NWA 8614: The Least Heated Winonaite?

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Introduction: Northwest Africa 8614 is classified as a winonaite on the basis of oxygen isotope ratios, mineralogy, and highly reduced chemistry [1]. Unlike other winonaites, it contains numerous and readily apparent chondrules, with over a dozen chondrules apparent in two small thin sections. Figure 1 below helps to illustrate the abundance of the chondrules in NWA 8614, which are circled in white. The large number of chondrules sets apart this meteorite from other winonaites. One other winonaite, NWA 1463, is reported to have multiple relict chondrules [2, 3]. Here we discuss various features of NWA 8614.

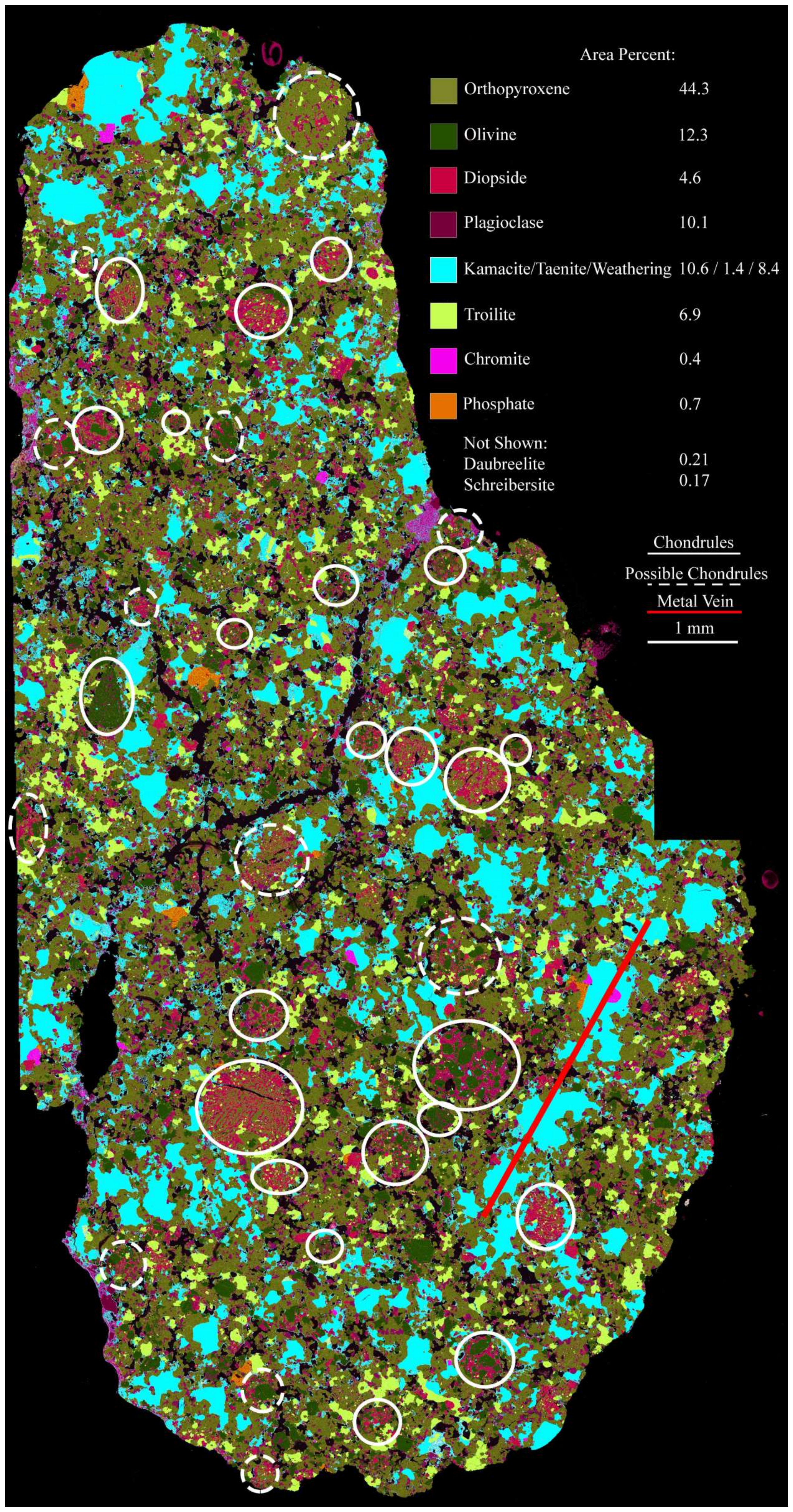


Figure 1 (above): False-color EDS map of NWA 8614, used to determine the mode. The area percent per mineral are located to the right of the legend. Chondrules can be seen in solid white circles. Possible chondrules or chondrules that are well integrated are circled in a dashed white line. A possible disconnected metal vein is shown in the lower right with a red line running through it.

