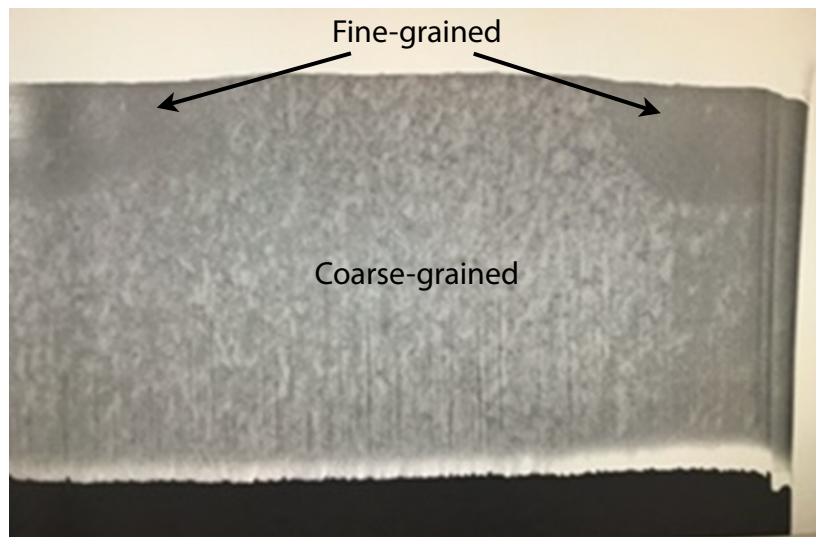
	Tremolite (Ahs 202)	Tremolite (WAR-0979)	Ti-pargasite (HS-177.4B)	Richterite (ASU-03)	Magnesio- hastingsite (HS-115.4B)
SiO ₂	57.50	56.76	41.63	54.72	44.97
TiO ₂	0.03	0.01	2.89	0.32	0.29
Al ₂ O ₃	0.32	0.16	13.58	2.00	11.17
Cr ₂ O ₃	0.05				
MnO	0.18	0.12	0.06	0.11	0.06
FeO	4.20	3.63	14.23	2.32	7.14
NiO	0.06				
MgO	22.50	21.98	11.36	22.55	17.28
CaO	12.50	12.86	11.59	9.21	12.33
Na ₂ O	0.80	0.39	1.76	4.15	2.24
K ₂ O	0.00	0.17	1.61	1.34	0.83
Total	98.16	96.08	98.71	96.72	96.31

Non-AhS 202 amphibole analyses are from *Christensen et al.* [2000].

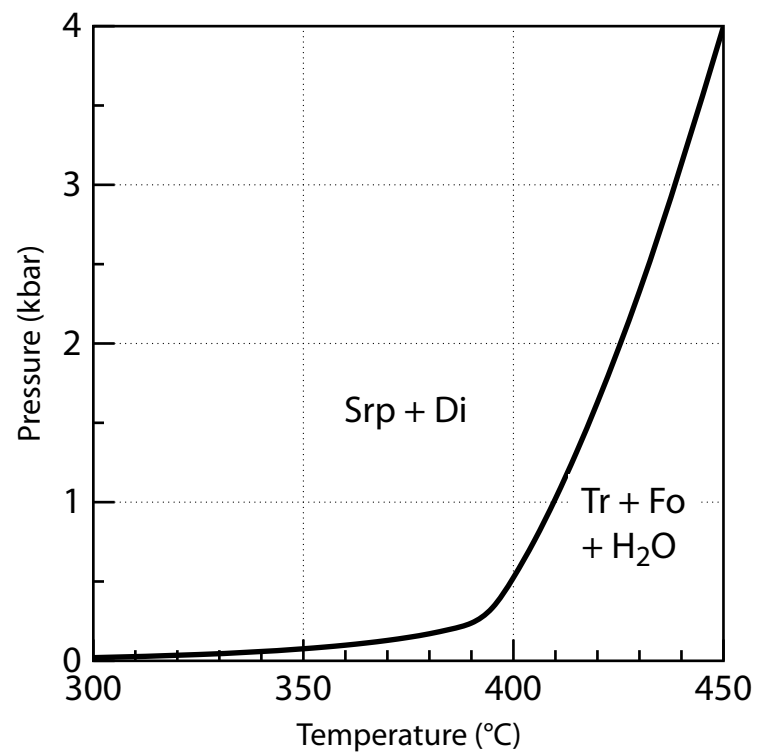
Supplementary Table 3. Amphibole formula assignments for the samples in Table S2 using the method of Locock (2014).

