

Natural Quasicrystals & the Khatyrka Meteorite: FAQs

Grains from the Khatyrka meteorite (a complex CV3 (ox) breccia), recovered from the banks of the Listvenitovyi stream in the Chukotka Autonomous Okrug north of the Kamchatka peninsula, have been shown to contain two distinct quasicrystalline minerals (icosahedrite and decagonite) and at least seven crystalline phases bearing metallic aluminum. In five of these cases, the phases also include metallic Cu.

MOST FREQUENTLY ASKED QUESTIONS THAT WE DO NOT YET KNOW THE ANSWER TO:

What was the original source of copper and aluminum and what kind of natural processes combined for them to form the variety of mineral phases found in the Khatyrka meteorite that contain metallic aluminum and copper, where aluminum requires extraordinarily low oxygen fugacity and the two metals have profoundly distinct cosmochemical properties?

FAQS we can answer:

How can we be sure where the meteorite samples come from?

With the exception of the original sample that was found in the mineral collection of the Università di Firenze and marked as coming from the Koryak Mts., we recovered the rest of the grains ourselves on a geological expedition to Chukotka in 2011 from a stratified, glacial outwash clay layer along the Listvenitovyi stream. The clay layer is more than 7000 years old, based on radiocarbon dating of wood fragments in the clay, and hence the grains are neither anthropogenic nor salted.

If the samples have been there for > 7000 years, how could the metals have been preserved?

Alloyed copper, the cold temperature of clay (always close to freezing), impermeability of clay, and anoxic environment due to carbon material in clay may all have contributed to the preservation of the metals.

How do we know the samples are meteoritic in origin?

Measurements of oxygen isotopes of silicates and oxides show the meteorite is a CV3 carbonaceous chondrite that formed 4.5 million years ago in the early solar system. All reported grains have been tested and produce the same fit. Absence of any excesses of ^{26}Mg (produced by the decay of the short-lived nuclide ^{26}Al , with half-life ~ 0.71 My, known to have existed in the early solar system) suggests the metal formed a few million years (or more) after the formation of calcium–aluminum–rich inclusions (CAIs) that represent the first solar system solids. Other evidence includes the presence in some samples of Allende-type matrix material and actual CAIs.

Is there any evidence of a chemical reaction between the metal and chondritic material?

Yes. In Grains 129 and 126, we have observed a redox reaction near the contact between metallic and non-metallic phases that led to the formation of Fe beads in the chondritic phases, mostly spinel and glass. See [LPSC abstract](#) for more details.

Why are all the samples a few mm in size or less?

In tracing the origin of the Florence sample, we discovered that it had been found by panning clay recovered from undisturbed clay along the stream banks, and so the expedition to Chukotka followed the same procedure in searching for new grains, not knowing at the time if any would be found. Conceivably, larger samples could be found in a return trip to Chukotka using a different search procedure. We note, however, that the recovered grains of meteorite are very friable due to differential expansion of meteorite matrix material and CuAl compounds, which may make it difficult for larger samples to have survived.

What mineral phases have been found with metallic Al and which ones also have copper?

metallic Al + Cu:

Icosahedrite ($\text{Al}_{63}\text{Cu}_{24}\text{Fe}_{13}$, Florence sample, grains from Chukotka) – [SCIENCE 2009](#), [MAPS 2013](#)

Khatyrkite (CuAl_2 , Florence sample, grains from Chukotka) – SCIENCE 2009, [MAPS 2013](#), [NatComms 2014](#)

Cupalite (CuAl , Florence sample, new 126) – [SCIENCE 2009](#)

β -phase AlCuFe (solid solution, Florence sample) – [SCIENCE 2009](#)

Al-Cu-bearing taenite ($\text{Fe}_{44}\text{Ni}_{26}\text{Al}_{18}\text{Cu}_{12}$; grain #126) – [NatComms 2014](#)

metallic Al w/o Cu:

Decagonite ($\text{Al}_{71}\text{Ni}_{24}\text{Fe}_5$; grain #126) – [SciRep 2015](#)

Steinhardtite ($\text{Al}_{38}\text{Ni}_{32}\text{Fe}_{30}$ to $\text{Al}_{50}\text{Ni}_{40}\text{Fe}_{10}$; grain #126) [NatComms 2014](#) and [AmMin 2014](#)

Al-bearing sulfide ($(\text{Fe}_{0.84}\text{Al}_{0.04})\text{S}_{1.12}$; grain #126) – [NatComms 2014](#)

Aluminum, in an eutectic (peritectic) texture with CuAl_2 – [NatComms 2014](#)

What evidence do we have that the metal and conventional CV3 minerals were in contact?

Icosahedrite inclusions in stishovite – [PNAS 2012](#), [ROP 2012](#)

Diopside in direct contact with icosahedrite – [PNAS 2012](#)

Cu-bearing troilite in contact with clinoenstatite (grain #126) – [NatComms 2014](#)

Khatyrkite in contact with forsterite (grain #129 and new grain #126) – to be published

Khatyrkite in contact with glassy pyroxene (grain #129) – to be published

Other contacts in Grain 129 and new 126, especially evidence of redox reaction producing Fe droplets – [LPSC abstract](#)

What do we know about the temperature and pressure conditions that the meteorite underwent?

We have found abundant evidence that the meteorite underwent an impact shock that produced a highly heterogeneous distribution of pressures (> 5 GPa) and temperatures (> 1500 K). The eutectic texture of the CuAl metal phases show that they solidified from a CuAl melt at around 1100K or so. The chondritic material was partially melted in some places, in some parts mostly melted. The CAI was partially melted, but some melilite was not melted. More specifically, we found:

Overall shocked texture: compressed barrels of olivine separate by veins – [NatComms 2014](#)

Ladder: injection into cracks of presumed liquid that rapidly quenched forming "ladders" (cotectic composition) of ahrensite (high P) interleaved with glassy silica – [NatComms 2014](#)

Veins of spinels and spinelloid (high P) – [NatComms 2014](#)

Magnetite grain surrounded by ladder; magnetite very likely existed in forsterite prior to impact

and then melt injected that surrounded magnetite and formed ladders – [NatComms 2014](#)

Fe beads in grain 129 and new 126 – [LPSC abstract](#)

What other minerals have been identified aside from the ones named above?

Stishovite – [PNAS 2012](#)

Coesite – unpublished data

Spinel – [MAPS 2013](#), [NatComms 2014](#)

Spinelloid $\text{Fe}_{3-x}\text{Si}_x\text{O}_4$ (with $x = 0.4$) – [NatComms 2014](#)

Ringwoodite-ahrensite solid sol. – [NatComms 2014](#)

Melilite – [MAPS 2013](#)

Diopside – [PNAS 2012](#), [MAPS 2013](#)

Clinoenstatite – [NatComms 2014](#)

Nepheline – [MAPS 2013](#)

Sodalite – [MAPS 2013](#)

Pentlandite – unpublished data

Taenite – [NatComms 2014](#)

Cu-bearing troilite (grain #126) – [NatComms 2014](#)

Possible cordierite? – in progress

Possible $(\text{Fe}_{1.8}\text{Cu}_{0.2})\text{Al}_5$? – in progress