Mineralogy and Texture:

- Primarily granoblastic (Fig. 1, 2)
- Barred and microporphyritic chondrule textures (Fig. 1, 2)
- Chondrules rich in olivine or low-Ca pyroxene, diopside enriched in chondrules compared to host (Fig 2)
- Chondrule diameters 0.42 ± 0.21 mm (N = 23) for better-defined chondrules, and 0.41 ± 0.20 mm (N = 35) including all possible chondrules
- NWA 8614 is pyroxene and metal rich (Fig. 1) with presence of daubreelite and schreibersite [4, 5]
- Collection of metal grains that form vein-like structure (Fig. 1), similar structures in other winonaites [4, 5]

Mineral Chemistry: Mineral chemistry is summarized in Table 1. Features:

- Mineral compositions overlap winonaites at the ferroan end (Fig. 3). Ferroan composition of NWA 8614 similar to NWA 4937 (Fig. 3), but not paired due to differing modal abundances [1]
- NWA 1463 contains chondrules [2, 3], not paired due to differing mineral chemistries (Fig. 3)
- Olivine and pyroxene compositions are highly uniform, suggests approach to equilibrium
- Two pyroxene and olivine-spinel geothermometry (Table 2) suggests that ferromagnesian phases largely equilibrated at ~820-860 °C, which are similar to but slightly lower than other winonaites
- Despite highly uniform compositions, olivine is too magnesian for equilibrium relative to low-Ca pyroxene (Fig. 3)
- Oxygen isotope ratios plot with winonaites and extend the field to the left (Fig. 4)

Olivine	Low-Ca pyroxene		Diopside		Plagioclase	
Fa	Fs	Wo	Fs	Wo	Ab	Or
6.5 ± 0.5	7.8 ± 0.3	1.4 ±0.2	3.5 ± 0.5	45.5 ± 0.3	79.9 ± 2.0	6.4 ± 1.2

Table 1: Mineral chemistry for major phases in NWA 8614.

	Temperature (°C)	Number analyses
NWA 8614 OPX	857 ± 26	12
NWA 8614 CPX	818 ± 20	14
Literature Data OPX	930 ± 52	16
Literature Data CPX	867 ± 89	12
NWA 8614 Olivine-Spinel	858	10 (Ol)/6 (Sp)

Table 2: The two-pyroxene thermometer [6] and the olivine-spinel thermometer [7] were used to calculate closure temperatures.

