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Investigation of Metalbending in the Avatar Universe and Proposals for Its Geological, Chemical, and Material Based Mechanisms of Action

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Abstract

In the universe of *Avatar: The Last Airbender*, the established explanation for earthbending of processed metals (so-called "metalbending") is inconsistent with depictions in canon sources and does not provide a rationale that adequately describes many of the discipline's abilities and limitations. This work endeavors to uncover mechanisms which are consistent with canon depictions and lore as well as established scientific fact. Metalbending is most likely enabled by the presence of metal oxides or other ceramic impurities either within a processed metal or on the surface. This reasonably explains the inability for sufficiently pure samples of precious metals to be bent, while simultaneously explaining the bendability of other metals regardless of sample purity. It is also likely that sample homogeneity plays a role in the ease of manipulation. As samples become more heterogenous on the macroscopic and structural level they become easier for earthbenders to manipulate. This assertion is consistent with observed material behaviors such as those involving metal meteorites and coal. Finally, the manipulation of chelated or aqueous metal ions is established to be possible. The difficulty of this manipulation may be directly correlated to an ion's hydrated radius in aqueous solution. The possibility for controlled manipulation of metal oxidation state in this case is also explored and is theorized to be possible for the Avatar.

Introduction

In the canon of *Avatar: The Last Airbender* and *Avatar: The Legend of Korra*, metalbending is a sub-discipline of earthbending developed by Toph Beifong in 100 AG.[1] For the following seventy years, this skill, long thought to be impossible, was refined and eventually passed along by the Beifong matriarch to countless students, where it became a—still rare—but well-known feat of earthbending.[2] It is popularly estimated that one in 100 earthbenders are naturally predisposed with the ability to metalbend.[3] The canon explanation for the phenomenon of metalbending states that earthbenders cannot bend pure metal and that the act of metalbending requires the sensing of impurities within the metal,

[1] Spaulding and O'Bryan, "The Earth King."
[2] Di Martino, Konietzko, and Yang, *The Promise*, Part One.
[3] Graham and Mattila, "Old Wounds."

which can themselves be bent.[4] This explanation raises many questions that focus on the very essence and definition of earthbending and, by extension, metalbending. At its heart, it creates the necessity for a geological, physical, or chemical rationale for what can and cannot be bent.

Another huge complication in the canon explanation arises from the fact that even the most capable metalbenders are unable to bend platinum.[5] Again, the canonical explanation is reliant on impurities within the metal being the target and active component in the act of bending. It states that, in the case of platinum, these impurities are not present because the metal is too pure and, as a result, it cannot be bent. This explanation lacks supporting evidence and is inconsistent with facts that can be deduced from canon sources. The remainder of this work will endeavor to provide a series of explanations for the observations and behavior of metalbending in canon sources and attempt to coalesce a coherent and consistent mechanism for the action of metalbending. It will present these theories in context, establish the predictions made by them, and discuss any limitations that currently exist in the models.

Discussion

Assessing the Facts

To begin the discussion of earthbending, it is first important to assess all of the facts which are presented by the canon source materials. As stated above, the ability to manipulate metal is possible courtesy of impurities in solid metal, and platinum is the one metal continuously singled out as being unbendable. It is not known for certain if other precious metals like gold or silver can be bent. There is some circumstantial evidence that bending gold may be possible; Kuvira is seen to crumple the Kyoshi Medal of Freedom, which appears to be made of gold.[6] However, the medal may have simply been a less precious core plated with gold and, as a result, this is not reliable evidence that gold can be bent. Another mention of possible gold bending originates in the teachings of Toph Beifong. During her years teaching metalbending at her academy, Toph on at least one occasion required students to practice metalbending on coins.[7] Earth Kingdom currency is composed of copper, silver, and gold pieces, but it again seems unlikely that these coins would be pure metal. Perhaps the most significant piece of evidence regarding gold's bendability is not explicitly stated and may instead be inferred from the metal's absence. If gold were unbendable—and is assumed to be more abundant than platinum—surely it would be the metal of choice to protect from bending for purely economical and logistical reasons. Instead, platinum is used widely for this purpose, implying that gold alone would not be sufficient to prevent bending. Again, this analysis requires many assumptions that complicate the theory. In reality, the abundance of gold and platinum in the earth's crust is almost identical, but gold

[4] Volpe, Di Martino, and Konietzko, "The Guru."
[5] Dos Santos and Ryu, Ki Hyun, "The Aftermath."
[6] Zwyer and Hendrick, "The Coronation."
[7] Di Martino, Konietzko, and Yang, *The Promise,* Part Two.

production has historically been much higher.[8] Gold is also an extremely soft metal when pure, which could explain why it is not used for these purposes.[9] At this point, if evidence directly from the canon is the only consideration, it remains unclear whether gold can be bent by even the most powerful metalbenders.

