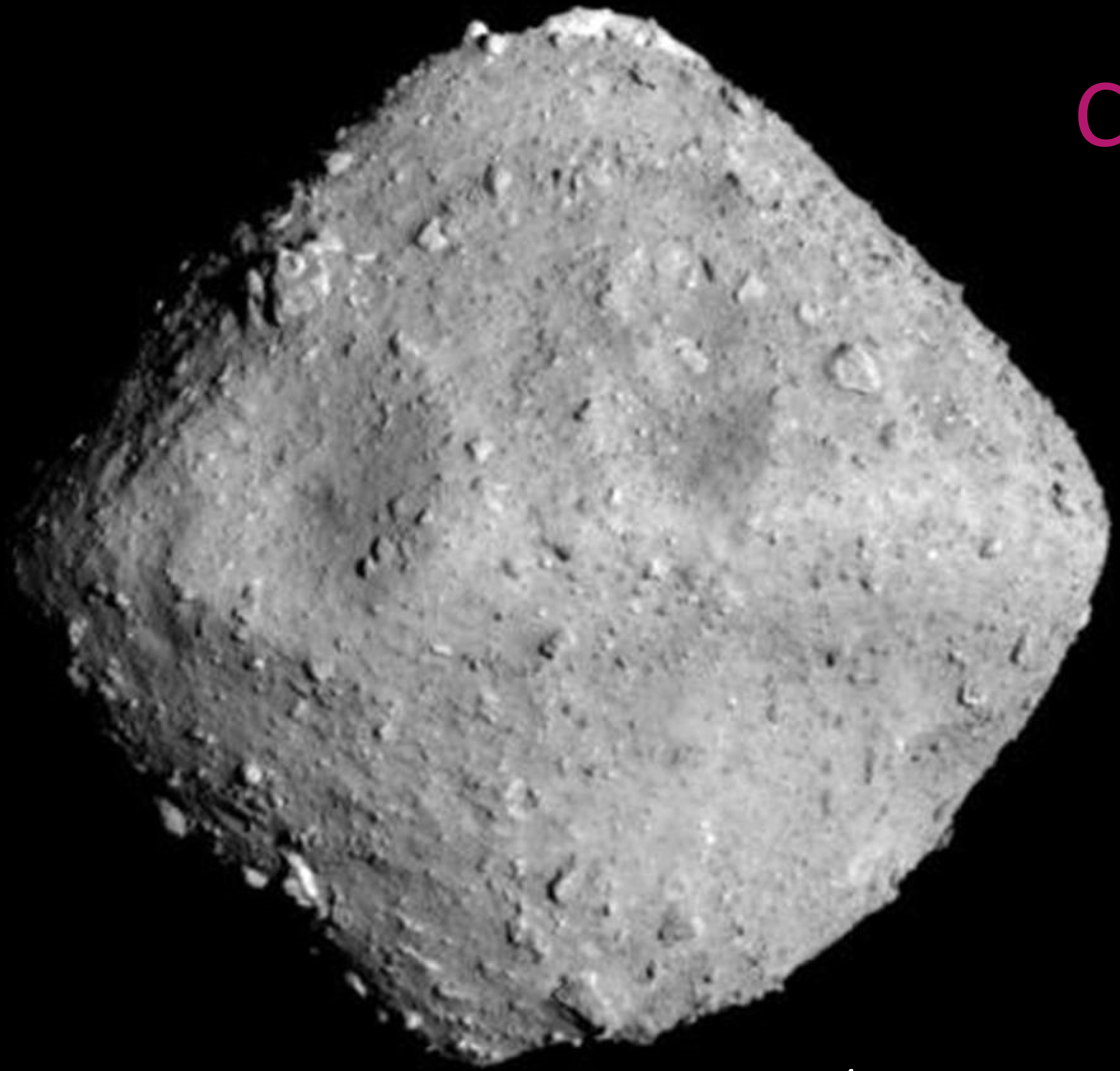

Cr-rich Oxide Grains with ^{16}O-rich Compositions in Ryugu Samples

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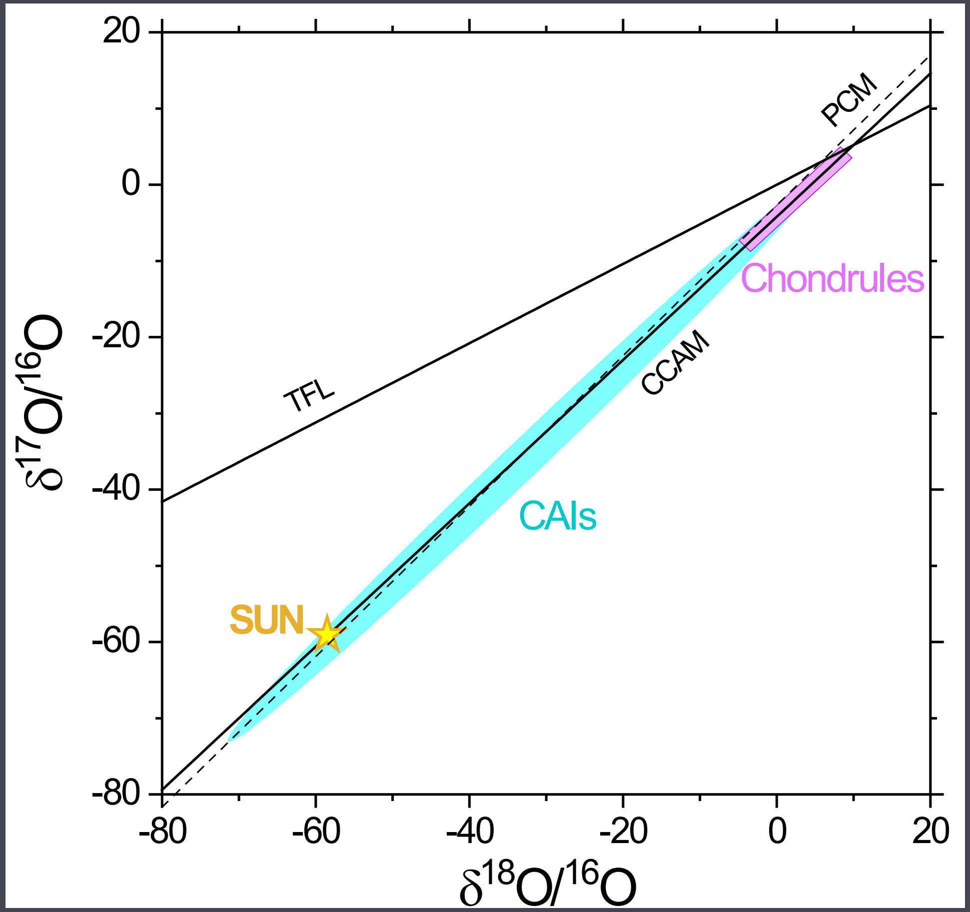
Introduction

- Refractory grains and inclusions that condensed in the inner solar nebula are common in most primitive meteorites
- In highly altered Ryugu samples, anhydrous primary minerals and intact inclusions are rare
  - Anhydrous minerals mainly exist in less-altered clasts
- Previously analyzed O isotopic compositions of < 2 μm-sized Mg-rich silicates in an exogenous clast in a Ryugu sample (Nguyen et al. 2022)