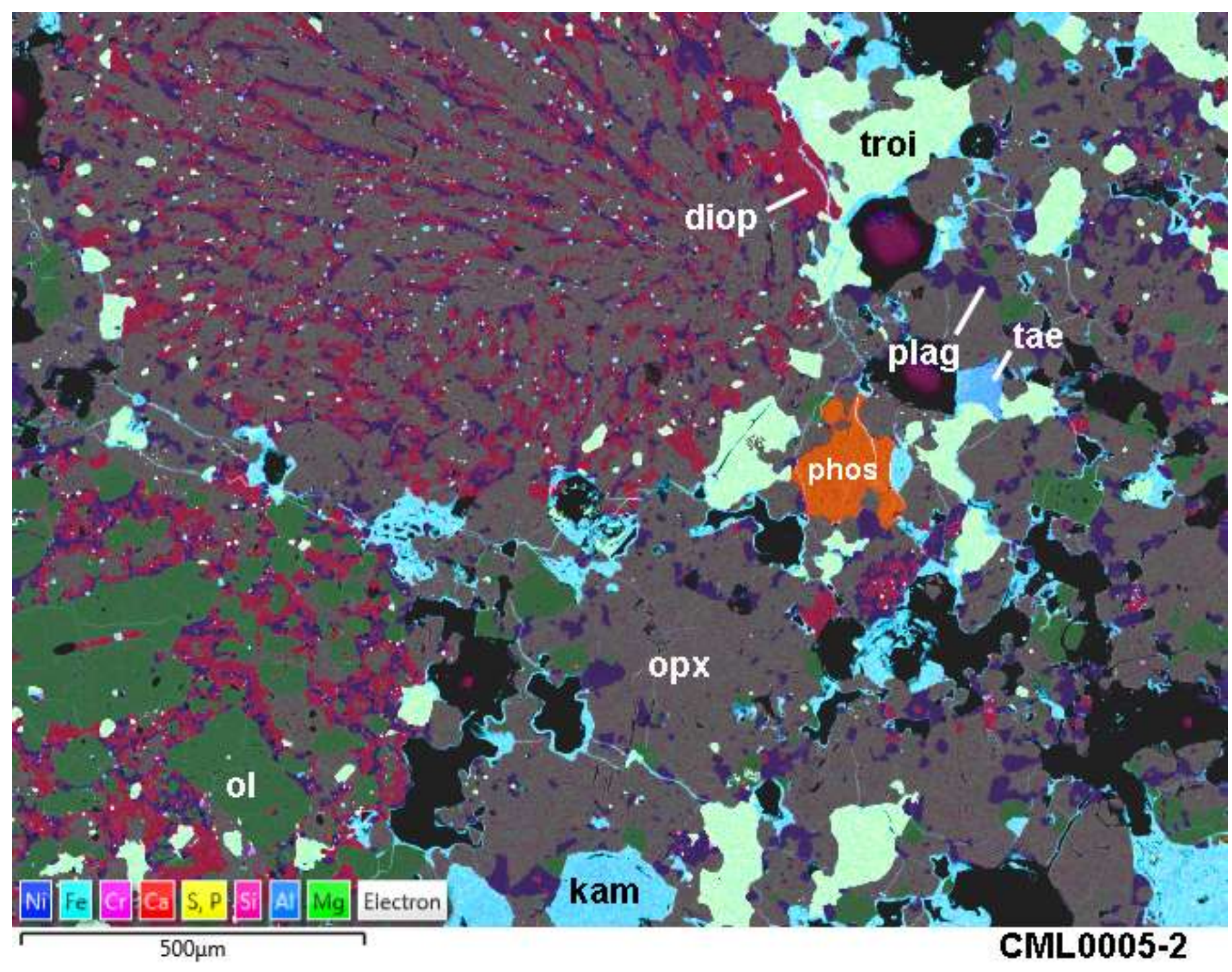


Figure 2 (right): False-color EDS map of NWA 8614 showing two chondrules (left side). Phases include olivine (ol, green), orthopyroxene (opx, brown), diopside (diop, purple red), plagioclase (plag, purple), kamacite or weathered low-Ni metal (kam, light blue), taenite (tae, dark blue), troilite (troi, light yellow), phosphate (phos, orange), and chromite (pink, too small to see clearly here). Dark areas with or without purple centers are pits produced by mineral plucking. Scale bar at lower left is 0.5 mm.

