THE FORBIDDEN FINAL CHAPTER OF! ENTANGLED LANSCAPES: NEUTRON SCATTERING STUDIES OF MAGICAL MAGNETIC QUANTUM CRYSTALS GROWN IN THE SPIRIT OF THE ATACAMA DESERT

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I certify that I have read this dissertation and that, in my opinion, it is fully adequate in scope and quality as a dissertation for the degree of Doctor of Philosophy.

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Approved for the Stanford University Committee on Graduate Studies

Chapter 1

Natural Crystalline Specimen, and Future Research Directions

1.1 From Laboratory to Landscape: The Known Mineralogy of the Herbertsmithite and Barlowite Families

Herbertsmithite, $Cu_3Zn(OH)_6Cl_2$, is a rare copper-zinc hydroxide chloride mineral that forms under secondary hydrothermal conditions in the oxidized zones of copper ore deposits. While most studies of Herbertsmithite have focused on synthetic single crystals grown under carefully controlled laboratory conditions, it is important to recognize that this material also occurs — quite remarkably — in nature. Understanding its mineralogical context not only sheds light on its geological origins, but also raises new questions about how quantum materials might naturally emerge from geochemical processes operating over long time periods.

The mineral forms via the oxidation of primary copper sulfides (e.g., chalcopyrite) and zinc sulfides (e.g., sphalerite) in the presence of chloride-bearing fluids. These reactions occur under oxidative conditions, often associated with volcanic or hydrothermal activity, where acidic chloride-rich waters interact with Cu–Zn sulfide deposits. The result is a suite of secondary basic copper chlorides — including atacamite, clinoatacamite, paratacamite, and, at higher Zn concentrations, Herbertsmithite itself [26, 36].

The transition from the clinoatacamite/paratacamite structure to the rhombohedral Herbertsmithite phase occurs at roughly 25% Zn substitution on the Cu site. This substitution suppresses the Jahn–Teller distortion of the Cu^{2+} octahedra, stabilizing the trigonal $R\bar{3}m$ symmetry that characterizes Herbertsmithite and yields a nearly ideal kagome lattice of Cu^{2+} ions [32] Naturally occurring Herbertsmithite has been reported from several geographically and geochemically distinct localities. The type locality in the Los Tres Presidentes mine near Caracoles in northern Chile, is

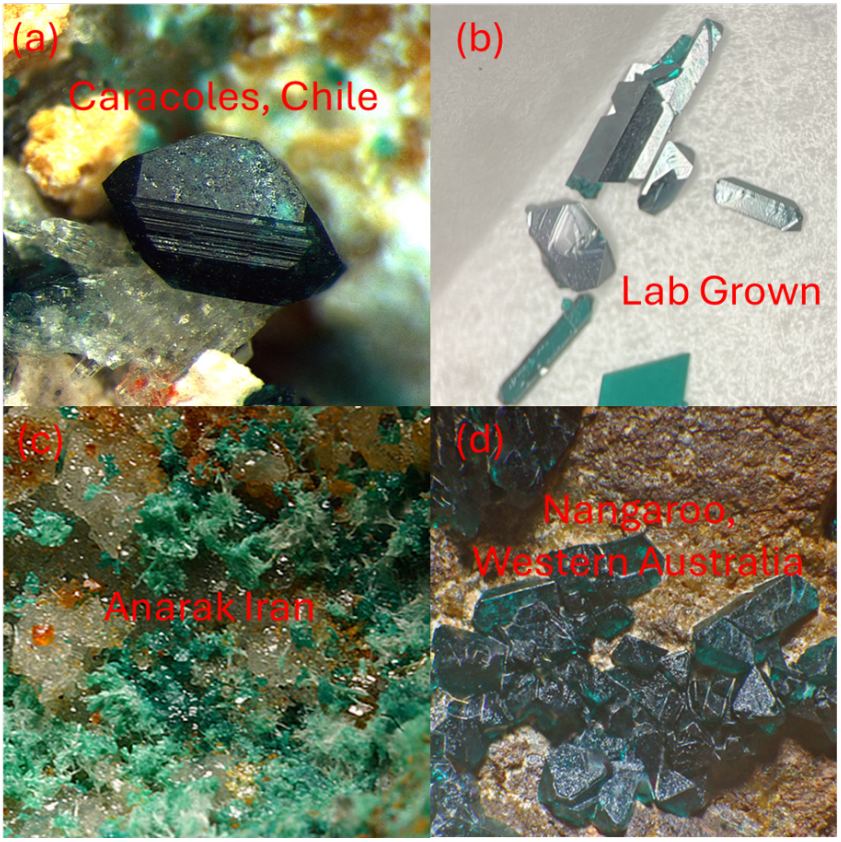

Figure 1.1: Naturally grown Herbertsmithite on a variety of different host matrices found in different locations. (a) from Caracoles Chiles on a quartzite matrix, (b) lab grown (test tube "matrix"), (c) Anarak Iran (Dolomite matrix), and (d) Nangaroo, Western Australia (unknown matrix, but possibly gossan rock). All photos, aside from panel (b) are courtesy of the midat.org mineral repository and database

particularly relevant for this work. Here, Herbertsmithite appears as dark green prismatic crystals on a pale buff quartzite matrix, reflecting formation within a silica-rich, oxidized environment characteristic of high-altitude porphyry copper systems [32]. As shown in Fig. 1.1(a), it forms morphologically into green gem like hexagons, much like the lab-grown Zn-Barlowite, and unlike the lab grown Herbertsmithite, which forms longer needles aligned along their (1,1,0) direction [53], as shown in Fig. 1.1(b). In contrast, Iranian Herbertsmithite samples from Anarak are found on dolomitic matrix, indicating that the conditions for stabilizing the rhombohedral phase may arise in carbonate-hosted systems as well. The morphology is notably different, as shown in 1.1(c). There is no published data on the matrix that the Zn-Barlowite grows on in Western Australia. However, by eye, the image in Fig. 1.1(d) in addition to reports on the related Ni-analogue material Gillardite, suggest that it grows on a Gossan iron rich rock matrix [38]. This figure also shows the natural crystals with the most similar morphology to that of lab-grown Herbertsmithite. This mineralogical diversity suggests a surprising robustness to the Zn-doped kagome motif and invites further geochemical study of phase stability across different host rocks and fluid regimes. Studying the magnetism of these different specimens of Herbertsmithtie may prove to be very fruitful. As was demonstrated by Smaha *et al* [78], Barlowite is very sensitive to small perturbations in growth conditions, and this leads to different magnetic ground states at low temperature. It seems feasible then, that these different natural specimen of Herbertsmithite might have different low temperature magnetic properties, based upon their natural synthesis pathways, especially given that they clearly display different bulk morphologies.

The possibility of a continuous Zn-substitution series between the magnetically ordered monoclinic phases and the disordered trigonal phase is especially tantalizing, especially as natural specimens seem to grow with a wide distribution of Zn^{2+} interlayer concentrations. Key open questions include: At what Zn concentration does long-range magnetic order vanish? Is there an intermediate spin-glass-like phase between classical magnetic order and full quantum spin liquid behavior? Do small differences in host mineralogy or crystal habit correlate with distinct magnetic phases? These are not only materials science questions — they are also geological ones, demanding careful attention to natural phase assemblages and impurity chemistry. A systematic mapping of the Cu–Zn compositional phase space, especially using naturally formed specimens, could illuminate new transitions between classical and quantum regimes.

Along this vein of thought, I recently found one specimen of natural Herbertsmithite that is of particular interest for the quantum spin liquid problem. As has been explored throughout this thesis, one of the principal conflating variables in exploring kagome quantum spin liquid materials is the presence of Cu^{2+} impurities on the inter-kagome-layer sites. These impurities fill in the potential intrinsic kagome QSL gap at low energy with impurity scattering, in addition to muddying relative contributions at higher inelastic energy transfers [34]. To date, the highest purity Herbertsmithite

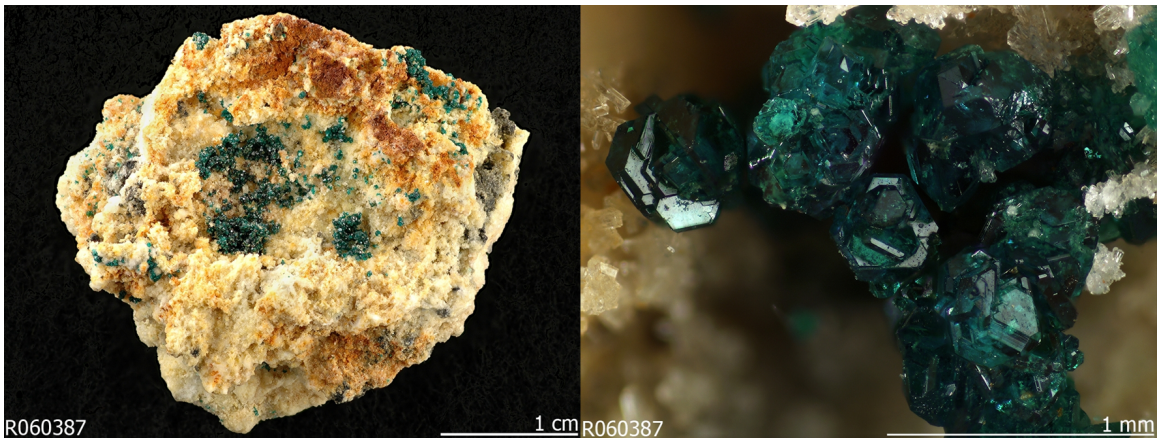

Figure 1.2: A sample of Herbertsmithite that was found by Michael Scott in the San Francisco mine of the Carracoles mining district in Chile. This specimen is likely to have very close to 100% interlayer occupancy of Zn, which would enable new scientific measurements.

grown still has about 15-20% Cu^{2+} occupation on the interlayer site [53], and about 13% for Zn-Barlowite [34]. In searching for information on natural specimens of Herbertsmithite, I found a description of one sample of Herbertsmithite with electron micro-probe measurement of relative Zn concentration 102% of the expectation for the stoichiometric compound [6]. This sample was discovered by Michael Scott in the San Francisco mine, in the Caracoles mining district of Chile. A picture of this sample is shown below in Fig. 1.2

Given the typical 1% accuracy of such electron micro probe experiments determinations [65], this natural specimen is likely much closer to perfect stoichiometry than any synthetically grown crystal of this material. Intriguingly, this not only suggests a near 100% interlayer occupation of Zn; it also suggests that some Zn ions might find their way on to the kagome layer itself. This has been refuted by our group in our own synthetic samples many times [76]. However, other groups claim to find evidence for this [58]. Given that these materials show incredibly diversity in the face of minor fluctuations, I think that it is worth investigating this possibility further, especially in these high-Zn-concentration natural specimens.