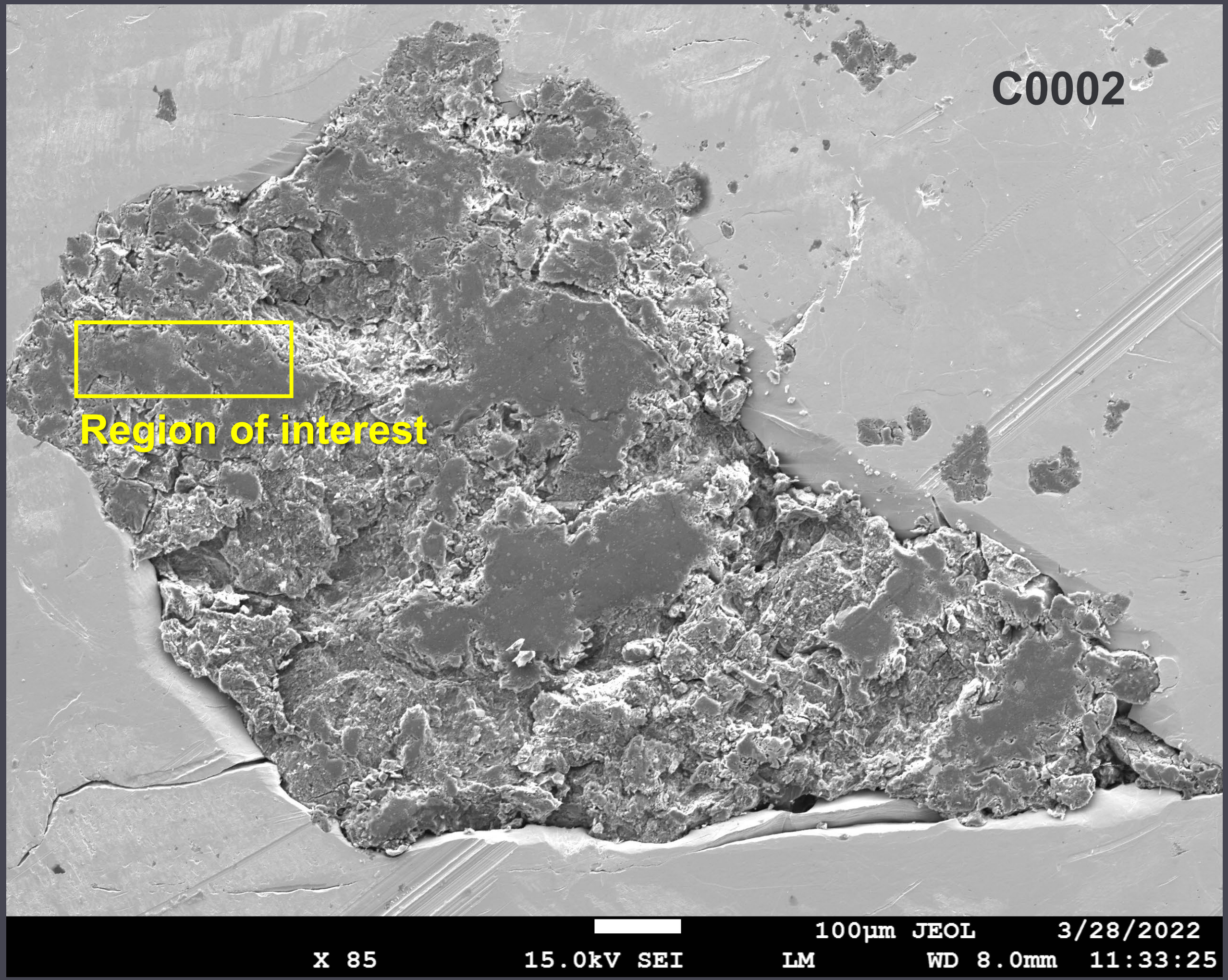
➢ O isotopic (NanoSIMS) and mineralogical (TEM) study of anhydrous oxides in Ryugu matrix



PCM: Primitive Chondrule Minerals line (Ushikubo et al. 2012)
CCAM: Carbonaceous Chondrite Anhydrous Mineral line (Clayton et al. 1977)

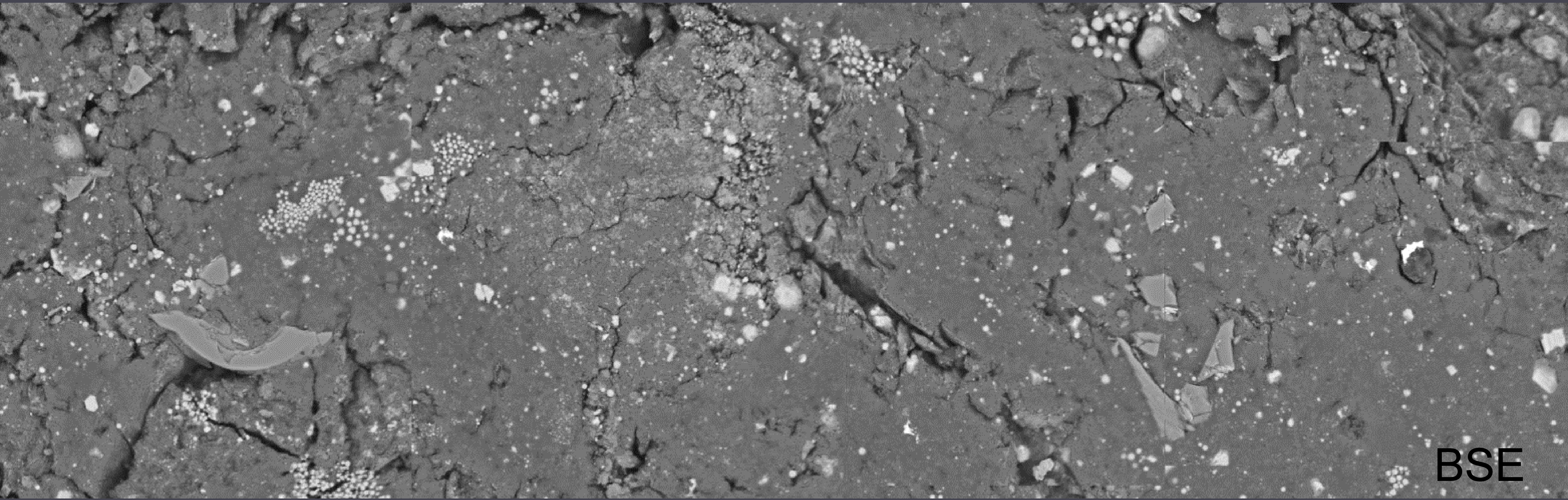
SEM – NanoSIMS – TEM Analyses

- Fragments of Ryugu grains C0002 and A0040 pressed into In along with isotopic standards (e.g., San Carlos olivine, Madagascar hibonite)
- Acquired SE, BSE images and EDX elemental maps
- NanoSIMS isotopic imaging
  - C and O isotopes, ^{28}Si, and $^{24}Mg^{16}O/^{16}O$ or $^{27}Al^{16}O/^{16}O$
- FIB-TEM of some grains of interest for mineralogical analysis



Chemical Analysis

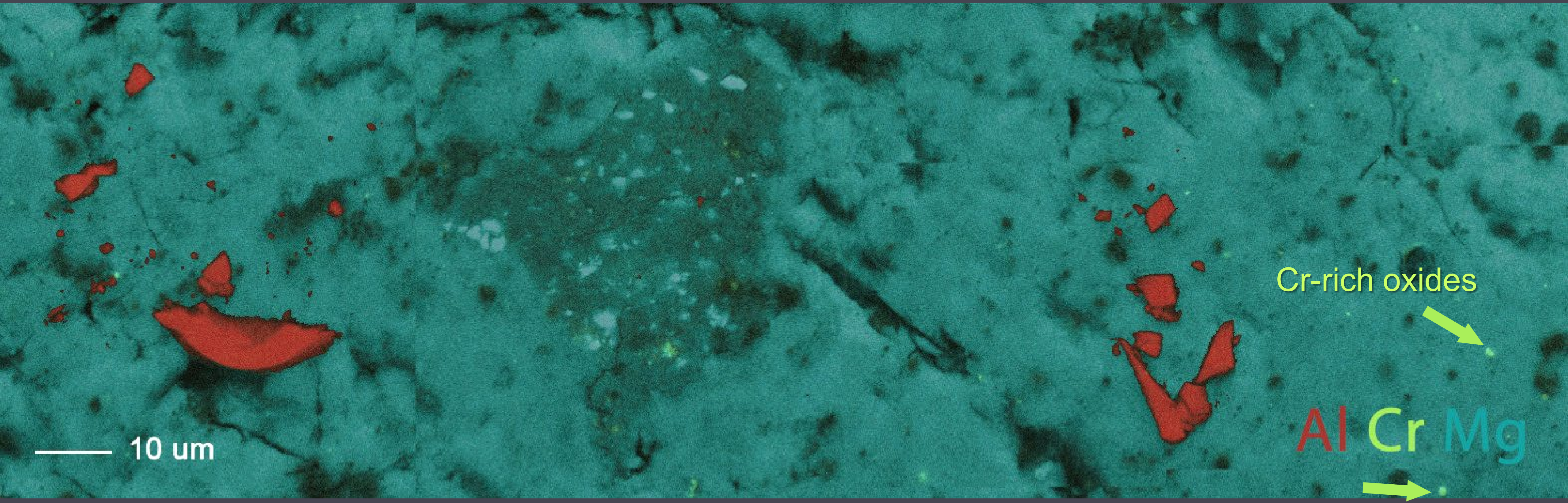
Fragment of grain C0002



- Phyllosilicates
- Magnetite (framboids, plaquettes, spherules)
- Carbonates
- Sulfides
- Carbonaceous veins, nodules, globules
- Oxides
- Clasts (Nguyen et al. Sci. Adv. 2023)
- Anhydrous silicates (Nguyen et al. MetSoc 2022)

