APPENDIX I: X-ray Computed Tomography

The XCT scan of the piece of NWA 11421 was performed on a Nikon XTH320, micro-focus, closed-cabinet style X-ray instrument fitted with a 225 kV rotating target to improve flux. This rotating target is capable of achieving a minimum spot size of 10 μm at the scan parameters here, per the manufacturer's specifications. The sample was placed on an OEM factory-supplied, low-density, black-plastic rod and secured into place using double-stick tape. The rod fits into an anodized aluminium holder and is secured with a setscrew. The holder fit which fits into the stage held in position via keyway, setscrew, and alignment pin.

The X-ray detector is a Perkin Elmer 1620 CCD array, of 400mm x 400mm area with 2000 x 2000 pixels (0.2mm pixel size). Using Nikon Inspect-X acquisition software, 3141 projections (radiographs) were recorded, which were optimized by the software to reduce data redundancy. A 1.0mm Cu filter was fitted between the source and the sample. Exposure was 0.353 frames/sec (2829 milliseconds) using 8 frames per projection frame averaging. The instrument acquisition software features "flux-normalization," which was used to prevent the detector from being saturated and to accommodate drift and any other changes that might result from particularly long scan times. The effective voxel size indicated by the acquisition software is 18.34 μm.

A "minimize-ring-artifacts" function was also employed which reduces or eliminate circular or arcuate artifacts in the images parallel and concentric to the center of rotation. This is accomplished by starting and stopping movement of the stage for each radiograph taken (as opposed to acquiring the images while the stage is slowly rotating) as well as shuttling the recorded images back and forth by a few pixels. Gain was set at 18 dB. No correction for beam hardening was applied. However, a proprietary enhancement filter was applied with the setting listed as "moderate" during reconstruction tomogram.

Appendix II: Thermobarometry

Cation fractions for minerals used to obtain *P-T* estimates for the D1 dunite were calculated based on 6 oxygens for pyroxenes, 4 oxygens for olivine, and 8 oxygens for plagioclase. We use average compositions for olivine and plagioclase since they show little chemical variation, unlike the compositions for individual pyroxene pairs in proximity to each other (Table 1, Table 2, Supplemental Material). Trivalent iron, estimated by the method of Droop (1987), is not detectable in the clinopyroxene analyses, and is at very low levels (~ 0.01 apfu) in orthopyroxene. It was therefore not considered in further calculations. Temperatures (Table A3) were calculated with initial pressure estimates of 0.3 and 0.5 GPa for two-pyroxene thermometry from adjacent augite-orthopyroxene pairs using the equation of Brey and Köhler (1990):

$$T_{BK}(^{\circ}\mathrm{C}) = \frac{23664 + \left(24.9 + 126.3\, X_{Fe}^{Cpx}\right)(P * 10)}{13.38 + (lnK_D^*)^2 + 11.59\, X_{Fe}^{Opx}} - 273.15$$

With K_D^* = (1-Ca*)^{Cpx}/(1-Ca*)^{Opx}; Ca* =Ca^{M2}/(1-Na^{M2}) and Fe_{Fe}^{Px} = Fe/(Fe+Mg); P in GPa.

Further, we use a global regression equation with the calibration data base restricted to include only Mg-rich systems with Mg#^{cpx} >0.75, using Eqn. 37 of Putirka (2008):

$$T_{P(37)}(^{\circ}\mathrm{C}) = \frac{10^4}{13.4 - 3.4\ln\left(\frac{X_{EnFs}^{Cpx}}{X_{EnFs}^{Opx}}\right) + 5.59\ln\left(X_{Mg}^{Cpx}\right) - 8.8(Mg\#^{Cpx}) + 23.85\left(X_{Mn}^{Opx}\right) + 6.48\left(X_{FmAl_2SiO_6}^{Opx}\right) - 2.38\left(X_{Di}^{Cpx}\right) - 0.44P}$$