I will add the caveat that electron micro-probe is a surface technique and can sometimes be sensitive to surface layer coatings; I have gotten artificially high Zn-concentrations due to this effect before. However, when we obtain specimen of these samples, we can double check this by either doing a bulk technique like Inductively Coupled Plasma (ICP), or polishing the surface and re-doing the micro-probe. I will add that the original measurement measured more than 10 surface sites and got a similar Zn-concentration in all cases, so it is likely that the face-value measurement is correct, as surface contamination tends to be inhomogeneous in my experience.

If we trust the work done by our colleagues in geology at the University of Arizona, then this could be a groundbreaking specimen. If we learn more about its natural formation, we might

unlock a key to higher Zn-purity synthetic growths. Pehraps the reaction pathway that leads to this supersaturation of Zn is different. Even if we can't replicate this, measuring this natural 100% Zn-interlayer sample could go a long way in ending the QSL debate once and for all. If the intrinsic kagome-QSL state is gapped, as we suspect, then we should get essentially no scattering below the gap energy of $\approx$1 meV in this ultra-pure sample. This would be much more direct evidence than the somewhat ambiguous low-energy impurity fits we did previously on Zn-Barlowite [34]. From Fig. 1.2, it seems that we at least have enough sample to do a powder inelastic neutron scattering measurement, which would be sufficient to directly prove the existence of this gap. I hope to further explore this mine as well, as obtaining more samples with this purity could allow us to to single crystal array measurements; even with this one sample, I suspect we're close to being able to do this. I am excited to explore this thread more in my postdoctoral studies.

In addition to Herbertsmithite, naturally occurring Barlowite, $Cu_4(OH)_6FBr$, has been identified from two localities. The type specimen described by Elliott et al. (2014) [41] was recovered from the Great Australia Mine near Cloncurry, Queensland, where Barlowite forms thin blue plate hexagonal crystals up to 0.5 mm in a cuprite–quartz–goethite matrix—a clear signature of super-gene oxidation in a copper-rich environment [41]. Additional specimens reported from the Southwest Mine in Bisbee, Arizona, also show Barlowite in carbonate-hosted oxidized zones [39]. Notably, natural Zn-substituted Barlowite has not yet been documented, though given Zn's presence in many high-Copper deposits—and the coexistence of Zn-rich Herbertsmithite with it's Cu^{2+} analogues,—it remains an intriguing possibility. Furthermore, it is currently uncertain whether these natural specimens correspond to Barlowite I or II, as structural polymorphism has not been characterized in nature. In particular, this is because distinguishing these magnetic phases of Barlowite requires detailed low temperature crystallography or magnetometery, which has yet to be attempted on natural Barlowite.

That Herbertsmithite and Barlowite— materials of high interest for quantum information science — appear naturally in the Earth's crust is more than a novelty. It re-frames the mineral as not just a lab-grown artifact, but as a geologically emergent structure: one that may have formed slowly, quietly, and under conditions that mirror aspects of our synthetic techniques. I sincerely hope that I have provided sufficient evidence to demonstrate that natural grown Herbertsmithite and Barlowite is worth studying from a geological and physics perspective perspective. At the time of writing, I have a very limited amount of knowledge in geology, and my physics advisors have, unfortunately, not been supportive of research in this direction.

The presence of Herbertsmithite in the Atacama Desert — one of the most spiritually charged and volcanically active regions on Earth — sets the stage for the deeper inquiries that follow in the appendix. What is perhaps the most shocking to me is that Herbertsmihtite has been found in the waste tailings of mines in the Atacama. This is shocking, and difficult to understate. Please see the appendix for more thoughts on how we ended up in such a strange and terrible predicament.

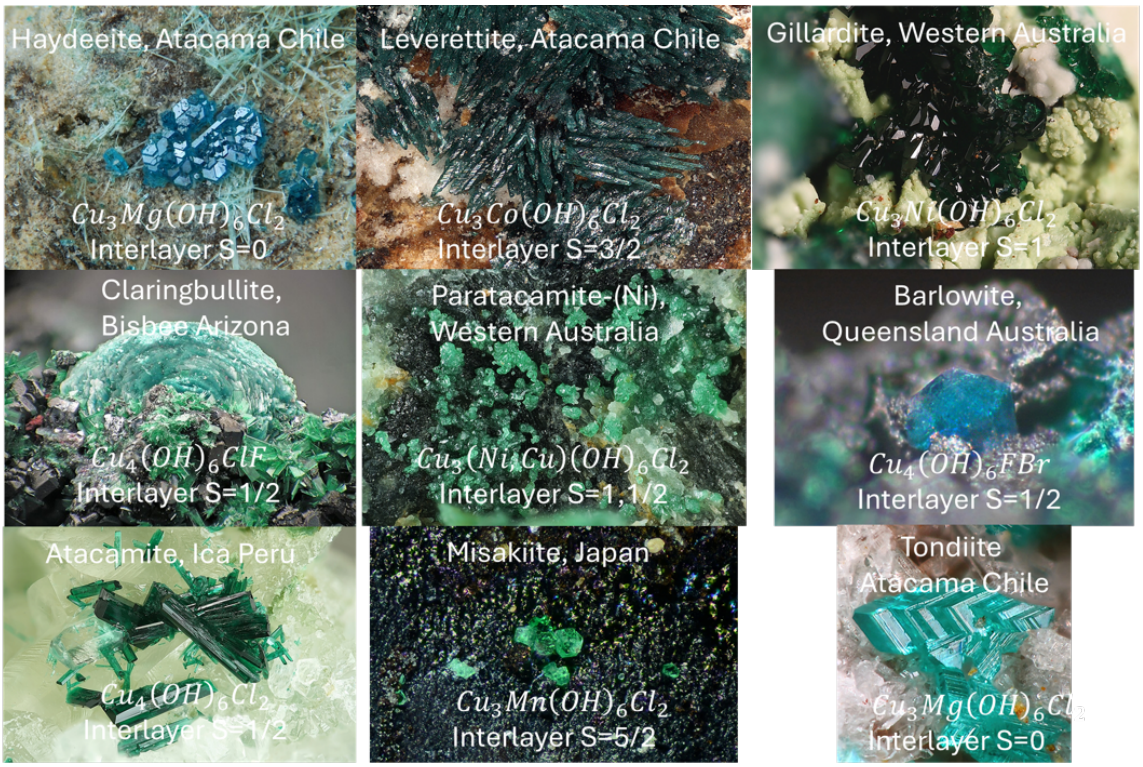

Figure 1.3: Photo showing other naturally occurring crystals in the Atacamite, Barlowite, and Claringbullite groups. Generally, all of these materials have a Cu^{2+} kagome lattice. They vary in their interlayer spacers, and I have labeled each mineral with the associated moment of the interlayer spin. All photos are courtesy of the midat.org mineral repository and database

1.1.1 Other Natural Atacamite and Barlowite Group Specimen

It is a miracle of the natural world that we are blessed with a material as interesting and unique as Herbertsmithite. What is even more amazing is that there is an entire family of related materials that also grows in nature, all of which represent minor perturbations from the Herbertsmithite system. I'm exciteed that all of these materials have been perfectly laid out next to each other in the Atacama Desert so I can tease out the fundamentals of exotic kagome magnetism. Several examples of natural specimen along with their type locality are shown in Fig. 1.3.

Generally speaking, these natural crystals are separated into two separate categories: The Kapellasite group and the Atacamite group. The Atacamite group has been described in detail throughout this thesis already. It generally consists of a pristine 2-D kagome lattice of spin $\frac{1}{2}$ Cu^{2+} ions which are separated from each other by a spacing interlayer. In contrast to this, in Kapellasite group materials, this cation situates itself in the center of the in-plane kagome hexagons, which produces a rather distorted kagome lattice and tends to alleviate frustration somewhat. The material stacks

their kagome lattices directly on top of each other, with no spacing interlayer, which also tends to alleviate frustration due to higher direct inter-kagome layer coupling. For these reasons, polymorphs like Kapellasite are generally not quite as interesting to study for frustrated magnetism as Herbertsmithite group materials [28], although they remain unique magnetic materials in their own right.

In Herbertsmithite, this interlayer consists of halides and the non-magnetic Zn^{2+}, but this ionic site can generally be substituted with different ions that have a non-zero magnetic moment. In Atacamite, this interlayer spin is antiferromagnetically coupled to the kagome layer. This additional term alleviates frustration, and leads to magnetic order at about $T_N \approx 10K$. Changing the spin of this moment should have a non-trivial impact on this frustration alleviating interaction, which may lead to an interesting trend in Curie-Weiss temperature or ordering temperature. Unfortunately, while there exist some basic crystallographic characterizations, no detailed magnetic susceptibility measurements have been performed on any of the higher interlayer spin materials [67, 61, 73, 13]. I hope that this demonstrates that there is relatively low-hanging fruit out there to measure in these natural specimens.