Chemical Analysis

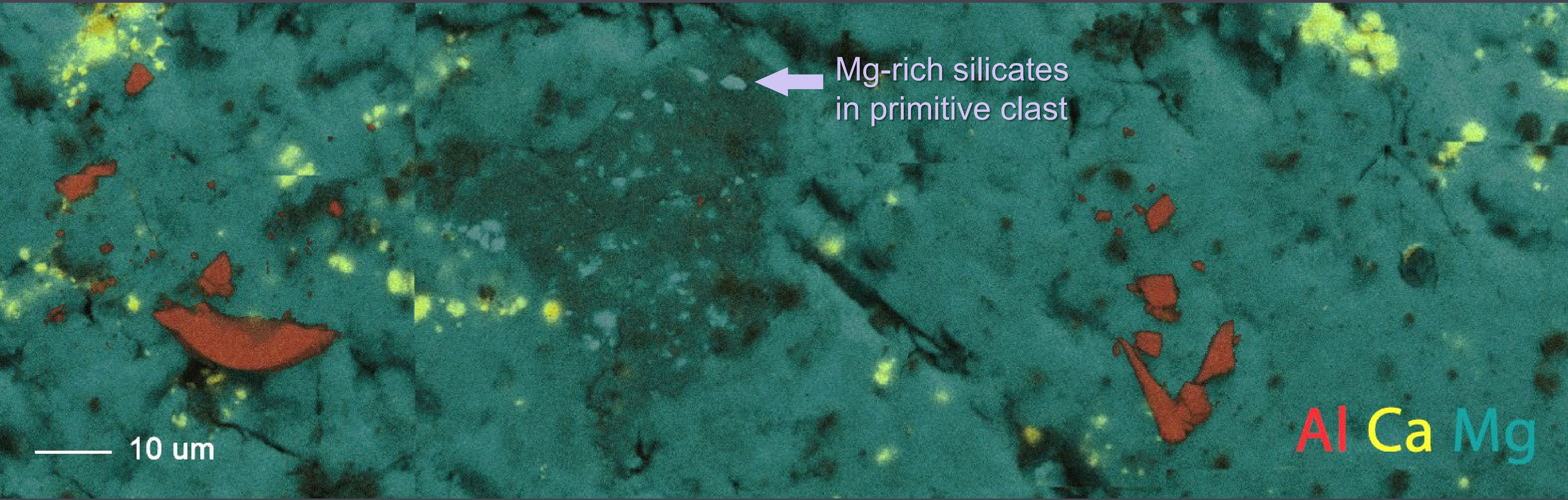
Fragment of grain C0002



- Phyllosilicates
- Magnetite (framboids, plaquettes, spherules)
- Carbonates
- Sulfides
- Carbonaceous veins, nodules, globules
- **Oxides: Cr-rich oxides**
- Clasts (Nguyen et al. Sci. Adv. 2023)
- Anhydrous silicates (Nguyen et al. MetSoc 2022)

Chemical Analysis

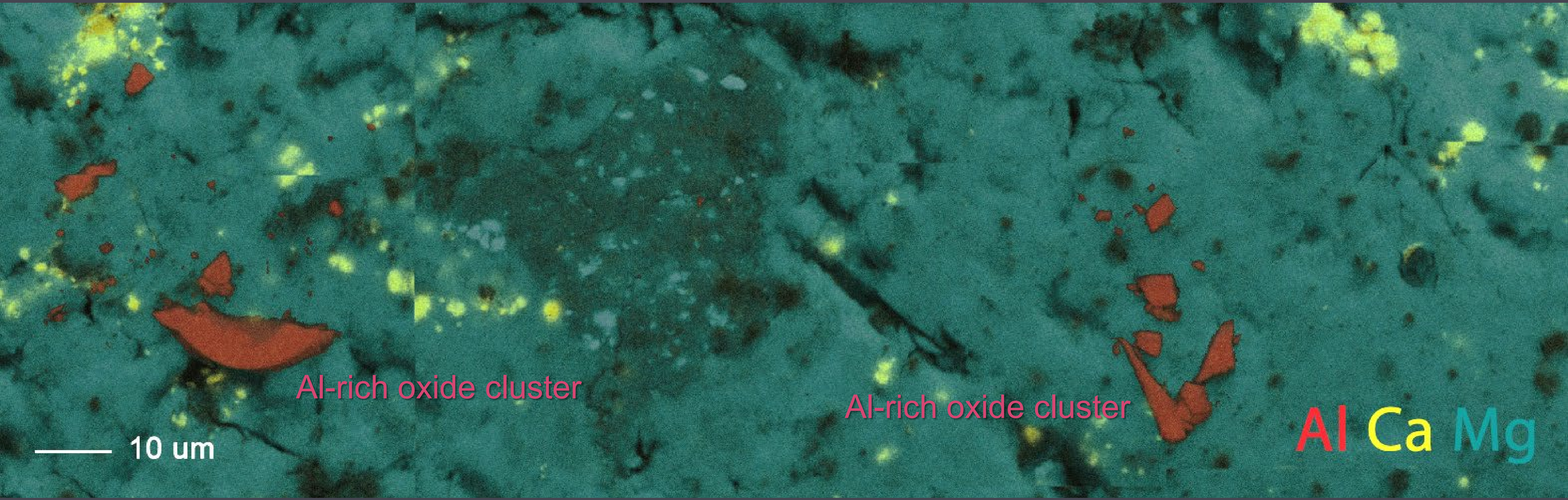
Fragment of grain C0002



- Phyllosilicates
- Magnetite (framboids, plaquettes, spherules)
- Carbonates
- Sulfides
- Carbonaceous veins, nodules, globules
- Oxides
- **Clasts (Nguyen et al. Sci. Adv. 2023)**
- **Anhydrous silicates (Nguyen et al. MetSoc 2022)**

Chemical Analysis

Fragment of grain C0002



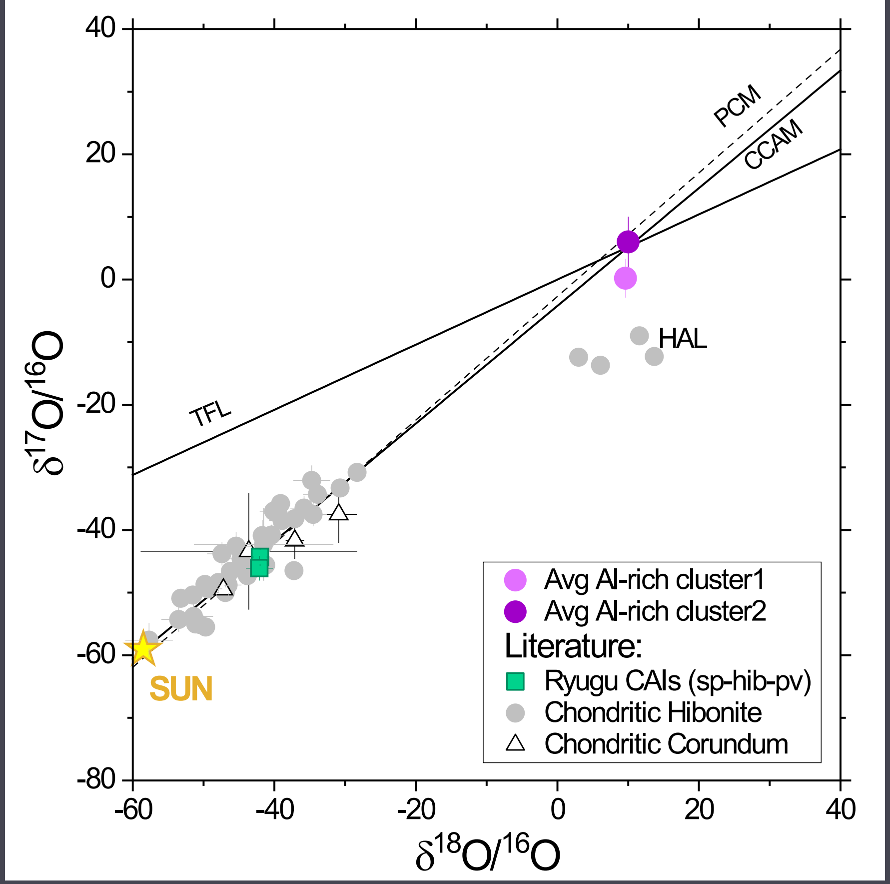
- Phyllosilicates
- Magnetite (framboids, plaquettes, spherules)
- Carbonates
- Sulfides
- Carbonaceous veins, nodules, globules
- **Oxides: Al-rich with Mg, Ca, Fe, REE**
- Clasts (Nguyen et al. Sci. Adv. 2023)
- Anhydrous silicates (Nguyen et al. MetSoc 2022)

O Isotopic Analysis Al-rich Oxides

- Cluster 1: 14 grains; 1-11 μm
  - Weighted avg $\Delta^{17}O = -5 \pm 6$ (2σ)
- Cluster 2: 7 grains; 1-11 μm
  - Weighted avg $\Delta^{17}O = 1 \pm 8$ (2σ)
- Chemical composition analogous to Madagascar hibonite standard