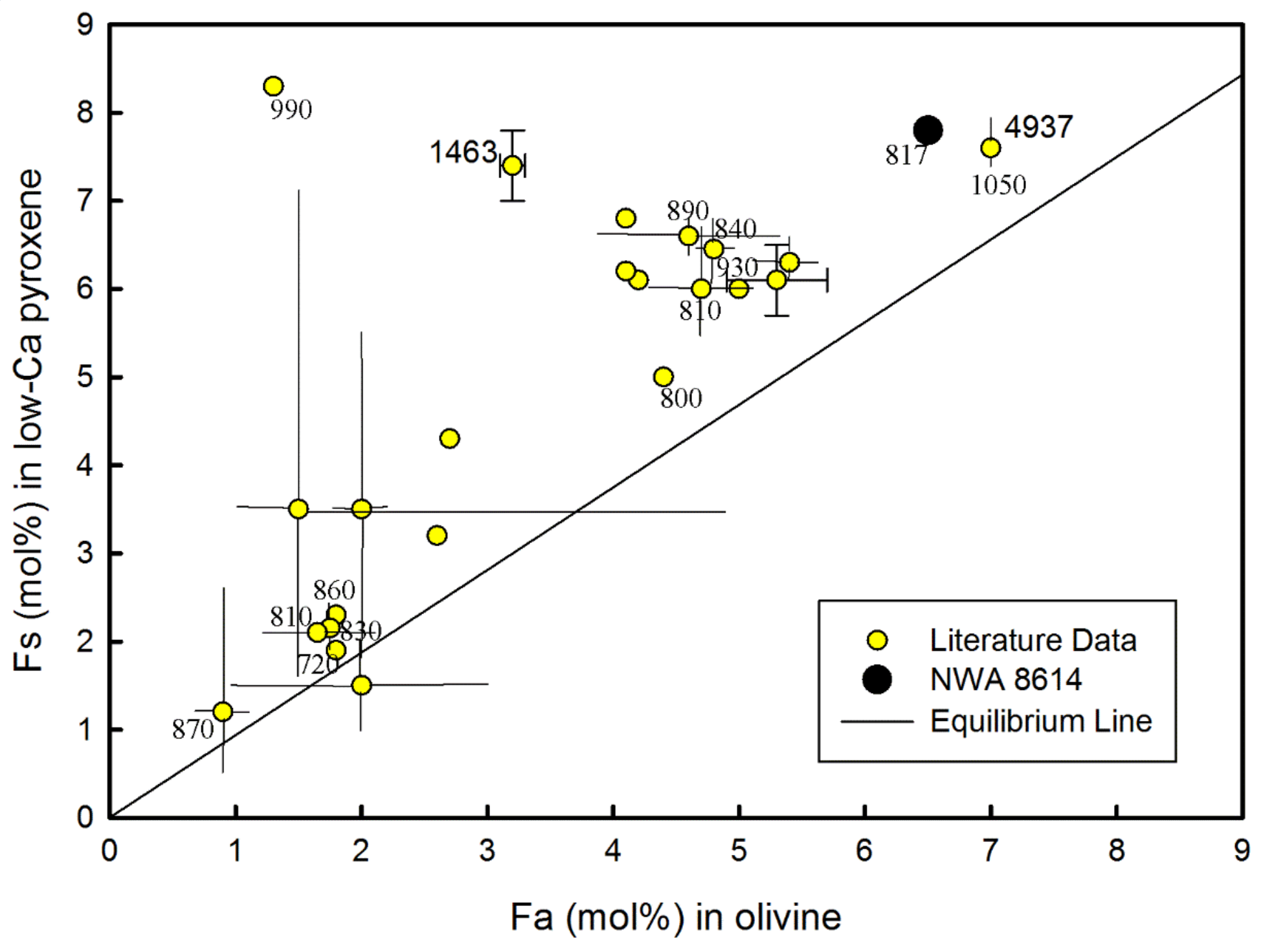
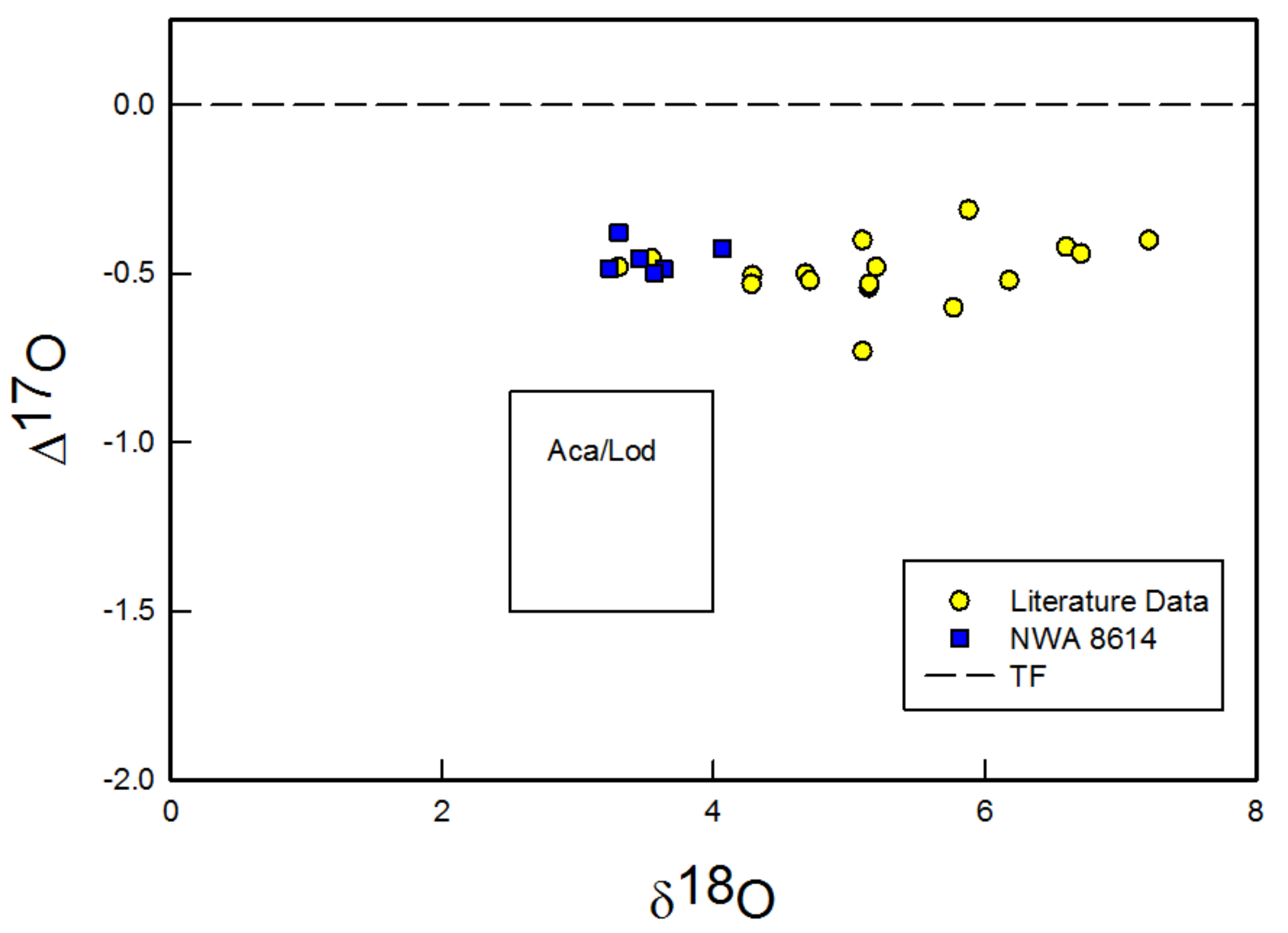