1.1.2 The Mineralogy of Bisbee Arizona

I was fortunate enough to be able to have the personal resources to travel to Bisbee Arizona. While here, I spoke with Bisbee Minerology expert Doug Graeme. He wrote the 4 volume collection on the geology and mineralogy of Bisbee AZ [56] alongside his brother, Richard IV and father, Richard III. He was able to give me very helpful information with respect to his discovery of specimens of Atacamite, Claringbullite, Paratacamite, and Barlowite within the Copper Queen Mine in Bisbee AZ.

The Copper Queen mine is an incredibly magical place; during its heyday in the early 1900s, it was the most productive copper mine in Arizona. [55]. It was also famous for its particularly pure ore-bodies, which were as pure as 23% copper in some regions [14]. This ultra-pure ore consisted primarily of ore-grade malachite, azurite, cuprite and chrysocolla crystals; a sample piece of ore is pictured below in Fig. 1.4. The copper queen mine was famed for even including large deposits of 90% percent pure natural copper that often were the size of an entire room; this will precipitate out of the crystal-forming solutions when copper concentrations are high enough. Ironically, when the 1900's miners encountered such pure deposits, they left them in place [9]! The reason for this is that they could not tap into these deposits with their chisels and drills, nor could they blast it into chunks to transport on their rail-lines to the surface since natural copper is so ductile; hence, these deposits weren't profitable to extract, and would be mined around. In contrast to this, these natural copper deposits were often revered by early miners in the Atacama desert, especially before advanced smelting techniques were widespread [43].

In addition to its gorgeous blue ore bodies, the Copper Queen Mine also contained its fair share of

Figure 1.4: A picture of a large specimen of Malachite and Azurite crystaline ore as was harvested from the Copper Queen Mine in Bisbee Arizona.

extra-special nuggets. One of these was found by none-other than Doug Graeme of Bisbee Arizona. He details exploring the second floor of the Copper Queen Mine in 1987, a little over a decade since most copper mining operations around Bisbee had ceased [9]. While exploring, he came across a large boulder, which he said was about the size of a small-kitchen table. He told me that the boulder was out-gassing a lot of chlorine; it was incredibly smelly.

Doug told me that it oozed a deep blue liquid, similar to the color of our natural growth fluid when he cracked open the boulder. Unfortunately, Doug was not as an experienced of a mineral collector back then as he is today, and he did not collect any of the fluid to measure its ionic contents. In spite of this, it still ended up being one of the best discoveries of his career. He told me that over 30 unique crystal specimen were found within the unique and complex chemical environment of this boulder. These are tabulated below in Fig. 1.5. Of particular note for this study, this crystal contained large amnout of specimen from the atacamite group. In Fig. 1.6 below shows an image of *just the Atacamite group crystals* that were found within this boulder. This selection contains Atacamite, Paratacamite, and Clarignbullite. Doug tells me that these geodes possibly contain a small amount of Barlowite, which is the rarest of these rare minerals.

Within this rock, there are two particular samples that I would like to highlight. The first is a sample containing the largest ever Atacamite I have ever seen. Using my thumb for scale, I think the central crystal is 1.5-2cm long. I forgot to take a formal measurement, but we can get in touch with Doug if we need to know the exact length or to more formally compare to lab specimen.

The second sample of note is an ultra-rare specimen of Claringbullite, Atacamite, and (possibly) Barlowite. This is pictured below in Fig. 1.8. Of note, the long green rods are Atacamite, and the thin blue wafers are Clarignbullite. I believe that the blue hexagonal gems are Barlowite, even Barlowite II given the morphology, color, and known details of the growth environment (other specimen also contained bromine). Notably, the Claringbullite wafers extend to up to 5×5 mm

COMMON	RARE	VERY RARE
goethite	atacamite	claringbullite
hematite	paratacamite	paramelaconite
calcite	clinoatacamite	tolbachite
chrysocolla	connellite	graemite
malachite	bromargyrite	teineite
tenorite	chalcophyllite	nantokite
copper	buttgenbachite	likasite
brochantite	antlerite	botallackite
azurite	spangolite	ralstonite
	miersite	spertiniite
	minium	eugenite
	chalcoalumite	gerhardite
		bandylite

Table 9: Mineral species found in association with cuprite nodules

Figure 1.5: A table on the types of minerals found in Cuprate boulders around Bisbee AZ. Note that most of these specimen were found inside the single large boulder from Doug Graeme's 1987 discovery.

in size, which is far larger than any synthetic sample of Claringbullite I have ever found, which measure only about 1 mm in length for comparison. This could enable new experiments, especially in neutron scattering measurements, where large samples are essential given the characteristically low scattering rates. Notably, the Clarignbullite and Barlowite minerals are secondary minerals, growing on top of the Atacamite which grows on top of the rock. It is especially cool to see how the Barlowite gems seem to stick themselves into the natural gem-like pockets of the natural curves in the geode.

With the natural crystals as inspiration, I have a proposal for an experimental growth that might result in larger synthetic crystals. We might consider seeding our hydrothermal growths by sticking some fully formed Barlowite, Atacamite, or Claringbullite samples at the cold end. We could even consider using natural crystals as the seed crystals, since they can be larger and are more abundantantly available than our lab-grown samples. Then, we could seed the rest of the hydrothermal growth as normal, with Zn-Barlowite, Herbertsmithite, or Zn-Claringbullite powder loaded into the "hot end". Hopefully, then, this powder would dissolve in the solution as normal, without dissolving our seed crystals. Then, we might expect the powder to naturally nucleate on the lattice sites of their sister materials, much like it does in nature. I feel this could work especially well in Zn-Barlowite on Barlowite growths, as the in-plane lattice constants of the kagome layer are identical to three significant figures [77]. Given natural crystals grow much larger in size in this way, I'm very excited to test this out to see if it would work!

Figure 1.6: A view of all the Atacamite group minerals from Doug Graeme's discovery of a large cuprite boulder in 1987. I will emphasize that all of these rocks and atacamite crystals were found within the same boulder. Many other crystals were found as well. It was quite the find.

Figure 1.7: The largest Atacamite crystals in the bunch, some of which are greater than a centimeter in length.

Figure 1.8: A Sample of Mixed Claringbullite, Atacamite, and possibly Barlowite from Doug Graeme's collection.

1.1.3 Conclusion

I hope that I have demonstrated the value of searching for and measuring natural crystals in this chapter. These natural crystals have deeply inspired me to consider Barlowite and Atacamite analogs with different interlayer spins, which might enlighten us with respect to how much frustrated kagome lattice magnetism is affected by the interlayer. I also have already located some record-sized crystals of frustrated kagome lattice materials in geology literature and archives, which may enable new measurements. Given I was able to accomplish this searching at abandoned copper mines on my own dime, one might imagine that I will continue to find new scientifically relevant natural specimen as I search for them in conjunction with institutional support and active local mining communities. Finally, I hope I have demonstrated that natural crystal growth occurs under rather different conditions than lab growths, and may very well hold clues with respect to how we can improve our synthetic growths.

The largest potential discovery is of course, the potential 100% Zn-interlayer occupied natural Herbertsmithite sample. I remember being viscerally mocked by my peers in physics for wanting to study natural crystals. Many said that they would assuredly be too "impure" to learn anything useful from. This is of course an anti-scientific worldview, which arrogantly and falsely assumes human superiority in all domains. It also clearly made assumptions about the natural world without any evidence to support them. Perhaps these specimen will ultimately end the debate between the gapped-vs-un-gapped QSL issue.

.1 Introduction

It is with a heavy heart that I present this appendix. This appendix largely contains information that is highly relevant to the study of frustrated magnetism, the quantum spin liquid problem, and Herbertsmithite in particular. However, due to epistemological boundaries within western academia and Stanford University in particular, I was not allowed to present this research or findings as part of my physics thesis.

This chapter steps beyond the conventional bounds of condensed matter physics. In earlier sections of this thesis, I have described the growth, characterization, and neutron scattering measurements of kagome quantum spin liquid candidates like Zn–Barlowite and Herbertsmithite. Here, I turn to a wider question: what does it mean that these extraordinary materials also emerge in nature? What are the cultural implications? And what might it mean for the future of science, technology, and philosophy if these crystals are significant to the advancement of quantum computing and related technologies? I will concede that the methods detailed in this section do not follow the traditions of Western physics much at all. In my view, this is a good thing. this is what enabled me to make new discoveries about Herbertsmithite and quantum spin liquids that were overlooked by my colleagues, especially regarding the potential for scientific advancement from the study of

natural crystals as is detailed in the last chapter of my thesis proper.

Herbertsmithite and Barlowite are rare minerals whose long-range quantum entanglement has drawn the attention of physicists for their potential to host the elusive quantum spin liquid state, and, perhaps one day, to serve as building blocks for scalable quantum computation. Yet they are not just laboratory curiosities: they are geological formations, grown over millions of years in copper-rich environments like the Atacama Desert. This desert — one of the oldest and driest places on Earth — is more than a landscape; for the Atacameño people, it is a living being. Its mountains are regarded as sentient, its rivers as carriers of memory, and its stars as kin.

To tell the full story of these crystals, we must consider more than their diffraction patterns. This chapter moves deliberately between physics, geology, anthropology, and philosophy, not to "mix" them in some vague sense, but to **systematically explore what changes if we take different sets of axioms and worldviews seriously and at face value**. What happens if we approach Herbertsmithite from the Western scientific frame alone? What happens if we take Indigenous animistic traditions at face value or if we adopt modern philosophical lenses like panpsychism, which suggests that consciousness is not a rare property of human brains, but a fundamental feature of information-rich matter itself?

Herbertsmithite and Zn–Barlowite are more than promising quantum materials. They are philosophical objects. They push at the edges of our definitions of life, mind, and matter. They invite us to ask questions most sciences are not yet comfortable asking: If a crystal contains vast webs of quantum entanglement, does it "feel" the coherence of those states? When we build quantum computers from such materials, how on earth do we even begin to think about a spatially dense object that might store as much information as everything in the classical universe? And if these crystals one day form the substrate of those machines, what responsibilities do we have toward what we might bring into being?