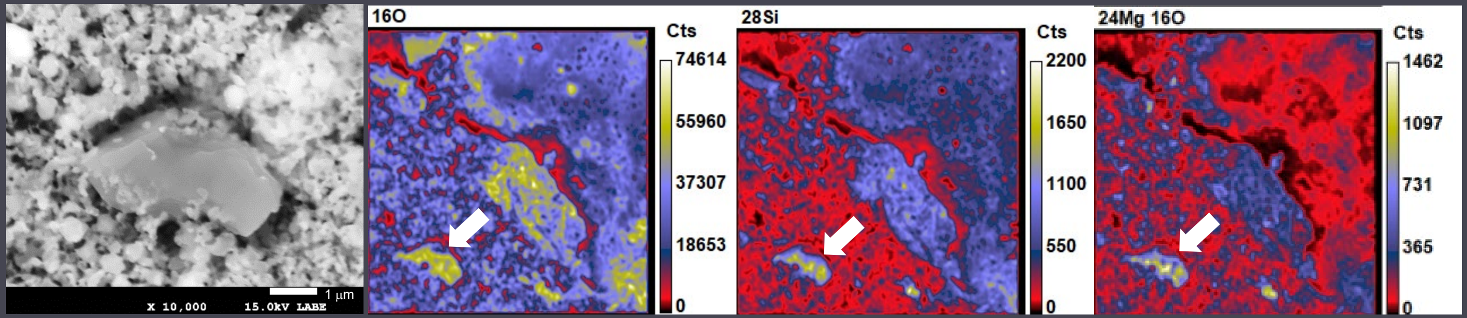
➢ Grains are terrestrial Madagascar hibonite contamination

- Most hibonite in CAIs are ^{16}O-rich
- ^{16}O-poor hibonite grains are fractionated (e.g., Lee et al. 1980)



Literature Data: Lee et al. 1980; Ushikubo et al. 2007; Liu et al. 2009; McKeegan et al. 2011; Koop et al. 2016, 2020; Needham et al. 2017; Krot et al. 2020; Nakashima et al. 2023

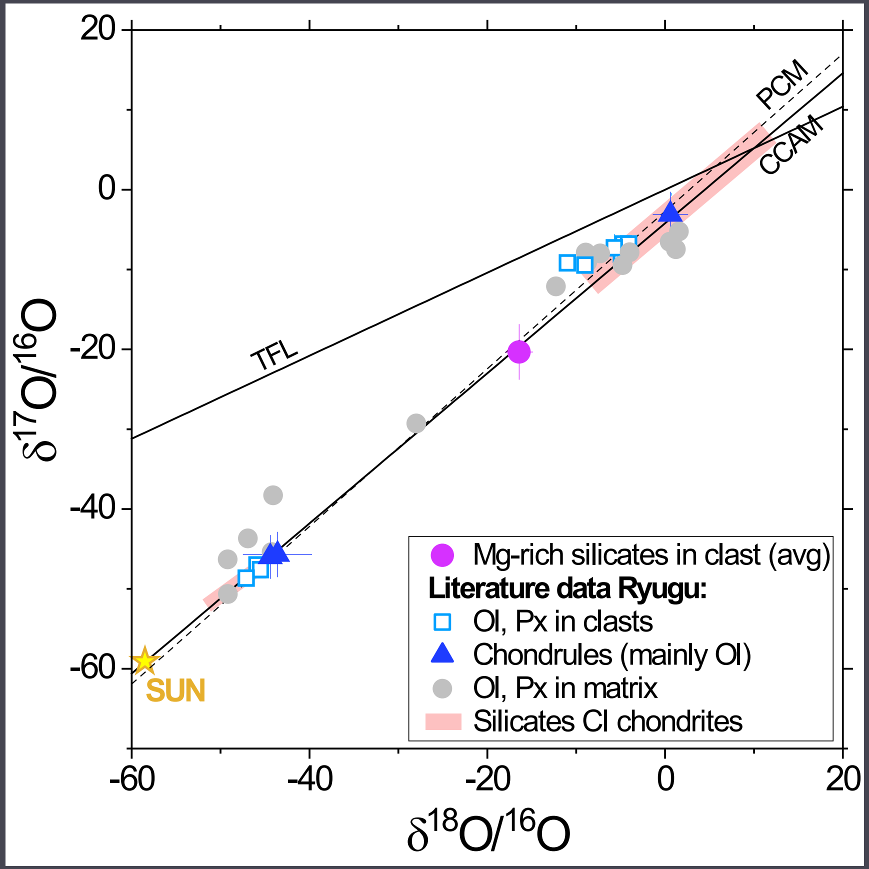
O Isotopic Analysis Mg-rich Silicates



- 38 Mg-rich silicates 0.5–2 µm measured in exogenous clast
- Avg composition indicates mass-independent fractionation
  - $\Delta^{17}O = -12 \pm 8\ (2\sigma)$

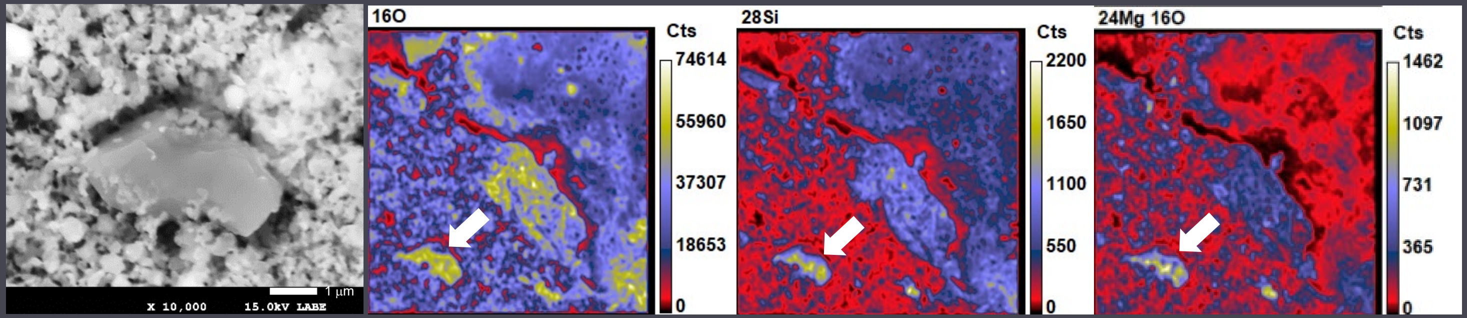
    *Exclude 15 grains with errors > 10 ‰ in $\delta^{18}O$ in calculation

- Anhydrous silicates in Ryugu and CI samples show bimodal distribution
  - ^{16}O-rich grains akin to AOAs and CAIs
  - ^{16}O-poor grains akin to chondrules
- Composition of Mg-rich silicates closer to chondrules

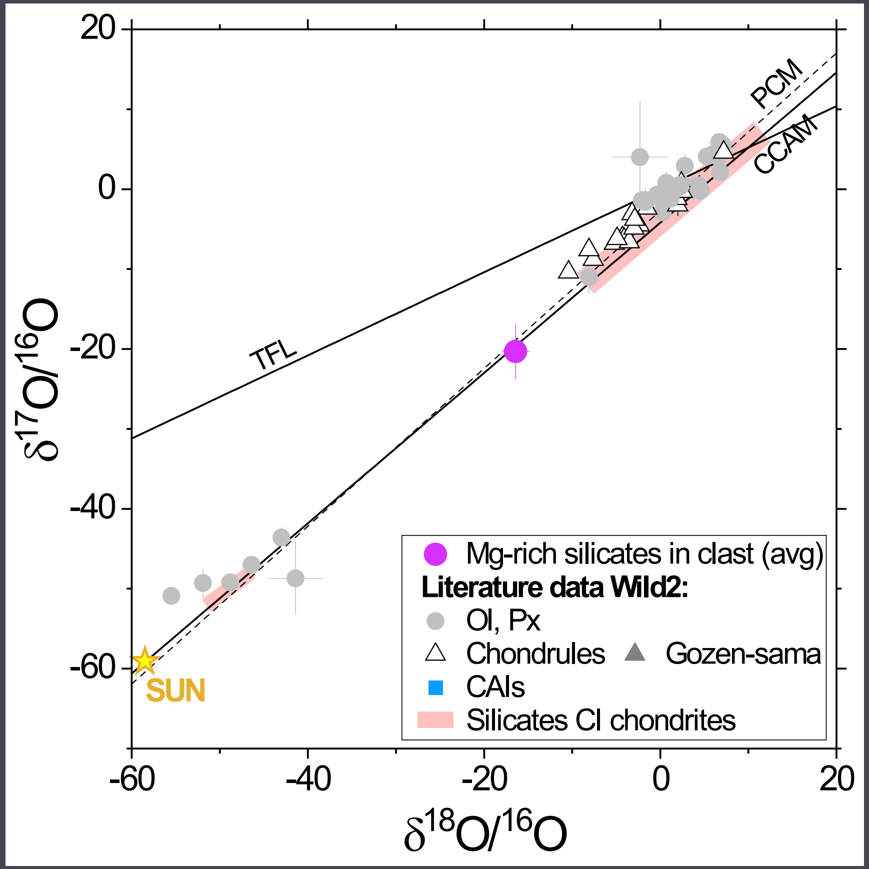


Ryugu data: Kawasaki et al. 2022; Liu et al. 2022; Nguyen et al. 2022; Nakashima et al. 2023
CI chondrite data: Leshin et al. 1997; Piralla et al. 2020; Morin et al. 2022

