

## EQUILIBRATION OF LOW-CA PYROXENE IN PETROLOGIC TYPE 3 CK CHONDRITES

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**Introduction:** The CK chondrites are the only carbonaceous chondrite group to exhibit the full range of thermal metamorphism (from petrologic type 3 to type 6) [1]. However, petrologic type 3 CK chondrites (which represent 12% of all CKs) are relatively equilibrated, with most being metamorphosed to petrologic subtype  $\geq 3.8$  [2-4]. At present, NWA 5343 is recognized as the least equilibrated CK3 chondrite (petrologic subtype 3.7) [5]. In previous work, we analyzed matrix and chondrule olivine in several unequilibrated CK chondrites in an effort to establish geochemical criteria for assigning petrologic subtypes to the CK3 chondrites [6]. Though olivine compositions are the most useful indicator of metamorphism in chondrites [7-9], pyroxene also becomes more equilibrated and Fe-rich during metamorphism [9-12]. In this study, we survey pyroxene in CK chondrites to assess whether petrologic subtypes based on pyroxene compositions are consistent with those based on olivine.

**Methodology:** We analyzed matrix and chondrule pyroxene in seven unequilibrated and one equilibrated (type 4) CK chondrites: Dar al Gani (DaG) 431, Northwest Africa (NWA) 1559, NWA 4423, NWA 4425, NWA 4964, NWA 5343, NWA 5956, and NWA 4422 (CK4). Pyroxene compositions were determined using a JEOL JXA 8200 electron microprobe at Washington University in St. Louis. Operating conditions include 15 kV potential, 25 nA beam current, and 2  $\mu$ m beam size. Fourteen to twenty-one pyroxenes were analyzed in the matrix and chondrules of each sample.

**Pyroxene Compositions:** Both high-Ca (augite and diopside) and low-Ca pyroxenes (enstatite and pigeonite) are present in the CK3 chondrites. Chondrules consist mostly of augite ( $\text{Wo}_{32-44}\text{En}_{54-66}$ ), though diopside ( $\text{Wo}_{45-51}\text{En}_{35-49}$ ), enstatite ( $\text{Wo}_{0.4-6}\text{En}_{72-97}$ ) are also present. Pigeonite ( $\text{Wo}_{10-17}\text{En}_{61-88}$ ) is also present in a few chondrules at very minor abundances. The matrix consists mostly of diopside ( $\text{Wo}_{46-51}\text{En}_{33-52}$ ), with minor augite ( $\text{Wo}_{35-38}\text{En}_{48-62}$ ) and enstatite ( $\text{Wo}_{0.6-3}\text{En}_{67-97}$ ). There is no significant difference between compositions of low- and high-Ca pyroxene in the chondrules and the matrices of the analyzed samples.

**Equilibration of Low-Ca Pyroxene:** As expected, low-Ca pyroxene in CK4 chondrite NWA 4422 is equilibrated in both the matrix ( $\text{Fs}_{26.3\pm0.5}$ ) and the chondrules ( $\text{Fs}_{25.6\pm0.9}$ ). Low-Ca pyroxene in NWA 4425 is also FeO-rich and homogenous (chondrules =  $\text{Fs}_{23.5\pm1.8}$ ; matrix =  $\text{Fs}_{27.6\pm2.4}$ ), indicating that it is nearly equilibrated (subtype 3.9). The remaining samples can be divided into two groups based on compositions and heterogeneity of low-Ca pyroxene in chondrules. In NWA 5343, 5956, and 1559 (group 1), low-Ca pyroxene is FeO-poor and homogenous. The average compositions of low-Ca pyroxene range from  $\text{Fs}_{1.7\pm0.5}$  in NWA 1559 to  $\text{Fs}_{3.9\pm0.3}$  in NWA 5343. Low-Ca pyroxene in NWA 4423, NWA 4964, and DaG 431 (group 2) is heterogeneous, with compositions ranging from  $\text{Fs}_{0.9}$  to  $\text{Fs}_{26.3}$ . The average compositions of low-Ca pyroxene range from  $\text{Fs}_{7.4\pm1.0}$  in DaG 431 to  $\text{Fs}_{11.4\pm1.3}$  in NWA 4423. Though low-Ca pyroxene in group 2 is more FeO-rich than in group 1, low-Ca pyroxene in group 2 has not yet reached equilibrated compositions. Overall, low-Ca pyroxene compositions indicate that the degree of metamorphism increases from group 1 to group 2, corresponding roughly to petrologic subtype 3.8 and subtype 3.9, respectively.

**Comparison with Olivine:** In previous work, we used percent mean deviation (PMD) and mean Fa content of chondrule olivine to establish geochemical criteria for delineating petrologic subtypes 3.7–3.9 in the CK3 chondrites [7]. Based on these criteria, we proposed that NWA 4423 and 1559 were subtype 3.8, and NWA 4425, NWA 5956, and DaG 431 were subtype 3.9. Because olivine was significantly less equilibrated in NWA 5343, we suggested that it was petrologic subtype 3.7. Petrologic subtypes based on low-Ca pyroxene compositions are consistent with those based on olivine in NWA 1559, NWA 4425 and DaG 431. However, the petrologic subtypes of NWA 5956 and 4423 are inconsistent (i.e., the subtype is 3.8 based on olivine and 3.9 based on pyroxene, or vice versa), and low-Ca pyroxene in NWA 5343 is not less equilibrated than the other group 1 samples.

The inconsistencies between the petrologic subtypes of some samples are not unsurprising, as the extent of metamorphism can be difficult to discern in samples that are nearly equilibrated. However, low-Ca pyroxene compositions confirm that the CK3 chondrites are highly equilibrated. A larger survey of samples is necessary to sufficiently establish criteria for petrologic subtypes in the CK3 chondrites.

**References:** [1] Kallemeyn G.W. et al. 1991. *Geochimica et Cosmochimica Acta*, 55:881-892. [2] Greenwood R.C. et al. 2010. *Geochimica et Cosmochimica Acta* 74:1684-1705. [3] Chaumard N. et al. 2014. *Meteoritics and Planetary Science* 49:419-452 [4] Rubin A.E. 2013. *Meteoritics and Planetary Science* 48:432-444. [5] Dunn T.L. et al. 2018. *Meteoritics and Planetary Science*, 53:2165-2180. [6] Dunn T.L. and Gross J. 2017. *Meteoritics and Planetary Science* 51; abstract #6429 [7] Huss G.R. et al. 1978. *Meteoritics* 13:495 [8] Huss G.R. et al. 1981. *Geochimica et Cosmochimica Acta* 45:33-51. [9] Dodd R.T. 1969. *Geochimica et Cosmochimica Acta*, 33:161-203. [10] Dodd R.T. and Van Schmus W.R. 1967. *Geochimica et Cosmochimica Acta*, 31:921-951. [11] Scott E.R.D. and Jones R.H. 1990. *Geochimica et Cosmochimica Acta*, 54:2485-2502. [12] McSween H.Y. 1977. *Geochimica et Cosmochimica Acta*, 41:477-491.