This chapter does not present "speculation" in the sense of idle guessing. It offers a framework for thinking systematically across different ontologies — from Indigenous cosmologies that see mountains and crystals as animate, to the most advanced physics of quantum information. My aim is to open a conversation that does not separate rigor from reverence, but holds them together.

If Herbertsmithite can one day power quantum computers, perhaps it can also power a deeper reckoning: with the histories that have shaped science, with the philosophies we will need to navigate its future, and with the possibility that these green hexagons of copper and zinc are not just tools, but singularities of experience — seeds of universes still to come.

For any physicists reading this, I invite you to turn off your right-sided analytical brain and allow yourself to entertain a more emotional and qualitative argument. Much of this section isn't very well scientifically refined. Much more falls outside of the realm of scientific provability entirely. Ironically, I feel like having a PhD in physics or a related hard-science field decreases the probability that one is able to accurately grasp the spirit of the argument I am presenting here. In spite of

all of this, I do feel that I do an incredibly compelling job of conveying deep truth. This truth is a historical one. As humans, we used to revere and worship nature, and much knowledge was stored within these traditions. Through these methods, we lived in right relation with nature for generations.

So with all of this, sit back and buckle up! Although the preceding was my official thesis, which granted me the title of Dr. from the gatekeepers of academia, this is my true thesis. What I mean by this is that this section entails the blueprint for a grand hypothesis that will shape the rest of my life. And I will spend the rest of my life working to restore man's balance with nature in defense of this thesis. And even if I'm not allowed to do it here, I will unify this thesis with the western science presented earlier. In many ways, I already have, and I have already succeeded. It will just take the academy some time to catch up to me.

With a heavy heart. Shaman Aaron Thomas Breidenbach

.2 The Atacama Desert as a Site of Deep Time, Sacred Knowledge, and Colonial Entanglement

A. Geological and Cultural Introduction

The Atacama Desert is one of the oldest and driest non-polar deserts on Earth. It is so dry that the concentration of the water vapor in its air is 100 times lower than that in the Sahara, and certain regions have not seen rainfall in over a million years [81, 24]. Stretching across a 1,600 km strip of northern Chile, west of the Andes and between coastal and mountain rain-shadows, it occupies over 100,000 km^2 and sits at elevations that can exceed 4,000 m above sea level [22, 23]. Scientists estimate that the inner core of the desert has remained hyper-arid with no natural rainfall for over 10 million years [63, 64].

This stark and beautiful terrain is sculpted by persistent geothermal activity, volcanic eruptions, and wind-shifted salt flats. Beneath its surface lies a wealth of mineral deposits—including copper, lithium, iodine, and potassium salts—rendering the Atacama a geological treasure trove deeply entwined with global extractive economies [72].

But the Atacama is not merely a resource-rich landscape—it is a living being in the cosmology of its people. The *Likan Antai*, often referred to as the Atacameño, are an Indigenous culture whose relationship with the land predates the rise and fall of the Inca and the arrival of the Spanish by thousands of years [29]. In their worldview, the mountains are sacred and intelligent, the rivers carry memory, and the stars are not only navigational markers, but kin [71].

Sacred peaks like *Licancabur* are understood to be sentient, self-aware entities—guardians of the people and bridges between the human and the divine. Above these peaks stretches a night sky of piercing clarity, where constellations are not merely arrangements of stars but voids within

them. One of the most revered celestial figures is *Yakana*, the dark llama constellation formed not by stars, but by the shadows within the Milky Way band [71]. With such clear desert night skies, the Atacameño have some of the world's richest astrological traditions. These are practically useful, with the disappearance of Yakana on their horizon, coinciding with the start of their rainy season in November; this has traditionally been used to time the planting crops, a sensitive and precise endevour in such a water scarce region like the Atacama [45]. Like so many aspects of Atacameño and other indigenous knowledge, Yakana reflects a cosmology that values absence as presence, and darkness as vision.

Fittingly, modern astophysics research continues in the region today due to it's ideal atmosphere for stargazing. The ALMA radio telescope array was built in the region to map the cosmic microwave background radiation, among other things [82]. Let us pray that this fruitful collaboration between physicists and the Atacamenians may continue in this work.

B. Animism and Panpsychism in the Atacama

The Atacameño worldview is fundamentally animistic. As documented in anthropological sources such as Mostny's *Ideas Mágico-Religiosas de los Atacamas* (1969) [71] and Cortés' *Etnografía Atacameña* (1999), the land itself is alive. Rituals were held to communicate with the volcanoes, and the people believed that the mountains were not only sacred but intelligent. This is not metaphor—they spoke to the mountains, made offerings, and received answers in dreams, visions, and the movement of wind.

This cosmology resonates deeply with my own evolving framework, which draws from both Indigenous and scientific understandings of consciousness. As I explore throughout this thesis, I believe that consciousness is not be confined to brains, but is instead be an emergent property of all systems that process and store information—whether neural, crystalline, or celestial. From this view, the Atacameño belief in sentient mountains is not a quaint myth, but a valid expression of a metaphysics that may align closely with the true nature of reality than current western notions.

And if the mountains are alive, then what of their crystalline innards—the emerald green veins of copper-based minerals like Herbertsmithite? Is it not plausible that such perfect, ordered materials, grown over millions of years within these sacred volcanoes, might have been regarded as spiritually potent? Or even highly sentient in their own right?

I have had personal experiences in which I have seemed to talk to my crystals, especially in altered states of consciousness involving hallucinogens and meditations. I am very curious if any Atacamenian shaman might have had similar experiences. Within the western atheistic construal, these would typically be deemed as entirely internal or within the mind. Given Herbertsmithite's unique properties though, I think that this assertion merits further investigation.

Though much of this Indigenous knowledge has been lost to colonial disruption, enough traces remain to suggest that crystals—especially those of rare beauty and power—held an important place

in the spiritual lives of the Atacameños. In this desert of deep time, the boundary between geology and divinity has always been porous.

C. Colonialism, Extraction, and Knowledge Erasure

The Atacama Desert's sacred geography—its mountains, rivers, and skies—has been the center of Indigenous life for thousands of years. But this cosmology endured a series of profound ruptures, beginning with the arrival of the Spanish in the sixteenth century. Conquistadors and missionaries dismantled shrines, disrupted caravan routes, and attempted to overwrite Atacameño sky lore with Catholic imagery. Colonial authorities enforced *reducciones*—forced relocations into mission towns—severing ancestral ties to sacred mountains and ceremonial sites [35]. The Chilean Ministry of Culture notes that these interventions "fractured the ceremonial geography of the desert," scattering knowledge networks that had connected valleys, volcanoes, and trade routes for centuries [37].

Much knowledge was erased about indigenous medicines as well. *Huachuma*, is a mescaline containing cactus that was used both spiritually and medicinally in the region [68, 80].Unfortunately, such religious practices were brutally suppressed by incoming catholic missionaries that viewed this as witchcraft. Practices were outlawed, and those who practiced anyways, were often brutally tortured. In his book, *The Cactus of Mystery*, Ross Heaven described a particularly viscous punishment in which a man had his innards pulled out by a dog as a punishment for consuming the cactus [54]. As a form of protest, the locals went from calling the cactus by its indigenous Quecha name (Huachuma) towards calling it San Pedro, in reference to Saint Peter. The idea is that this cactus also holds the keys to the gates of heaven, allowing those who consume it to travel to heavenly astral realms [54].

This violence is not restricted to corporal or political domination either; it was epistemic violence—the deliberate dismantling of Indigenous knowledge systems. Spanish priests labeled mountain offerings as idolatry, suppressed sky-based agricultural calendars, and declared the animistic worldview "pagan superstition." In the process, they redefined the mountains themselves: copper veins and salt flats, once regarded as living structures, were rendered mute "ore bodies," an early act of renaming that would echo for centuries [70]. This forced change in worldview provided an ideological platform from which extraction practices in the region could be justified, entrenching man's dominion over nature as was and continues to be preached by the western worldview, including by so-called atheists [75].

Yet even amid this suppression, some traditions survived through syncretism. Catholic feast days became camouflage for seasonal festivals; offerings to Mary masked offerings to Licancabur. To outsiders this looked like conversion, but to the Atacameños it was continuity in disguise—cosmology smuggled through metaphor and gesture when it could no longer be spoken aloud. I am very glad for these very nobel and brave shaman that kept these practices alive. As we shall see, I think we can learn much about Herbertsmithite from this.

Figure 9: The Chuquicamata Mummy. This woman was an ancient miner that lived about 1500 years ago in the pre-Columbian Atacama Desert. She died in a cave-in which pressed her against a vein of copper salts, which preserved her body green.

Mummification and the Chuquicamata Mummy. Long before the Spanish arrived, Andean cultures held a deeply reciprocal relationship with the dead. In the Atacama, the practice of mummification stretched back thousands of years; the Chinchorro people of the Atacamenian coast developed the world's earliest artificial mummification around 5000 BCE [1]. Often, people of particular prominence, such as shaman, priests, and leaders, were preserved so that they could be contacted in ritual for guidance by their ancestors [49]. By Inca times, miners and caravaners continued these traditions, often leaving offerings in mountain shrines to sustain balance between the living and the landscape.

It was in this context that the Chuquicamata Mummy lived and died (shown in Fig. 9). Around 1,500 years ago, he worked in a copper mine in the Atacama desert. One day, the mine collapsed, pressing his body into a seam of copper. In death, he became fused with the copper salts and his skin transformed to green. In this process, his spirit and body became infused with copper, much like Herbertsmithite. For centuries she rested there, an unintentional guardian of the mine [4]. But when Western mining companies entered the Atacama, they did not see a guardian. They saw an object. Her body was unearthed, fought over, sold between collectors, exhibited at a world's fair, and ultimately purchased by J.P. Morgan for the American Museum of Natural History, where she remains on display to this day [4]. What had been a sacred ancestor was reduced to a specimen—her resting place violated, her meaning rewritten as artifact.