O Isotopic Analysis Mg-rich Silicates

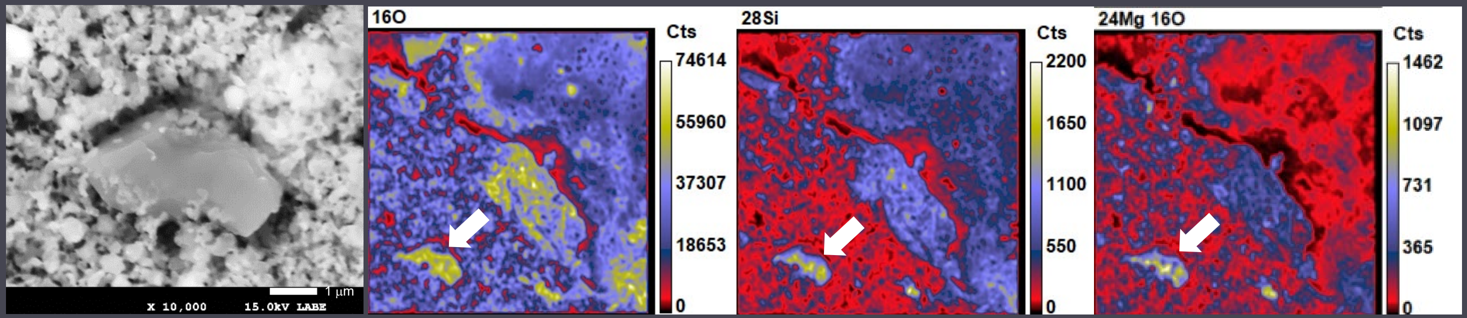


- Clast could have originated from a comet (Nguyen et al. 2023)
- Anhydrous silicates in Wild 2 samples also show bimodal distribution
- Most chondrules are ^{16}O-poor

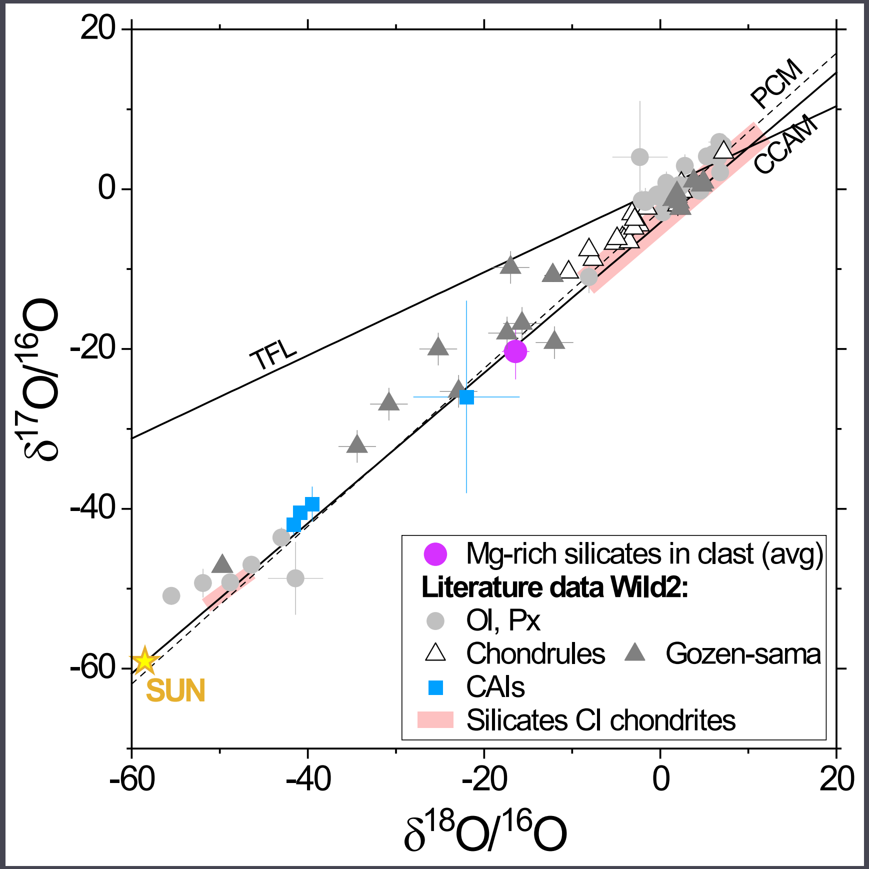


Wild 2 data: McKeegan et al. 2006; Nakamura et al. 2008; Nakamura-Messenger et al. 2011; Nakashima et al. 2012; Joswiak et al. 2014, 2017; Gainsforth et al. 2015; Defouilloy et al. 2017

O Isotopic Analysis Mg-rich Silicates

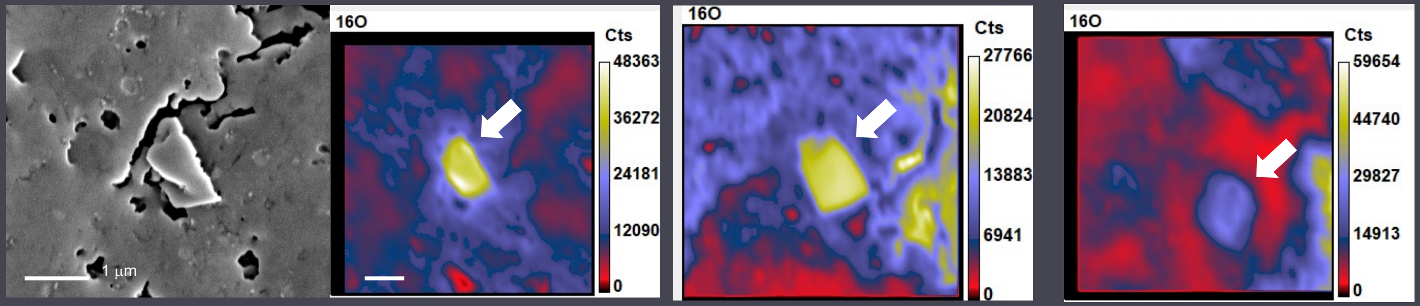


- Clast could have originated from a comet (Nguyen et al. 2023)
- Composition of clast silicates are similar to:
  - Ol in chondrule Gozen-sama – Precursors had variable O isotopic compositions (Nakamura et al. 2008)
  - ~2 µm-sized CAI WF216 (Di-An-Sp) – Formed in more ^{16}O-poor region of nebula, or re-equilibrated with ^{16}O-poor gas (Joswiak et al. 2017)



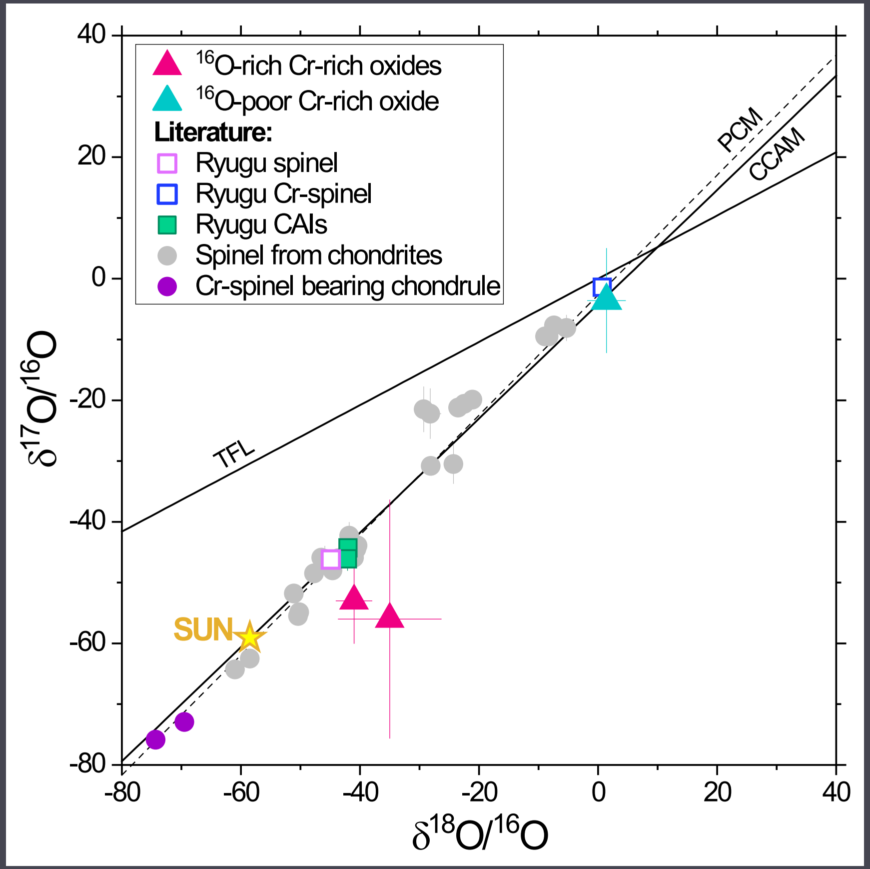
Wild 2 data: McKeegan et al. 2006; Nakamura et al. 2008; Nakamura-Messenger et al. 2011; Nakashima et al. 2012; Joswiak et al. 2014, 2017; Gainsforth et al. 2015; Defouilloy et al. 2017