Figure 3 (left): Olivine and pyroxene compositions in NWA 8614 compared to various winonaites. Error bars for NWA 8614 are roughly the size of the symbol. For literature data, ranges are represented as lines, error bars are represented as thicker bars. Clinopyroxene temperatures (in °C) are shown in small font. NWA 4937 and 1463 are labeled. The equilibrium line shows Fe-Mg equilibrium between olivine and pyroxene at 1127 °C [8].

Figure 4 (right): $\delta^{18}O$ (‰) vs $\Delta^{17}O$ (‰) values for NWA 8614 compared to literature data for winonaites [1, 5, 9-12]. NWA 8614 extends the winonaite line to the left. Acapulcoite/Lodranite shown for comparison [13].



Discussion and conclusions: Owing to the abundance of chondrules, NWA 8641 may be one of the least heated winonaites, and therefore may provide clues to the chondritic protolith of the winonaite parent body.

- Overall textures are similar to those found in type 6 chondrites that escaped significant melting.
- Despite similar geothermometer temperatures for various mineral pairs, NWA 8614 apparently did not attain Fe-Mg equilibrium between olivine and pyroxene.
- Like other winonaites, NWA 8614 has olivine compositions that are too magnesian for equilibrium relative to low-Ca pyroxene (Fig. 3). This discrepancy could be caused by preferential FeO-reduction of olivine [5].
- Although NWA 8614 lies closer to olivine-pyroxene Fe-Mg equilibrium than some winonaites, other winonaites with different Fe/Mg plot similarly close to the equilibrium line (Fig. 3).
- Among winonaites as a whole, there is no evidence for a curved trend between Fa and Fs compositions as would be expected for FeO-reduction during metamorphism [5], nor for mineral compositions that correlate with geothermometry temperatures (Fig. 3).
- This argues against a single metamorphic FeO-reduction trend from a common chondritic precursor. Instead, protoliths for different winonaites may have varied slightly in composition.

References: [1] Meteoritical Bulletin Database, accessed 2014. [2] Floss C. et al. (2008) *Meteoritics & Planet. Sci.*, *43*, 657-674. [3] Benedix G. K. (2003) *Meteoritics & Planet. Sci., 38*, A70. [4] Hutchison, R. (2004) Meteorites—A petrologic, chemical and isotopic synthesis, 506 pp. [5] Benedix, G.K. et al. (1998) GCA, 62, 2535-2553. [6] Lindsley, D.H (1983) Am. Mineral., 68, 477-493. [7] Wlotzka, F. (2005) Meteoritics & Planet. Sci., 40, 1673-1702. [8] Beattie, P. (1993) Contrib. Mineral. Petrol., 115, 103-111. [9] Greenwood, R.C. et al. (2012) GCA, 94, 146-163. [10] Clayton, R. N. and Mayeda, K. (1996) GCA, 60, 1999-2017. [11] Kimura, M. et al. (1992) Antarctic Met. Res., 5, 165-190. [12] Yugami, K. et al (1998) Antarctic Met. Res., 11, 49-70. [13] Franchi, I. (2008) Reviews in Mineral. & Geochem., 68, 345-397. **Acknowledgment:** The writers thank supporters of the Cascadia Meteorite Laboratory whose donations partly enabled this research.