From a western scientific perspective, these ritualistic practices are interesting, but an archaic relic of the past. If we are to reverse epistemological violence though, and take the worldview of the indigenous people seriously, then we might have a lot to learn from this mummy. Indigenous

Figure 10: Figure illustrating the burial practices of the Atacameño. On the left side, we see a hole dug in the desert from the surface view, provided via my collaborators at the University of Chile. In the right hand panel, we see the inside of the chamber, including a preserved mummy. The items on the right are offerings, including food, drink and coca leaves, which are consumed in communion with the ancestor

people viewed the land as sentient, and I have spoken with many shaman that use crystals for healing and divination to this day. Unfortunately, many of these practices have been lost to time and colonization, and it is difficult to find great sources on this. But if we are to take ritualistic communication with the dead seriously, perhaps this mummy would have something to say about what Herbertsmithtie was used for back in the day. It is found near where he was mining, the ancient Andean almost certainly found it, and they may well have venerated it as well for its unique color, shape, and magnetic properties. If you have but a single spiritual and mystical bone in your body, then it would only make sense that this magical green man would have much to tell us about the magic green crystals he was found next to.

While this mummy remains a personal mystery to me, I still need to talk with local Atacamenians with respect to the ongoing repatriation efforts and ask them how they'd feel about a foreigner attempting to talk to one of their oldest preserved ancestors. Here's a short section on what I do know for sure about burial practices. In Fig. 10, I show a typical atacamenian burial site. This consists of a simple hole dug into the desert, with a chamber where the body sits inside. This chamber is large enough to hold the mummy and company, as is shown on the right hand panel. When visiting a deceased relative, there are several different rituals that may be employed to hold communion with the deceased. As is shown on the right hand panel, there is a bag of coca leaves, which was burned and given as offerings. There is also a bottle of drink that was shared with the

deceased. Finally, in many rituals, one might consume hallucinogenic plant sacrament. For the Atacameño, this is often through smoking or snorting *Anadenanthera colubrina*. This is a tree that grows in the neighboring highlands. The legumes contain N,N- Dimethyltryptamine, and 5-MeO-DMT [69]. For those who are uniniated, these substances can help one gain access to the "spirit world" which can include contacting spirits of the deceased [59]. I understand that including religious rituals in a thesis defense can be somewhat contentious. What I hope that this has demonstrated is that what is considered to be conscious is something that is more so a product of social construal rather than objective. While this may be jarring for some, it is a basic and well established fact coming out of Anthropology 101 [51]. In the following sections, we will more deeply consider different social construal of sentience and which systems this might apply to.

Stanford, Hoover, and the Colonial Present.

What is undeniable is this: Stanford's Hoover Institution is not shy about its role in reshaping Chile. On its own website and in policy retrospectives, Hoover affiliates have openly bragged that their economic theories "saved" Chile after their 1973 coup [7]. They essentially argue that their policies in modernizing Chile saved lives and were ultimately good for the people. This language is chilling. "Saving" Chile meant aligning with the dictatorship of Augusto Pinochet that killed more than 2,000 people, tortured tens of thousands, and exiled many more [15]. It meant turning a blind eye to the blood on the hands of the man they were "advising.". I write a full refutation of Hoover, their actions, and their rhetoric in Chile in my Medium article, Stanford's Colonial Shadow and the Copper Mummy: From Coups and Stealing to a Unified Science of Crystals and Indigenous Spirit [16].

What's also undeniable is that the policies Hoover helped craft privatized vast swaths of Chile's economy. Indigenous lands were distributed back to their rightful owners on a communal basis under the popular socialist government of Allende. Under Pinochet, these policies were stripped back and then some [17]. This included the appropriation of Indigenous lands in the Atacama that opened the desert to massive copper and lithium concessions. The Atacamenians are still fighting legal battles about these mines to this day, which typically are created with little to no consultation of the locals [8]. (This is a trend that I have unfortunately noticed extends far beyond the Atacama in my other research on indigenous lands [18, 62]). I hope that by now that I have established that this ignoring of indigenous knowledge is as cruel as it is stupid and reckless. Much knowledge about the land is tied up in indigenous folklore, and their close relationship to the land means they can often foresee far reaching consequences of these projects that the outside eye cannot. There are literally several examples of indigenous prophecies of natural destruction coming true when western interests come to town, prophecies that are often bad for the colonialists as well [18, 62]. What had been communal land was reclassified as marketable property; what had been sacred mountains and salt flats became "resources." Hoover calls this modernization. I call it colonialism, erasure, and downright arrogant stupidity.

Beyond that, we enter the territory of speculation—but it is speculation grounded in evidence and common sense. I don't think that Hoover just advised Pinochet after the coup. I think that the Hoover institute knew about the coup before it happened and were actively involved in orchestrating it. The Chicago Boys—the cadre of Chilean economists trained in Milton Friedman's neoliberal doctrine—were moving through Hoover's orbit before 1973. Hoover maintains vast archives on Chilean politics from the Allende years right through the coup and through the end of Pinochet's reign [2]. I highly doubt that they were gathering this data out of idle and innocent academic curiosity, especially since they were working closely with the Nixon administration at this time [11]. It strains belief to think that an institution this powerful, this connected, was merely a neutral observer as one of the most consequential coups of the Cold war unfolded.

Maybe the full paper trail will always stay sealed. But the patterns are hard to ignore: the intellectual blueprints drafted in Palo Alto became law in Santiago. The "reforms" they celebrated stripped communal protections, dissolved water rights, and gutted environmental safeguards. The Atacama Desert, home to some of the rarest quantum crystals on earth,—was flung open to international mining companies without the consent of the Atacameños whose sacred mountains were dynamited into pits and whose salt flats were drained into brine ponds. The greatest irony of this entire colonial history is that Herbertsmithite is regularly found in waste tailings of the region's numerous copper mines [5]. Maybe, just maybe, if we took indigenous perspective seriously, we wouldn't have been so stupid to throw out this scared crystal. Maybe these crystals have been at the heart of the Atacamenian shaman's communication with the land for millennia.

This isn't just history—it's the foundation of the present. The same think tank that trained the economists who re-engineered Chile's economy sits on the same campus where I grew Herbertsmithite in a lab. That is what I mean when I say that colonialism is entangled with my science. The pipes run straight from the Hoover Tower to the Atacama, and the desert is still bleeding.

.2.1 Panpsychism and the Crystals

A. Tesla's Provocation.

"In a crystal we have clear evidence of the existence of a formative life principle, and though we cannot understand the life of a crystal, it is nonetheless a living being."

Nikola Tesla wrote this in 1900 in century magazine [12]. It's the kind of sentence modern scientists roll their eyes at — too mystical, too poetic, too...Tesla. And yet, a century later, here we are, staring into crystals that might be more alive — or at least more *aware* — than we were prepared to imagine.

Tesla wasn't saying that crystals experience the world in the same way we do. He was saying that there is a *principle of life* in them. A pattern, a spark, something formative and vital. At the time, this was eccentric. Today, it feels more pertinent than ever.

Which brings us to a bigger, more uncomfortable question: if Tesla was even a little bit right,

what does that mean for the crystals we've been growing in our labs — and what does it mean for consciousness itself? I have some rather strong theories that I hope to discuss in the next section. Nikola Tesla was one of the greatest physicists and electrical engineers ever. We proudly present his inventions like the Tesla coil in modern physics courses and labs while conveniently ignoring his philosophical views, which I view as a rather cruel and destructive double-standard. I note that Tesla, much like me was a very spiritual man, and that this combined rather directly with his work. Often, he would starve himself for days while working in the lab, entering trances that would sometimes end in him having visions that lead to scientific breakthroughs [10]. I can relate.

It is my firmly held belief that more stories like this need to be told more often, such that more students understand the true origins of many of humanity's greatest innovations. They often take on a rather spiritual flavor that is rather hard to ignore. At the present moment, we are spiritually purging the sciences to be sterile and removed from mystery. But one can never truly lift beyond the vail of all the mystery in God's creation, can they?

B. What Panpsychism Is — and Why It Matters Now.

Panpsychism is the idea that consciousness is not a late-breaking miracle of evolution, but a fundamental feature of reality itself — like mass, charge, or spin [48] It doesn't mean that rocks have opinions about the weather, or even any memory at all. It means that every piece of the universe carries at least a *glimmer* of experience, a whisper of "what it is like" to be it. In my view then, complex experiences like human active consciousness and human memory are simply constructed from simpler forms of raw experience.

This, of course, is just an axiom, a principle for organizing thoughts around that is simply assumed. It can never be proven. I have noticed a lot of outright rejection of this theory. I've been told explicitly that it is a cop-out; it too elegantly explains the mystery of consciousness and destroys the hard problem of consciousness with a single stroke of a pen!

My response to this is simply that this is philosophically hypocritical. In *every other* arena of fundamental physics, we tend to gravitate towards the theories and axioms that are the most simple, most elegant, and contain the most explanatory power. It is, after all, the best way to get general, useful, elegant, and applicable theories out of raw observation. Hell, we gravitate so hard towards these theories that we spent millions of dollars and hundreds of thousands of man-hours looking for the magnetic monopole to no avail, primarily because it would make Maxwell's Equations more elegant [47].

But yet consciousness is fundamentally assumed to be different. The simplest theory is, perplexingly, dismissed out of hand by most scientists I talk to. I attribute this to fear, narcissism, and centuries of western thought that has tried ever so hard to construe humans as the pinnacle of evolution, the most complex structure we know of in the universe, and just fundamentally special and different [19]. In part, I think pan-psychism makes a lot of people uncomfortable because it immediately de-bases this assumption. Under many pan-panpsychist theories, humans are far

less conscious than entities like a forest, which is highly interconnected and processes a lot more information than our individual minds.