With $X_{EnFs}^{Cpx} = (X_{Fe}^{Cpx} + X_{Fe}^{Cpx} - X_{DiHed}^{Cpx})/2$ where $X_{DiHed}^{Cpx} = X_{Ca}^{Cpx} - \left(X_{Al(IV)}^{Cpx} - (X_{Al(VI)}^{Cpx} - X_{Jd}^{Cpx})\right) - \left(X_{Al(VI)}^{Cpx} - X_{Jd}^{Cpx}\right) - (\frac{X_{Cr}^{Cpx}}{2})$; $X_{Jd}^{Cpx} = X_{Al(VI)}^{Cpx}$ *or* X_{Na}^{Cpx}, *whichever is less*; Mg#^{Cpx} = $X_{Mg}^{Cpx}/(X_{Mg}^{Cpx} + X_{Fe}^{Cpx})$; $X_{Di}^{Cpx} = X_{DiHed}^{Cpx} * (X_{Mg}^{Cpx}/(X_{Mg}^{Cpx} + X_{Mn}^{Cpx} + X_{Fe}^{Cpx})$; $X_{FmAl_2SiO_6}^{Opx} = X_{Al(VI)}^{Opx} - X_{NaAlSi_2O_6}^{Opx} - X_{Cr}^{opx}$ where $X_{Al(VI)}^{Opx} = 2 - X_{Si}^{Opx}$; $X_{NaAlSi_2O_6}^{Opx} = X_{Al(VI)}^{Opx}$ *or* X_{Na}^{Opx}, *whichever is less*; $X_{EnFS}^{opx} = ((X_{Fe}^{Opx} + X_{Mn}^{Opx} + X_{Mg}^{Opx}) - X_{FmAl_2SiO_6}^{Opx} - X_{Ti}^{Opx} - X_{Ca}^{Opx})$; P in GPa.

A third temperature estimate was obtained using a modified version of the clinopyroxene-only thermometer by Putirka (2008), their Eqn. 32d, based on activity models of Nimis and Taylor (2000):

$T_{P(32d)}(°C) =$

$$\frac{93100 + 7550P}{61.1 + 26.6(X_{Ti}^{Cpx})/4 + 10.9(X_{Fe}^{Cpx})/4 - 0.95(X_{Al}^{Cpx} + X_{Cr}^{Cpx} - X_{Na}^{Cpx} - X_{K}^{Cpx})/4 + 3.5[\ln(a_{En}^{Cpx})]^2} - 273.15$$

Here, pressure is in GPA, X_{Al}^{Cpx} is the total Al on octahedral and tetrahedral sites, and the activity of enstatite in clinopyroxene is calculated as:

$$a_{En}^{Cpx} = (1 - X_{Ca}^{Cpx} - X_{Na}^{Cpx} - X_{K}^{Cpx})\left(1 - 0.5(X_{Al}^{Cpx} + X_{Cr}^{Cpx} + X_{Na}^{Cpx} + X_{K}^{Cpx})\right).$$

The resulting minimum and maximum temperatures were then used as input (T_0) to calculate pressures using THERMOCALC's av*P* algorithm (Powell and Holland, 1994, 2008), selecting the temperature that produced the av*P* result with the minimum value of σ_{fit}. We calculate the compositional variables for the activity-composition (*a*-*x*) models as described by Ziberna et al. (2017), using average compositions for olivine and plagioclase but individual augite grains (Table A4). Standard deviations were estimated to be 2% of the composition variable, mainly deriving from analytical uncertainties of the EMPA analyses. Compositional variables <0.001 were set to 0.001. We used THERMOCALC (version tc347) with the dataset version 6.3 and *a*-*x* model files ("tc-ax-SCOlP.txt") from (Ziberna et al., 2017) with the mineral assemblage of clinopyroxene, olivine, and plagioclase and the following set of independent reactions:

cenh + cats = fo + an;

cfs + cats = fa + an; and

cenh + jd = fo +abh.

Abbreviations here are: cenh, clino-enstatite (high), $Mg_2Si_2O_6$; cats, Ca-Tschermak's pyroxene, $CaAl_2SiO_6$; fo, forsterite, Mg_2SiO_4; an, anorthite, $CaAl_2Si_2O_8$; cfs, clino-ferrosilite, $Fe_2Si_2O_6$; fa, fayalite, Fe_2SiO_4; jd, jadeite, $NaAlSi_2O_6$; and abh, albite (high), $NaAlSi_3O_8$.

