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 Listevenitovyi 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 ($Al_{63}Cu_{24}Fe_{13}$, 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 ($Fe_{44}Ni_{26}Al_{18}Cu_{12}$; grain #126) – NatComms 2014

metallic Al w/o Cu:

Decagonite ($Al_{71}Ni_{24}Fe_5$; grain #126) – SciRep 2015
Steinhardtite ($Al_{38}Ni_{32}Fe_{30}$ to $Al_{50}Ni_{40}Fe_{10}$; grain #126) NatComms 2014 and AmMin 2014
Al-bearing sulfide ($(Fe_{0.84}Al_{0.04})S_{1.12}$; 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 $Fe_{3-x}Si_xO_4$ (with x = 0.4) – NatComms 2014
Ringwoodite-ahrensite solid sol. – NatComms 2014
Melilite – MAPS 2013
Diopside – PNAS 2012, MAP 2013
Hollisterite – Am. Min. 2017
Clinoenstatite – NatComms 2014
Nepheline – MAPS 2013
Sodalite – MAPS 2013
Pentlandite – unpublished data
Taenite – NatComms 2014
Cu-bearing troilite (grain #126) – NatComms 2014
Stolperite – Am. Min. 2017
Kryachkoite –Am Min 2017