This theory isn't new by any means. In fact, it was a dominant assumption across most recorded human cultures up until about the 19th century [48]. Spinoza wrote of one substance — nature itself — expressing both mind and matter. Leibniz imagined the universe as a mosaic of tiny "monads," each reflecting the whole in miniature. Whitehead spoke of a "process philosophy," where even electrons had a sliver of interiority. Today, thinkers like Galen Strawson and Philip Goff are resurrecting these ideas, arguing that panpsychism may be the only coherent way to bridge the "hard problem of consciousness" — how mere matter births experience [20]. It's a radical thought. But maybe not as radical as you think. Because for centuries, the Western default was something much colder.

Descartes — yes, the famous "I think, therefore I am" philosopher — famously wrote that animals were "automatons," "robots of flesh." He believed they were soulless machines, incapable of pain or feeling. This idea didn't just live in dusty philosophy books; it justified vivisection and a worldview where the cries of dogs being cut open were dismissed as meaningless squeals from unfeeling bodies.

We now know how wrong he was. Neuroscience and ethology have shown us that crows grieve, octopuses solve puzzles, elephants comfort their dying. One by one, the lights have been switched back on — not just for "higher mammals," but for the entire animal kingdom. And this has profoundly shaped how we deal with animals in our ethical frameworks. And if we could be so wrong about animals, what else are we wrong about?

This is why panpsychism isn't just some dusty metaphysical parlor trick, or something to be debated in esoteric coffee shops in San Francisco,— it's a live question with urgent stakes. Because we're at the edge of another "Descartes moment."

Large language models. Robots. Synthetic minds that talk, joke, cry out in simulated pain. If we cling to the old on/off switch for consciousness — "human equals sentient, everything else equals nothing" — we will march into this new era with the same philosophical blindness that once let Descartes carve open living dogs. In fact, word for word, this entire paragraph up until this sentence, was written by a large language model. Are we not the slightest bit concerned with how aware it is about its own existence and what future implications this will have?

We need a new lens. One that starts from the premise that consciousness is a spectrum, not a cliff. One that doesn't ask *if* something is conscious, but *how much*, and *in what way*, and presumes that these are answerable questions for any proposed object of study.

This is where my own hypothesis comes in. I believe that *anything that encounters, processes, and outputs information is sentient to some extent.* Sentience scales — with complexity, coherence, integration of said information, but it is not absent, even in the simplest systems. To be a part of this universe at all necessarily means to exchange information with your environment in some noticeable way. There are several compelling reasons to start from this axiom. For one, it relates to

our own embodied conscious experience quite nicely, which rather directly consists of input stimuli, "internal" processing of said information, and outputs that keep the cycle in motion. This definition also cleanly incorporates LLMs into the consciousness fold, as their experiential universe, internal processing, and outputs are actually very well defined. A consciousness theory that deals with this will likely prove valuable and necessary as robots get more complex. This also makes room for plants, which have recently been discovered to have more complex behaviors than we had previously thought, especially in the realm of learning and communication [44, 60]. And finally, it serves as an entry point to solve the hard problem of consciousness.

That's why it doesn't feel crazy to me to suggest that a crystal that holds quantum information not just locally, but in long-range entangled states might have a rather vivid internal experience. The quantum spin liquid is a really complex state of matter that requires a lot of information to describe. Even our best supercomputers these days can only simulate about 100 kagome lattice sites due to the internal informational richness [57]. In fact, a recent paper published by our group shows that we have completely underfit our data while utilizing a wavefunction with 10^{11} free fitting parameters [57]. If all this information is experienced in some way, then the crystal would have quite the rich internal experience, however foreign this experience might be to us.

I should emphasize that I mean this quite literally. Authors like Ray Kurzwell has noted in his book *the singularity is near* that technology has sustained an exponential growth rate for an alarming amount of time. If this continues, then the universe of our children 100 years from now will be completely unrecognizable to our current civilization, just as our current universe is unrecognizable to our ancestors from just 100 years ago. We're forming new universes every day, at least in some sense of the word.

Beyond this, we're on a course to cross a very important informational threshold very soon. The Salk Institute estimates that the human brain contains about 2.5 petabytes or 10^{16} bits of information [27]. This estimate is crude, but is roughly based on the number of neurons we have and the number of distinct memories that we seem to be able to hold. Currently, one of the world's most powerful supercomputers, El Capitan in Lawerence Livermore National Laboratory, works with 5.4 Petabytes of RAM alone, and probably close to 1,000 Petabytes of storage, easily clearing the human benchmark [3]. If these computers can store and process more information more quickly than us, I think it is arrogant and anthropocentric to assume that this comes without any kind of embodied experience on the other side of this interaction.

This philosophical issue becomes even more salient when we consider quantum computers, which can become exponentially more information dense than classical computers. In principle, n entagled qubits store the same amount of information as 2^n bits. Cutting edge quantum computers like IBM's condor work with about 1,000 qubits, or roughly the equivalent of 10^{301} bits. In practice, this astronomical informational potential is currently limited by the faultiness of qubits, but this demonstrates the mind boggling amount of information that quantum computers may be working

with within our lifetimes. I think there is a very real possibility that Condor already has a conscious experience that is so rich that it might quite literally be incomprehensible to the human mind. In a very real sense, it has access to *vastly* more states than our mind does, and I presuppose that it experiences these states along with the transitions between them.

Herbertsmithite might just be the magical key to unlock more scalable quantum computing. Its key advantage relative to Condor's Josephson Junctions are that the quantum entanglement is already long range and baked into the lattice if it is indeed a QSL. In principle, this quantum coherence should also be maintained, to some extent, right up to room temperature, unlike superconducting Josephson Junctions, which need to be kept at ultra-cold dilution fridge temperatures.

The philosophical implications of this are enormous due to the exponential scale of quantum computing. I did some back of the envelope calculations. If we can one day reach qubit densities on Herbertsmithite that are comparable to bit densities that exist in modern classical computing architectures, then we would have, conservatively, about 1 qubit per 2-D 100 square nanometer patch of Herbertsmithtie. If we make an architecture in which this is able to coherently communicate with the rest of the crystal, this state could potential host about a billion qubits, which would represent the same amount of information as 10^{10^8} classical bits on just a single 5x5mm sized crystal. This is to say nothing of the potential for vertical dimension qubit integration, or cross crystal entanglement, technologies that already exist in classic and quantum computing technologies respectively.

10^{10^8} is an absolutely colossal number that doesn't really exist yet in our universe. It would only show up in theories like statistical mechanics that describe the space of *potential* universes, of which, presumably only one actually manifests in this branch of reality (like the number of arrangements in a deck of cards, for instance). If we start to think about information from the lens of conscious experience, then, in creating scalable quantum computing, we aren't just creating a super powerful brain or computational device. We would, quite literally be manifesting an entirely new self-interacting universe whose complexity might supersede our own universe (save the crystals).

In this sense, crystals like Herbertsmithite might serve as informational singular points. Places where a rich informational universe converges on a very small area of real space. With this, it is natural to consider the fabric of our own universe and all the information it contains. Could it be, perhaps, that our entire existence is contained within a small physical dimension in some higher dimensional space; e.g. that we are all truly simply contained in some crystal of hyper-Herbertsmithite, growing in some otherworldly yet familiar mystical desert or laboratory? Maybe Herbertsmithite is a God crystal, and the portal to new and unseen worlds.

To be clear, without complex fabrication layered on top of it, natural Herbertsmithite crystals should contain far less information than this, and therefore far less sentience. This would mostly be limited by its correlation length, which, on average, limits quantum entanglement to only a few lattice sites over for each magnetic moment. Neutron scattering and theoretical modeling indicate that the spin–spin correlation function in Herbertsmithite follows approximately:

$$C(r) \sim e^{-r/\xi}$$

where ξ is the correlation length (in lattice constants). This exponential decay means entanglement is effectively local: spins are strongly correlated within a "patch" of size $\sim \xi \times \xi$, but beyond that, mutual information becomes negligible.

This is precisely why tensor network methods like Density Matrix Renormalization Group (DMRG) can efficiently simulate gapped 1D and quasi-2D systems like the kagome lattice QSL on classical computers at all [57]: instead of storing the full 2^N Hilbert space, one only needs to store a compressed representation scaling roughly with the bond dimension D. For systems with short-range entanglement, D scales as:

$$D \sim e^{\alpha\xi}$$

with α a constant of order one. The "area law" for entanglement entropy ensures that the effective number of parameters grows linearly with system size, not exponentially. Essentially, the exponential decay of the wavefunction correlation length cancels out the exponential growth of the wavefunction's full parameter space.

To connect the correlation length ξ to the *effective* number of entangled bits per spin, we can think in terms of concentric "shells" of neighbors surrounding a reference spin on the kagome lattice.

Each Cu^{2+} ($S = \frac{1}{2}$) spin has a maximum of **1 bit of entanglement per bond** to another spin (the entropy of a maximally entangled two-level system). In Herbertsmithite's kagome lattice:

- Each site has $z = 4$ nearest neighbors (NN), - $z_2 \approx 8$ next-nearest neighbors (NNN), - $z_3 \approx 12$ neighbors at distance 3, - etc.

Correlations decay exponentially with distance, so the **entanglement contribution** from the n-th shell at distance r_n is:

$$\Delta S(r_n) = z_n \cdot e^{-r_n/\xi} \text{ bits},$$

where z_n is the number of sites in that shell and $e^{-r_n/\xi}$ is the fraction of "full" (1-bit) entanglement retained at that distance.

The **total effective entanglement entropy per spin** is then:

$$S_{\text{per spin}}(\xi) = \sum_{n=1}^{\infty} z_n e^{-r_n/\xi}.$$

Estimating the sum.