Formula Assignments	Tremolite (AhS 202)	Tremolite (WAR-0979)	Ti-pargasite (HS-177.4B)	Richterite (ASU-03)	Magnesio-hastingsite (HS-115.4B)
T					
Si	7.862	7.946	6.102	7.652	6.527
Al	0.051	0.026	1.898	0.330	1.473
Ti	0.003	0.001		0.019	
Fe ³⁺	0.083	0.026			
T Total	7.999	7.999	8.000	8.001	8.000
C					
Ti			0.319	0.015	0.032
Al			0.447		0.438
Cr	0.005				
Mn ³⁺					
Fe ³⁺	0.243	0.059	0.372	0.176	0.188
Ni	0.007				
Mn ²⁺	0.021	0.014	0.007	0.013	
Fe ²⁺	0.149	0.340	1.372	0.096	0.604
Mg	4.576	4.587	2.482	4.701	3.739
C Total	5.001	5.000	4.999	5.001	5.001
B					
Mn ²⁺					0.007
Fe ²⁺					0.075
Mg					
Ca	1.837	1.929	1.820	1.380	1.917
Na	0.163	0.071	0.180	0.620	
B Total	2.000	2.000	2.000	2.000	1.999
A					
Ca					
Na	0.049	0.035	0.320	0.505	0.630
K		0.030	0.301	0.239	0.154
A subtotal	0.049	0.065	0.621	0.744	0.784
O (non-W)	22.000	22.000	22.000	22.000	22.000
W					
OH	2.000	2.000	2.000	2.000	2.000
F					
Cl					
O					
W Total	2.000	2.000	2.000	2.000	2.000

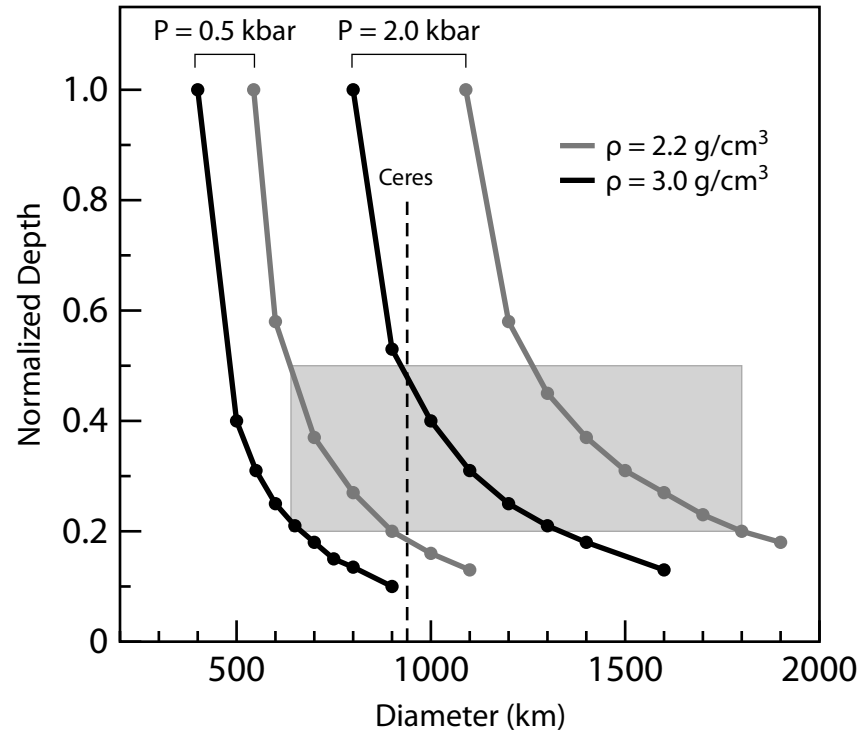
*All Fe calculated as Fe²⁺ in EMP analyses.



Supplementary Figure 1. (Left) Focused ion beam (FIB) slice from matrix serpentine in AhS 202 showing fine- and coarse-grained textures. FIB section is $\sim 15 \mu\text{m}$ across. (Right) TEM image from coarse-grained region of FIB slice showing chrysotile structure with $\sim 0.74 \text{ nm}$ lattice fringes.



Supplementary Figure 2. Modeled pressure-temperature relations for the reaction serpentine + diopside = tremolite + olivine + H₂O (see Methods) for the mineral compositions in AhS 202. Formation of tremolite is hindered by sluggish kinetics at temperatures below ~400-425° C, implying minimum pressures of 0.5-2.0 kbar.



Supplementary Figure 3. Calculated parent body sizes as a function of material density for normalized depths to the target pressures shown (see Methods), where a normalized depth of 0.0 is at the surface and 1.0 is at the core. For the most reasonable depths (0.2 - 0.5) and material density (2.2 g/cm³), AHS 202 parent body diameters range from 640 - 1800 km, encompassing the diameter of Ceres (~940 km).