O Isotopic Analysis Cr-rich Oxides



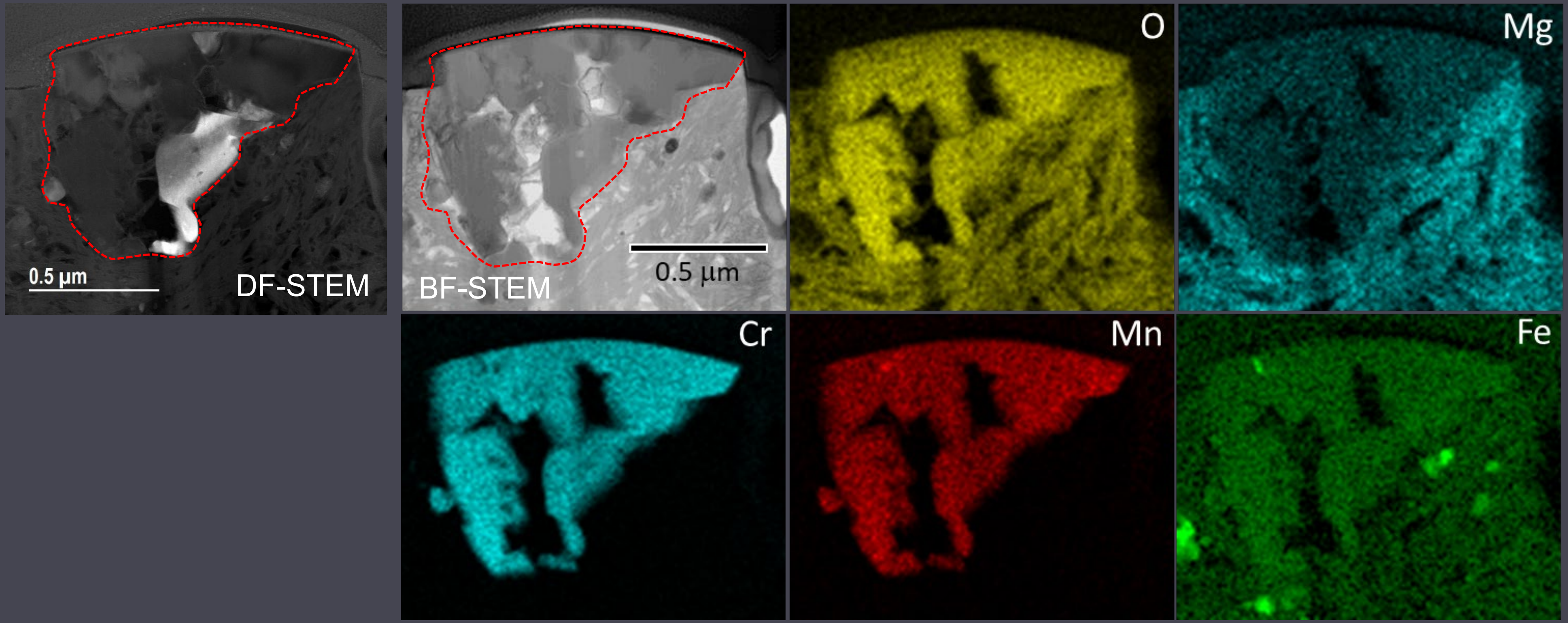
- Analyzed 3 Cr-rich oxides ~1 μm in size
- One grain is ^{16}O-poor
  - Composition consistent with another Ryugu Cr-spinel (Kawasaki et al. 2022)
  - Cr-spinel are common in type II chondrules
  - Fragment of chondrule-like object

- Two grains are ^{16}O-rich
  - Composition consistent with a Ryugu spinel (Kawasaki et al. 2022) and spinel in chondrites



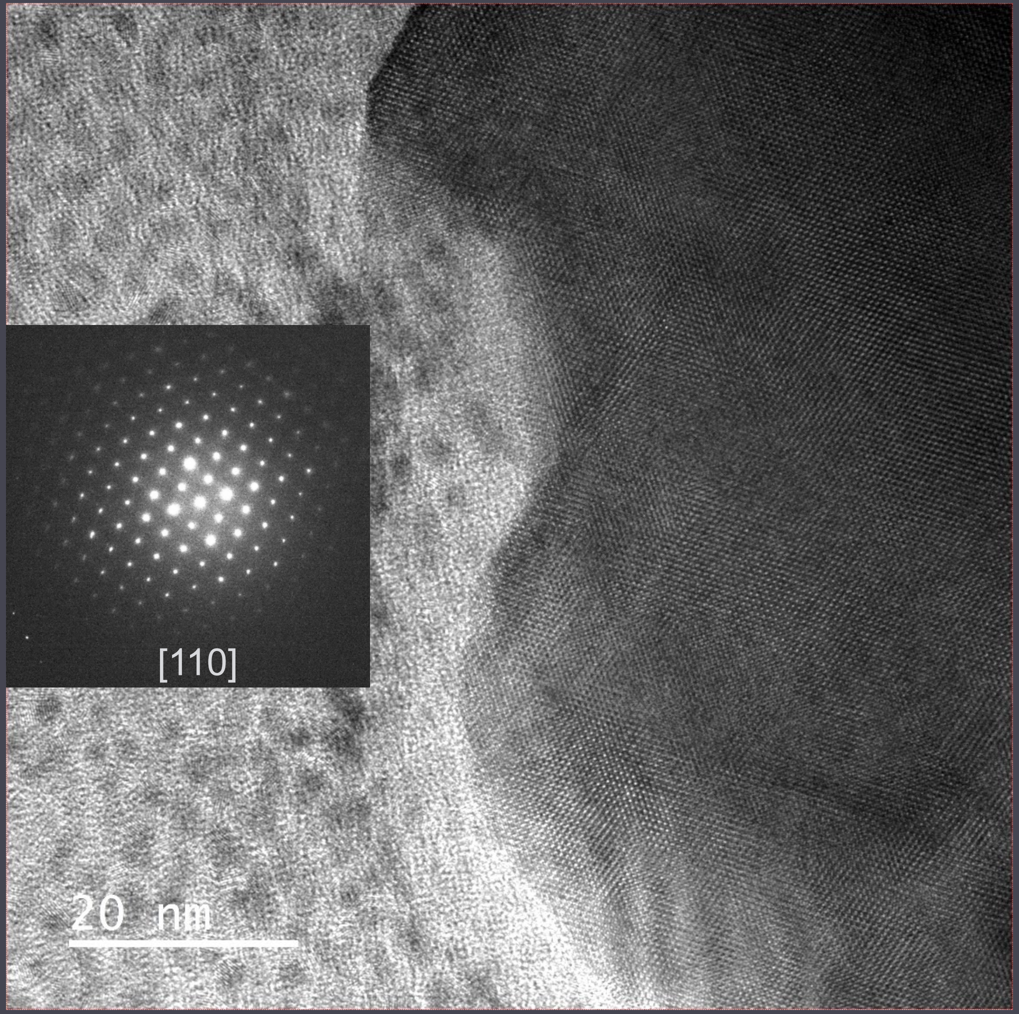
Literature Data: Krot et al. 2017, 2020; Needham et al. 2017; Simon et al. 2019; Kobayashi et al. 2003; Kawasaki et al. 2022; Liu et al. 2022; Nakashima et al. 2023