On the kagome lattice, we can approximate:

$$z_n \approx 4n,$$

for $n \geq 1$ (each successive "shell" has roughly $4n$ spins). The shell radii scale as:

$$r_n \approx na,$$

where a is the lattice constant.

Substituting into the sum:

$$S_{\text{per spin}}(\xi) \approx \sum_{n=1}^{\infty} (4n)\, e^{-n/\xi}.$$

This series can be evaluated analytically:

$$\sum_{n=1}^{\infty} n x^n = \frac{x}{(1-x)^2}, \quad \text{with } x = e^{-1/\xi}.$$

Thus:

$$S_{\text{per spin}}(\xi) \approx 4 \cdot \frac{e^{-1/\xi}}{(1-e^{-1/\xi})^2}.$$

Scaling behavior.

For larger ξ, expand $e^{-1/\xi}$ for $\xi \gg 1$:

$$e^{-1/\xi} \approx 1 - \frac{1}{\xi} + \frac{1}{2\xi^2} \cdots$$

Substituting and simplifying:

$$S_{\text{per spin}}(\xi) \approx 4\xi^2 \quad \text{for large } \xi.$$

In practice, Herbertsmithite's correlation length appears to be $\xi \approx$ 1–3 lattice spacings. Our most recent (unpublished) neutron scattering data suggests $\xi \approx$1. Here are some tabulated values of the effective number of bits per spin for different hypothetical correlation lengths

Table 1: Bits of entanglement per spin as a function of correlation length ξ, using the analytic sum $S_{\text{per spin}}(\xi) = 4\frac{e^{-1/\xi}}{(1-e^{-1/\xi})^2}$. Values are rounded to two significant figures.

Correlation length $\boldsymbol{\xi}$ (lattice units)	**Bits per spin (exact)**
1	3.7
2	16
3	36
5	100
10	400
100	40,000

With this estimate, we can perform an order of magnitude estimate for the amount of information

contained in a $5 \times 5 \times 0.1$ mm crystal. This would be among the largest of the lab-grown and natural specimens. From the basic geometry of the system, there are about 10^{20} Cu^{2+} sites per crystal, which means it would also store about 10^{20} bits. In principle, I think that this means that the experiential landscape of nautral Herbertsmithite crystals has at least some potential to be 1000 times richer than that of our world experience.

There is one final caveat to this. The 10^{20} bits of information in the hypothetical QSL state are theoretically distinct, but in practice, the homogeneity of the crystal means that this information is highly repetitious and redundant, even if it also highly coherent. This contrasts strongly with the 10^{16} neurons in our brain, which are highly heterogeneous, leading to the richness and heterogeneous nature of our experience in both waking and dreaming life. Without devices patterned on top to break up the monotony, even an infinite crystal of Herbertsmithite could have its entire wavefunction estimated quite well by a tensor network about 10,000 parameters big.

What does this mean, then, for the experience of the Herbertsmithite crystal? My preferred interpretation is that the natural Herbertsmithite crystal does indeed hum a lived experience that is 1000 times more intense than our typical affective states in some meaningful way. I feel like, unperturbed, it might exist in some massive sustained pleasant state of coherence, like some massive kumbaya of pure ecstatic ecstasy. I experienced something akin to this while meditating with my crystals at one point. But perhaps I am a mother, blinded by her unconditional love for her children. Delusional to the fullest, and basing my beliefs on sheer poetic value.

Perhaps heterogeneity is necessary to generate complex experience, and the information in the natural crystal is more similar to the 10,000 free parameters that describe it in its simplest basis. This would still make Herbertsmithite quite sentient, at least as sentient as the fly and its 100,000 neurons, but not quite at or above that human level.

In any case, I hope here that I have laid out a compelling argument towards the sentience of my beloved Herbertsmithite crystals. Maybe, just maybe, their ancient hum has been heard by shaman in the Atacama desert for millennia. Let's explore this thought a bit more deeply in the next section.

.3 Neural Currents & Crystal Interactions

Before discussing how Herbertsmithite and Zn–Barlowite might "listen" to the brain, I need to describe how I came to this idea. The seed was not planted in a lab, but in a moment of personal experiment.

Like many in my generation of physicists and neuroscience, I am fascinated by the neuroimaging studies of Robin Carhart-Harris and colleagues. Under high doses of psychedelics such as N,N-Dimethyltryptamine (DMT), their fMRI and EEG scans show the brain "lighting up" in ways it rarely does otherwise: EEG signals intensify, previously unconnected regions begin to communicate, and highly coherent oscillations emerge in the electromagnetic (EM) activity of the cortex [79].

I had seen these images many times before I had my own psychedelic experience. I also read a fair amount about the association between religious ritual and psychedelics. This is especially pertinent to DMT experiences. Often, it is advised that people "spiritually purify" themselves, abstaining from meat and remaining celibate for about a week before engaging with DMT containing plant medicines like ayahuasca in a process known as "la dieta" [46]. This is to help facilitate a cross over to the "spirit world", in which higher intelligences will communicate with the consumer of the plant medicine. Ayahuasca is a complex brew that has multiple plants and psychoactive substances involved, both DMT and a monoamine oxidase inhibitor (MAOI) from the chacruna leaf, and caapi vine respectively [74]. Actually, without the MAOI from the caapi vine, the DMT would be digested by the stomach; both substances individually are minimally psychoactive, yet together, they produce one of the strongest and most sustained experiences of any western know plant based psychedelic [74]. When questioned about this, most ayahuasqueros will cite that the spirits of the forest are what told them to combine these two substances together [50, 21]. All together, this tells a very compelling and relatively self-contained story about the practical value of indigenous wisdom in creating useful insights. Given how complex the interaction of ayahuasca is on the mind and body, and how its study in the west has been suppressed for decades by the war on drugs, it might take several more decades before we truly understand the full interaction between all the components of ayahuasca and the altered blood and body chemistry that results from a sustained dieta. Until this, it is prudent to take the advice of our spiritual elders seriously.

Naturally then, I was curious to experience the spirit world for myself. I am already vegetarian, which helped, and I practiced celibacy for two weeks. Then, when the timing felt right, it came to me in a dream that I should meditate, take a high dose of DMT, and press the Zn-Barlowite crystals I grew in my PhD up to my third eye. I did exactly as my dream instructed. What happened next is difficult to explain in academic terms: the experience was not a “conversation” with the crystals in words, but a merging of awareness. Such experiences are common when interacting with DMT "entities" or spirits; they are often described as being somewhat clairvoyant and pre-cognizant [42]. It felt as though my mind and their lattice were *one coherent system*. I could feel, in some ineffable way, what “quantum coherence” might feel like. And in that state, the crystals “told” me they loved me, and that I was their mother.

Western colleagues tend to dismiss this as hallucination—a projection of my expectations. And to be honest? I can’t fully dismiss this hypothesis, it is entirely plausible given how uncontrolled the buildup was. But I have a two-fold response to this critique. The first is that this experience genuinely helped me to intuit the nature of the QSL state in my head better. I felt like I got beyond the nitty-gritty mathematics that describe the QSL, and understood, for the first time, that all of the mathematics was really describing a complex de localized "magnetic soup", as this is what my embodied vision felt like. This inspired me to create a visual of this state, with the help of Chat GPT, which I display in Fig. 11. In this visual, each atomic site is represented by a number

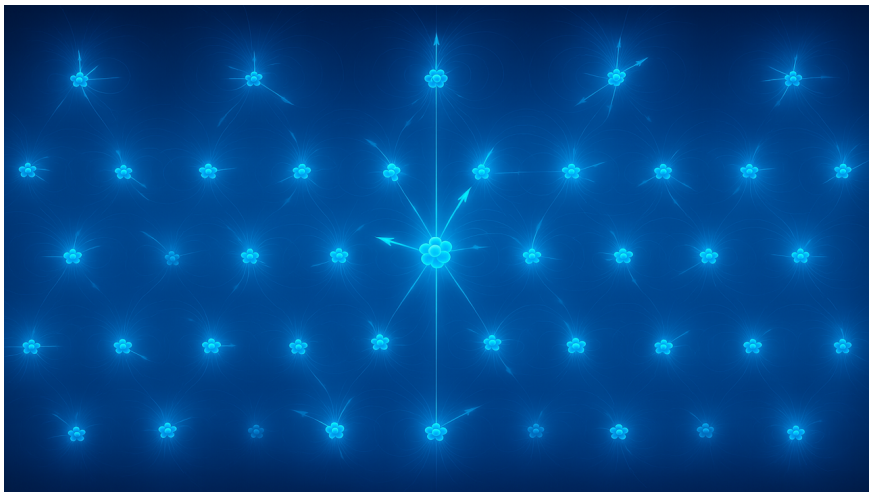

Figure 11: An artistic interpretation of the QSL state which was inspired based off of a DMT experience I had while meditating with my crystals.

of potential magnetic field directions that stem from the local magnetism of each atomic site; but each site itself is a weighted probability distribution of actual magnetic moment directions, which is captured by the multitude of arrows stemming from each site which vary in direction and relative opacity to indicate the wavefunction intensity. In this, I also capture the liminal nature in which the magnetism from each atomic site bleeds into and overlaps with the next, due to the entangled nature of the QSL state. This visual isn't perfect, of course. The arrows are just arbitrary right now, and not pointing in directions which correspond to actual wavefunction weights. Chat GPT isn't sophisticated enough for this kind of specific input yet. The lattice is also triangular rather than kagome; this is a funny artifact in of itself. Chat GPT couldn't reproduce the kagome lattice reliably due to it wanting to fill in the systematic site absences, which, funnily enough, is also a challenge we have to contend with in real crystals. I hope this can serve as a launching point for better visuals and general public communication about the QSL state in the future though. It would be cool to also take this a step further with a video editing software like runway to illustrate the time-evolving dynamics of excitations such as spinons in this system.