Table A1: Clinopyroxene EMP analyses and calculated mineral formulae

wt%	Cpx6	OCP3-c1	OCP3-c2	OCP1-c2	OCP4-c1
SiO_2	52.78	52.59	53.07	52.00	52.25
TiO_2	0.86	1.06	0.91	0.98	1.21
Al_2O_3	1.55	1.91	1.47	2.82	2.33
Cr_2O_3	0.63	0.75	0.64	0.68	0.83
FeO^T	4.10	4.27	4.23	4.11	4.42
MnO	0.11	0.12	0.12	0.15	0.12
MgO	17.06	17.18	17.31	16.19	17.03
CaO	22.65	22.18	22.28	21.85	21.92
Na_2O	0.05	0.04	0.04	0.07	0.07
Sum	99.79	100.06	100.07	98.85	100.18
cations					
Si	1.936	1.923	1.939	1.921	1.910
Ti	0.024	0.029	0.025	0.027	0.033
Al	0.067	0.082	0.063	0.123	0.100
Cr	0.018	0.022	0.018	0.020	0.024
Fe	0.126	0.131	0.129	0.127	0.135
Mn	0.003	0.004	0.004	0.005	0.004
Mg	0.933	0.936	0.942	0.891	0.928
Ca	0.890	0.869	0.872	0.865	0.858
Na	0.003	0.003	0.003	0.005	0.005
Cat. total	4.000	3.998	3.997	3.983	3.997

Table A2: Orthopyroxene EMP analyses and calculated mineral formulae

wt%	Opx5	OCP3-O1	OCP3-O2	OCP1-O1	OCP3-c1
SiO_2	55.33	55.20	55.79	55.57	53.15
TiO_2	0.64	0.69	0.59	0.59	0.49
Al_2O_3	1.52	1.53	1.41	1.53	1.77
Cr_2O_3	0.62	0.64	0.63	0.67	0.61
FeO^T	9.99	10.18	10.18	10.00	11.25
MnO	0.19	0.21	0.21	0.20	0.21
MgO	30.84	30.52	30.97	30.97	31.69
CaO	1.51	1.57	1.54	1.54	1.51
Na_2O	0.00	0.01	0.00	0.00	0.02
Sum	100.64	100.55	101.32	101.07	100.70
cations					
Si	1.936	1.942	1.951	1.940	1.883
Ti	0.017	0.018	0.016	0.016	0.013
Al	0.063	0.063	0.058	0.063	0.074
Cr	0.017	0.018	0.018	0.018	0.017
Fe	0.293	0.292	0.298	0.292	0.333
Mn	0.006	0.006	0.006	0.006	0.006
Mg	1.612	1.601	1.605	1.612	1.674
Ca	0.057	0.059	0.044	0.058	0.057
Na	0.000	0.000	0.000	0.000	0.001
Cat. total	4.004	3.999	3.995	4.004	4.059

Results

Temperature estimates obtained from the three thermometers are within 20°C of each other for 0.55 GPa pressure, but with a slightly larger range for 0.3 GPa. Temperature calculated with the Brey and Köhler (1990) thermometer are less dependent on pressure than those calculated with the Cpx-only thermometer (Nimis and Taylor, 2000; Putirka, 2008). Three pyroxene pairs yield temperatures at 960-970°C, while one pair is significantly below that (~922-940°C), and one pair is higher (>993°C).