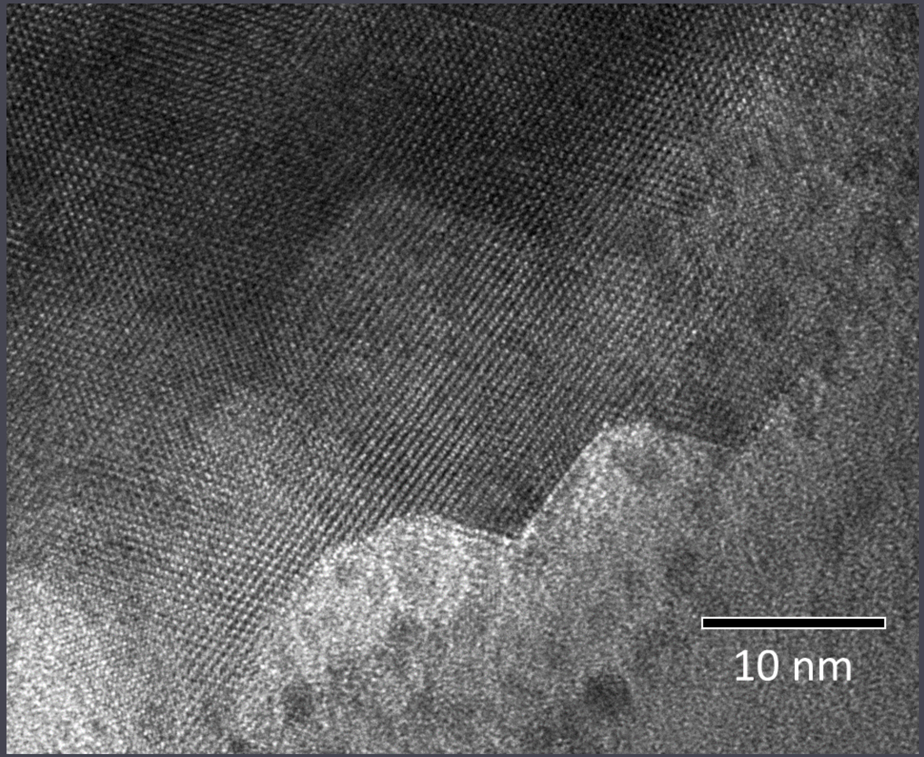
TEM ^{16}O-rich Cr-Rich Oxide 1



- Porous polycrystalline aggregate of multiple crystals
- Grains are a homogeneous solid solution of manganochromite ($MnCr_2O_4$), magnesiochromite ($MgCr_2O_4$), and chromite ($FeCr_2O_4$)
- Overall stoichiometry $(Mn_{0.42}Mg_{0.36}Fe_{0.22})Cr_2O_4$
- ➢ Mn and low-Fe contents are similar to LIME silicates, which are high-T condensates (Klöck et al. 1989)

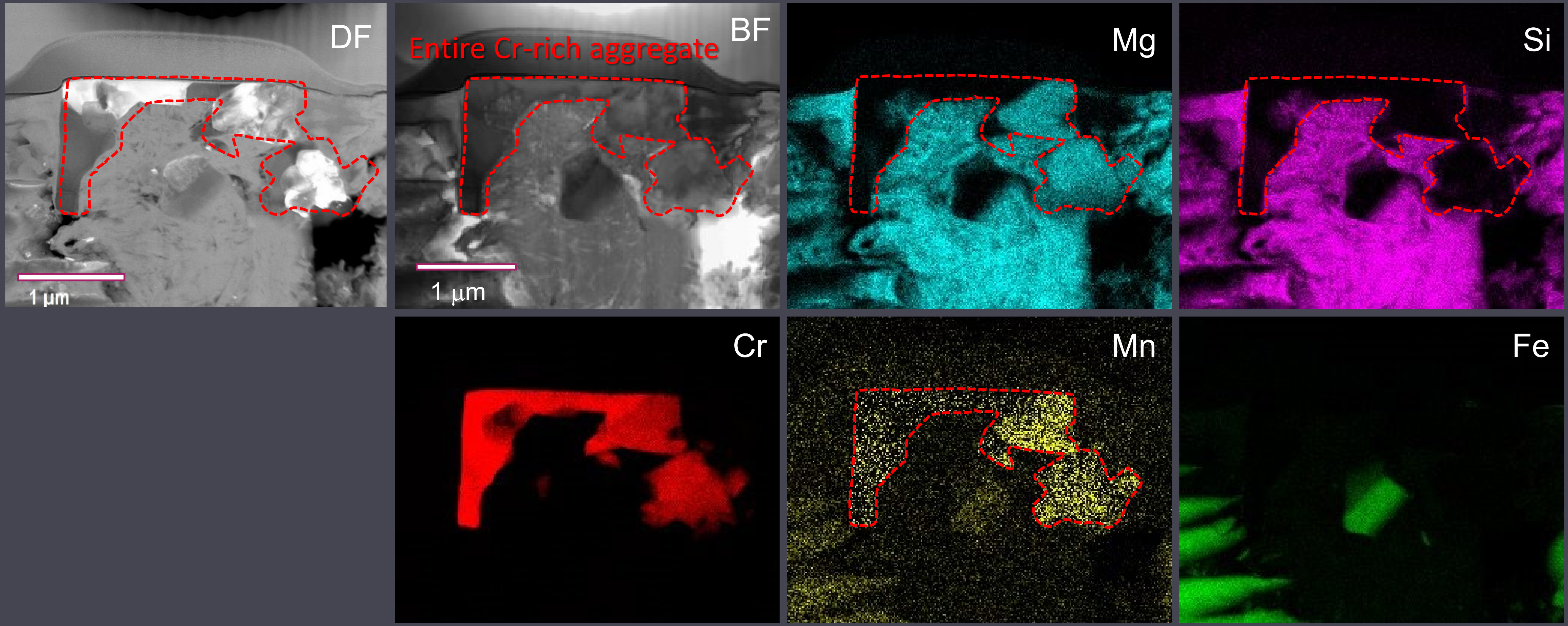
TEM ^{16}O-rich Cr-Rich Oxide 1



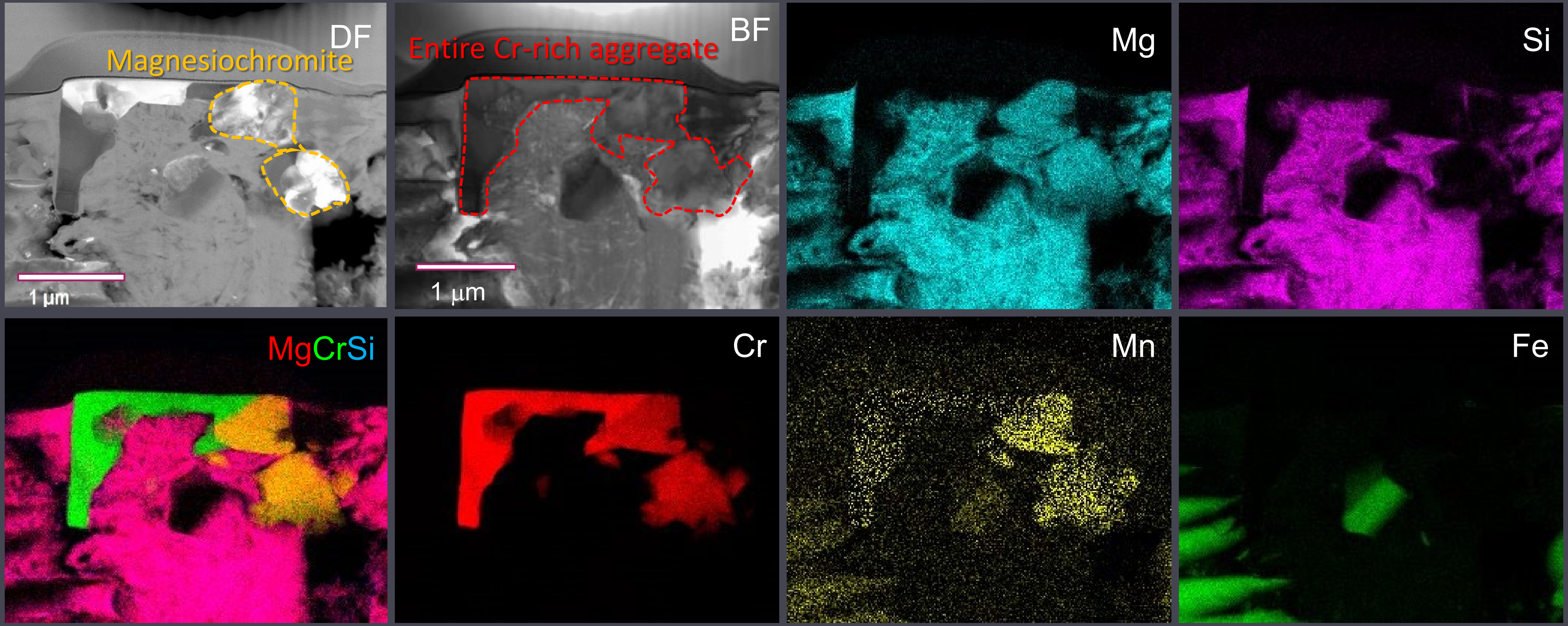


- Grains are well-crystalline and defect-free
- No surface alteration or amorphization
- Electron diffraction data consistent with chromite structure
- HR-TEM images show euhedral surfaces that are indicative of primary growth surfaces