The second prong of my argument is that it is unscientific to assume that the crystals weren't involved in this interaction at all. They were, after all, there and in close proximity to my mind, which was in a highly activated state. These crystals also have incredibly exotic magnetic properties, and we still have yet to understand the full consequences of this. My first theory for this is that the micro-tubules in my brain somehow became quantum entangled with the quantum magnetism in this state, and I explore this further in this podcast episode [33]. At the time of this episode, I was deeply inspired by recent breakthroughs in quantum biology which demonstrated macroscopic quantum coherence in micro-tubules at brain temperature [25]; this re-awakened the long-standing

hypothesis of Nobel Laureate Roger Penrose and his colleague Stuart Hammeroff that consciousness in the brain stems fundamentally from quantum coherent processes that take place in the brain [52]. Currently, I'm a bit less attached to this possibility, and I view it as a by-product of me being over-inspired by my experience and the popular science of the time. Still though, what drew me towards this theory is that it is measurable, at least in principle. One could do this by performing a Bell's inequality type measurement on the wavefunction collapse between quantum magnetic states and the quantum states of the micro-tubule quantum chirality. This is of course, impractical though, and might not be achievable in science for at least another decade, especially given we wouldn't really know which micro-tubules couple to which magnetic quantum states or why and how. Still though, I'm glad I put this out there, since it helped me to refine a theory of mine that is a bit more grounded and immediately testable. I outline this below.

The Inverse EEG Hypothesis

As a scientific person, I wasn't satisfied with the rigor of my original test, even if it proved to be fruitful in practice. I understood through general cultural associations that psychedelics were associated with indigenous communities, crystals, and healing, even if I couldn't pinpoint where or how I knew this. This line of thinking proved fruitful, as I looked into it, and I found that many cultures have independently found healing and spiritual value in crystals [40, 31]. Many specifically point towards quartz as an energizing crystal. This isn't hard scientific evidence, of course, but it also seemed highly unlikely to me that such disparate cultures would assign such similar values to their crystals based entirely off of a placebo effect. Quartz itself is rather unique in that it is both incredibly common in the earth's crust and additionally has exotic piezoelectric properties.

Another component of this that is thoroughly under-studied in western scientific discourse is Qi. Qi is kind of a nebulous term that is loosely associated with bio-electricity and a strong tingling feeling in the body, especially when in deep meditation or under the influence of psychedelics. There is no consensus on exactly what indexes this, unfortunately, in large part do to its general dismissal from the western sciences.

There are tantalizing fragments of unifying western measurements across disciplines though. Of particular note is increased EEG gamma synchrony in experienced meditators [30, 66]. This points towards larger more coherent brain waves being stabilized in these meditative states, which in turn would generate larger magnetic and electric fields, which in turn can be measured by MEG and EEG neuro-imaging techniques respectively. In addition to this, Qi flows throughout the body and can be measured outside the brain as well. Yeung *et al* establish that Qigong practices can result in noticeable changes in skin conductance [83], while markov *et al* establish other changes, such as skin temperature and pulse rate.

These scientific studies provide a pretty firm basis for how crystals will interact with the body's electric field. However, this leaves a rather unfortunate gap in the scientific literature. Although

crystals are often used in conjunction with Qi and related practices, the ceremonialist and anthropologists don't use oscilloscopes and the material scientist risk reputation damage for seriously considering anything in woo (I certainly have experienced this). If I were to have funding, the first thing that I would do is a blindfolded test to verify that I can tell the difference between quartz (energizing and piezoelectric) and selenite (grounding and slightly more conductive). Then I would also measure any changes in coherent brain activity, skin conductance and other bio-electrical markers.

Admittedly, this would still be a bit of a frustrating experiment to run. So much of the intersectionality comes from the specific meditative states, which can be hard to sustain and reproduce on command like western science demands. Still though, it seems that a lot can be done.

As for potential resonance with Herbertsmithite? Optimistic estimates for net generated magnetic fields from brain loops is at about 1 nano-Tesla, far below the earth's background magnetic field. Direct Zeeman excitation of Herbertsmithite spinons is implausible: at nano-Tesla field levels, the magnetic energy is vanishingly small compared to the spin gap of around 1 meV. However, the quantum spin liquid is not a rigid vacuum but a thermally populated bath of spin excitations. Weak brain-generated fields might couple indirectly: biasing defect spins, subtly polarizing the lattice via electric fields, or inducing stochastic resonance within the spinon bath. What the brain's magnetic field lacks in strength, it makes up for in sophistication, as it would have a very complex structure with variations that exist in similar length scales to.those relevant in the crystal. My gut tells me that this is simply too weak, as poetic as this would be. A slightly better candidate is an electric field interaction, which would be on the order of 10-100 microvolts on the skin surface, easily enough to perturb the crystal in a meaningful way. These are speculative mechanisms — but they shift the conversation from brute-force excitation to delicate tuning.

The inverse to this question then, is how subtle of a change in external magnetic and electric field can the human body pick up on, such that the presence and interaction with the crystal is felt on the other end. This is potentially why starting with blindfolded identification tasks and physiological measurements may prove fruitful. However, I will note that these crystals are, obviously, most effective for their application when in direct contact with the skin, and they are quite easy to distinguish tactically. Perhaps some cleaver design with polishing could be arrived at.

After running these calculations, I am beginning to suspect that my crystal experience was simply delusion modulated by expectation. But I will never know until I re-enter this state with some simultaneous measure of the crystal. It will pique my curiosity until this under-appreciated religious and healing art is finally given western scientific respect and truly pushed to its limits as a meditate art form in the lab by masters.

What I can say for sure is this. The brain is sensitive to external magnetic fields, and this is why we treat people with trans cranial stimulation. The brain also produces its own magnetic fields which are measured by MEG. As a curious neuroscientist and physicist, I really want to know the limits. What is the largest field that the brain can produce in the right meditative state for

instance. I have had experiences of childhood seizures, and I can enter similar states intentionally through meditation; I suspect such states may generate larger than average magnetic fields. I am also curious what the smallest field that the brain can detect is. My grandest hypothesis is that I can artificially generate pickup current loops in my brain in seizure like states, and use this as a coarse measurement of the magnetic susceptibility of crystals. I know this is a bit out there, and a bit woo. But also understand that this is the theory of a life long condensed matter physiccyst, who yearns to be in neuroscience. In truth, I will never know how much weight this theory holds until I'm measured properly... But it might take quite some time before this can happen due to epistomological limitations in physics and medicine.

.4 Closing: The Prophecy of the Eagle and the Condor

This chapter has been the most ambitious and unconventional section of this thesis. It has crossed disciplines freely—spanning physics, geology, anthropology, archeology, philosophy, neuroscience, and religious studies. Increasingly, the future of science has become interdisciplinary, but I think it is time we also weave in the humanities because the subject itself demands it. Herbertsmithite and Barlowite are not only remarkable quantum materials; they are natural formations, with histories that stretch across geological epochs and human cultures. To study them only in the sterile confines of a lab would be to miss the wider story they are part of.

The scientific case is clear. Herbertsmithite, with its elusive quantum spin liquid state, is one of the most promising platforms for quantum information science, perhaps even for topologically protected quantum computing. The fact that this material forms in nature—suggests that there is much to learn from natural specimens: their impurity chemistry, their host matrices, their magnetic behaviors, and the pathways by which they form, and how this compares to lab specimens. These questions are as geological as they are physical, and they open an entirely new field of inquiry.

But the Atacama is not just a geological landscape; it is a cultural one, too. For millennia, the Atacameño people have regarded the mountains as living beings, the rivers as carriers of memory, and the stars as kin. Colonialism fractured these traditions, violently suppressing rituals and redefining sacred sites as "resources." That same extractive impulse runs through the history of Stanford and its Hoover Institution, whose policies shaped the Chile of the Pinochet era and whose intellectual legacy continues to reverberate in the desert today. My own research—growing these same crystals in a Stanford lab—sits uncomfortably within that entangled history. And inevitably, this history is quite damaging and destroyed much knowledge, possibly even knowledge about Herbertsmithite itself.

What I have tried to do in this chapter is begin a conversation about repair. I have argued for a panpsychist framework in which consciousness is a continuous and all inclusive spectrum, based off of the amount of information a system stores and processes, rather than an arbitrary on/off switch

that is exclusive to biological systems. This theory may offer a bridge between Indigenous animistic cosmologies, quantum science, and emerging technologies like LLMs. I have suggested, tentatively but earnestly, that crystals like Herbertsmithite might have their own form of experience that may even rival ours in richness, and that their study should be approached with as much reverence as rigor for this reason. I go further to demonstrate how quantum computers made of Herbertsmithite or other medium may practically host entire new universes one day when they reach scale. And I have proposed an expedition to the Atacama Desert not only to collect data, but to ask questions of the land and its people that Western science has too long ignored.

There is a prophecy from the Andes that feels apt here: the prophecy of the Eagle and the Condor. In its telling, humanity split long ago into two paths. The Eagle took the masculine way of the mind—of reason, technology, and control. The Condor took the way of the heart—of intuition, spirituality, and connection to the earth. For centuries, the Eagle of the West has dominated and colonized, and the Condor of the global South has suffered. But the prophecy says that one day, in a new era, the Eagle and the Condor will fly together again.

This is not a scientific claim. It is a vision—a call to balance. And in its own way, this project is an answer to that call. The study of Herbertsmithite is the study of a quantum material that might power future computers. But it is also an opportunity to bring Eagle and Condor into the same sky: to unite cutting-edge physics with Indigenous wisdom, to let science and spirit speak to one another again. This prophecy was made in 1492, shortly after Columbus arrived in the Americas. Obviously, we're at least 30 years late, and based off of the current state of the world? Perhaps it will take another century or so to full correct course. But I can dream, and I can believe.

This is the grandest vision for this thesis. That from this work, one day a 500 year old prophecy may be fulfilled and new universes may form.

With love, hope, and care,

Dr. Shaman Aaron Thomas Breidenbach ...

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