Table A3: Temperature calculated with two-pyroxene and cpx-only thermometers

Mineral pairs	P input (GPa)	T(BK)[1] (°C)	P37[2] (°C)	P32d[2] (°C)
Opx5/Cpx6	0.3	922	927	921
	0.5	926	934	940
OCP3-O1/OCP3-c1	0.3	970	968	961
	0.5	975	977	981
OCP3-O2/OCP3-c2	0.3	958	951	958
	0.5	962	959	978
OCP1-01/OCP1-c2	0.3	975	951	961
	0.5	980	959	980
OCP4-O2/OCP4-c1	0.3	978	965	973
	0.5	982	974	993

[1] Brey and Köhler (1990). [2] Putirka (2008)

Results from average pressure calculations are shown in Table A5 here and Figure 6 of the main text, using compositional variables for individual clinopyroxene measurements and average olivine and plagioclase (Table A4). Estimates for average pressures were calculated for the temperature range obtained by thermometers (Table A3), while selecting the temperature pressure pair with the lowest value of σ_{fit}, which is the highest temperature and lowest pressure pair for all clinopyroxene compositions. A standard deviation of 20°C was assumed for all temperatures while the standard deviation for pressure is calculated by THERMOCALC. Temperatures vary between 940 and 990°C with the majority at 980°C. Pressures estimates vary between 0.27 and 0.51 GPa.

Table A4: Compositional variables for calculated for av*P* calculations as described in Ziberna et al. (2017) for individual clinopyroxene measurements, and average olivine and plagioclase compositions

	x	y	f	z	j	Q	ca	k
Cpx6	0.119	0.064	0.001	0.890	0.003	0.05		
OCP3-c1	0.122	0.077	0.001	0.869	0.003	0.05		
OCP3-c2	0.121	0.061	0.001	0.872	0.003	0.05		
OCP1-c2	0.125	0.079	0.001	0.865	0.005	0.05		
OCP4-c1	0.127	0.090	0.001	0.858	0.005	0.05		
Ol	0.167					0.05		
Pl							0.965	0.001

Table A5: Average P-T (*avP*) calculated value for the D1 dunite (Powell and Holland, 1994, 2008).

	T (°C)	s.d.	P (GPa)	s.d.
Cpx6	940	20	0.35	0.10
OCP3-c1	980	20	0.41	0.09
OCP3-c2	980	20	0.27	0.09
OCP1-c2	980	20	0.45	0.08
OCP4-c1	990	20	0.51	0.08
Average	974	40 (2σ)	0.40	1.9 (2σ)

To test the robustness of our approach, we also calculate pressures for lunar troctolite 76535, which contains symplectites with a comparable mineral assemblage to the dunite of this study. Thermobarometric calculations for the troctolite have yielded temperatures of 800-900°C at pressures of 0.2-025 GPa (McCallum and Schwartz, 2001) and 880±22°C using two-pyroxene thermometry and a pressure of 0.2 GPa from Elardo et al. (2012). We use the THERMOCALC av*P* algorithm to calculate pressures for assemblage 1, 3, and 4 (Table 1 of McCallum and Schwartz (2001)) at 880°C, resulting in an average pressure of 0.21±0.2 GPa (2σ). Assemblage 2 is not included in av*P* calculations due to its high σ_{fit} values.

Appendix III: Spinel Cataclasites & Peridotites

The lunar sample collections include many fragments of spinel-bearing peridotites, many of which are calculated to have formed at significant depth in the Moon, e.g. (Anderson, 1973) (Baker and Herzberg, 1980) (Nazarov et al., 2011) (Wittmann et al., 2019). The chemical compositions of these samples, being strongly aluminous, are unlikely to be mantle material in current models of lunar mantle evolution (Wieczorek et al., 2006; Gross and Joy, 2016). It seems more likely that they represent hybrids of ultramafic rock (including mantle dunite) and crustal anorthosite (Prissel et al., 2014) (Prissel et al., 2016) (Treiman et al., 2019). Most of the calculated equilibration pressures for spinel-bearing peridotites are near 0.2 GPa (Wittmann et al., 2019) (Nazarov et al., 2011), near the nominal crust-mantle boundary (Wieczorek et al., 2013). The precision and accuracy of these pressure estimates is not clear. One spinel-bearing fragment is reported to have an equilibration pressure greater than 0.5 GPa (Wittmann et al., 2019). However, the mineral assemblage in that clast, spinel + augite + low-Ca-pyroxene, lacks olivine and so has limited significance for calculating pressure (Herzberg and Baker, 1980) (McCallum and Schwartz, 2001) (Nazarov et al., 2011).