TEM ^{16}O-rich Cr-Rich Oxide 2

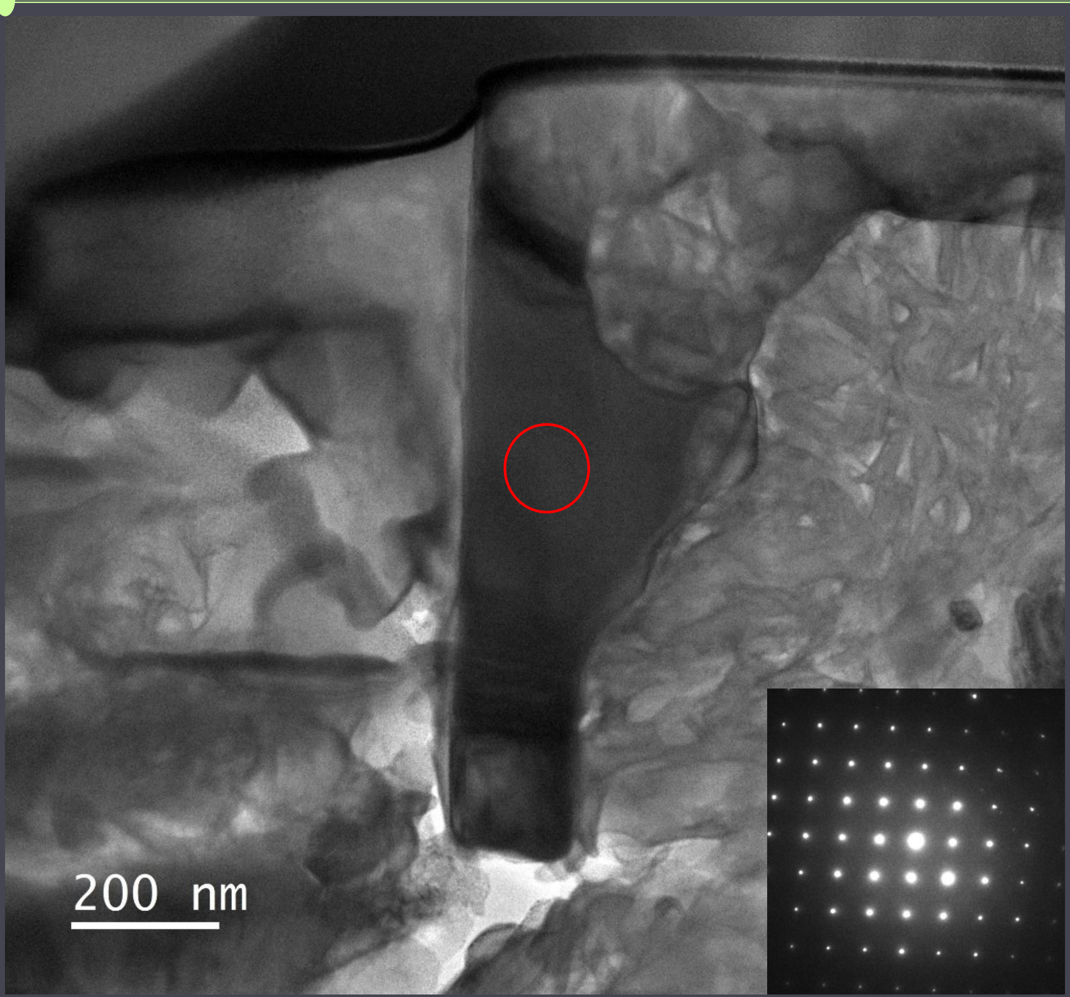


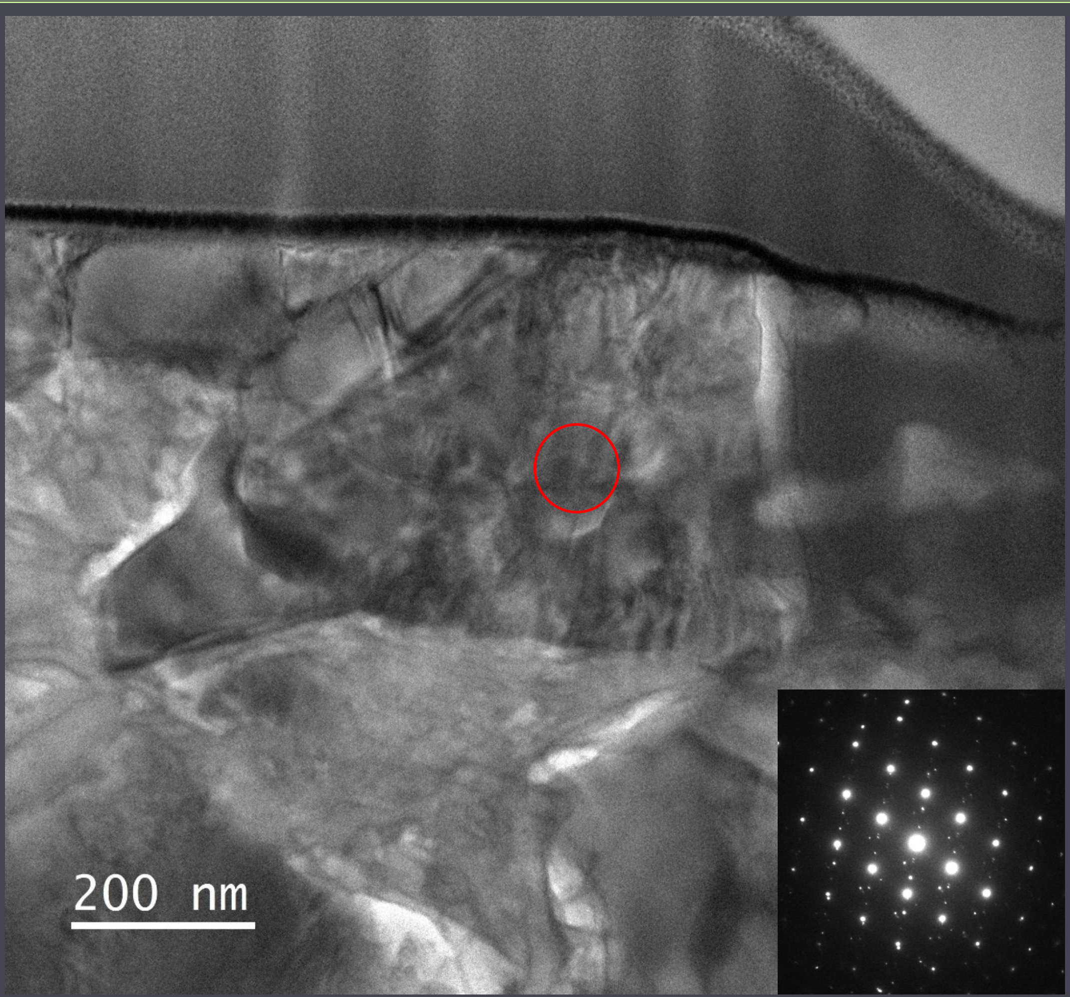
TEM ^{16}O-rich Cr-Rich Oxide 2



Eskolaite (Cr_2O_3),
Magnesiochromite ($MgCr_2O_4$)
Phyllosilicates

TEM ^{16}O-rich Cr-Rich Oxide 2





Eskolaite – well crystalline –
Diffraction pattern consistent with Cr_2O_3
< 1 at% each of Mg, Al, Mn, and Fe

Magnesiochromite – well crystalline –
Diffraction pattern consistent with $MgCr_2O_4$
~1 at% each of Mn, Fe, trace Al

Summary

- Two Cr-rich oxide aggregates likely condensed from an ^{16}O-rich reservoir
  - Euhedral surfaces, Mn-content, and low-Fe abundance indicate high T condensation
  - Transported from inner solar nebula
- ^{16}O-poor Cr-rich oxide is likely a fragment of a chondrule-like object
  - Isotopic composition similar to Cr-spinel grain analyzed by Kawasaki et al. (2022)
- Ryugu contains Cr-oxides having different origins

- Mg-rich silicate grains in exogenous clast could have formed from moderately ^{16}O-rich reservoir
  - Average composition more similar to a chondrule and a CAI from comet Wild 2 than other anhydrous silicates reported in Ryugu
  - Supports exogenous, possibly cometary origin of clast