It is widely stated that metal obtained from meteorites is much easier to bend than refined metals. Suyin Beifong successfully taught many students including Avatar Korra to metalbend by beginning with metal meteorites.[10] This is a valuable piece of information due to the extensively documented composition and structure of metal meteorites.[11]

Other materials that are known to be bendable include metallic mercury, coal, and mineral crystals.[12] These all have important roles in defining the abilities and limitations of metalbending. As a liquid metal at room temperature, mercury is unique, and knowing that it is bendable may provide useful insight into the mechanisms at play. It is unclear whether mercury is relatively harder or easier to bend than more mundane processed metals. Coal bending is apparently a beginner or intermediate level earthbending form that has important implications considering coal's ancient biological origin and high carbon content. The carbon found in coal is technically organic, and regularly takes the form of large nonregular aromatic networks.[13] Even anthracite, the most heavily coalified form, is still considered organic. It does have a considerably reduced nitrogen, oxygen, and hydrogen content compared to early-stage coalification products, and is defined by a more aromatized structure, but remains a nonregular polymer distinct from inorganic carbon ceramics like graphite.[14] Curiously, coal bending is the only confirmed occasion on which manipulation of organic carbon is observed. It is believed that in general only inorganic carbon is bendable, yet for some reason, coal is an exception to this rule.

As with coal bending, crystal bending will be pertinent to later discussion. The practice of crystalbending is considerably rarer than garden variety earthbending but is still assumed to be significantly easier than metalbending. Little is known about the crystals seen being bent, and although there appear to be at least two distinct varieties, even this is unclear. The first is seen in the Crystal Catacombs of Ba Sing Se, and there is little information regarding its composition besides apparent phosphorescence (or luminescence) and its pale green color.[15] Due to the similarity in appearance (Figure 1), there is a possibility that these catacomb crystals are in fact jennamite, the other mineral crystal which is observed to be bendable.[16] For further

[8] Haynes, *CRC Handbook of Chemistry and Physics, 97th ed.*; Barbalace, "Periodic Table of Elements." EnvironmentalChemistry.Com.
[9] Samsonov, "Mechanical Properties of the Elements."
[10] Graham and Mattila, "Old Wounds."
[11] Wasson, *Meteorites*.
[12] Zwyer, Hendrick, and Hamilton, "Venom of the Red Lotus"; Di Martino and Ehasz, "The Crossroads of Destiny"; Filoni and Hubbard, "Imprisioned."
[13] Malvadkar, Forbes, and McGurl, "Coal Resources, Formation Of."
[14] Orem and Finkelman, "9.8 - Coal Formation and Geochemistry."
[15] Di Martino and Ehasz, "The Crossroads of Destiny."
[16] Di Martino, *The Legend of Korra*, 2018.

speculation on the composition of jennamite, see Additional Information.

Defining Earthbending

Before any meaningful discussion may be had about the intricacies of earth- and metalbending, it is necessary to define what constitutes earthbending, and what an earthbender can manipulate. Using a geocentric definition to outline this problem is tempting, but that line of thinking is recursive and flawed. As is demonstrated by meteorite bending, a metal or mineral does not necessarily have to originate on Earth to be bendable. Not only does this mean that terrestrial origin is not a factor in defining bendability, but it implies a dependence on material identity instead of origin. This gives hope for a definition of bendable materials which is independent of the sample's place of origin.

While terrestrial origin of a material is not sufficient evidence to prove its bendability, it can be used to investigate what compounds or mixtures are likely to be bendable based on their ubiquity in commonly bent materials. Investigating what constitutes the rocks and earth being bent can reveal what chemical and mineralogical structures are likely to be bendable. For example, the majority of Earth's crust is composed of feldspars, silicon-based minerals also containing aluminum and oxygen.[17] In addition, it is known that the discipline of sandbending has traditionally been used by tribes in the Si Wong Desert for transportation, defense, and survival since at least 310 BG.[18] Desert sand is primarily silicon-based as well and is composed overwhelmingly of quartz grains with the chemical formula SiO_2, silicon dioxide. Quartz is the second most abundant mineral in the earth's crust.[19] This seems to indicate that silicon-based minerals are commonly bendable. Although this may not be a steadfast rule, it is a solid starting point.

Many metal oxides such as aluminum, calcium, magnesium, and iron oxide form a considerable amount of the material found in the Earth's crust as well (Figure 2).[20] Of these, iron oxide is particularly interesting. The iron oxide most often found in Earth's crust is in the form of ferric oxide, Fe_2O_3, and more rarely as ferrous oxide or magnetite (FeO and Fe_3O_4, respectively).[21] By weight, iron is the fourth most common element in the Earth's crust.[22] It seems fitting then that metal oxides in general could be bent by earthbenders. Although abundance alone is not a valid method of justification, the chemical and structural similarities to other bendable minerals and oxides seem to indicate that the possibility is indeed real.

These compounds, as well as the majority of other materials observed to be bent can be defined as ceramics. In the field of materials science, a ceramic is a crystalline or amorphous network solid with ionic or covalent bonds that contains a metal or metalloid. The properties of ceramics can vary greatly, but minerals, inorganic

[17] Rudnick and Gao, "3.01 - Composition of the Continental Crust."

[18] Yee and Di Martino, *Avatar, The Last Airbender*.

[19] Anderson and Anderson, *Geomorphology*.

[20] Rudnick and Gao, "3.01 - Composition of the Continental Crust."

[21] Greenwood et al., *Chemistry of the Elements*.

[22] Morgan and Anders, "Chemical Composition of Earth, Venus, and Mercury."

crystals, and metal oxides would all be classified under this umbrella. The only common earthbending material which would not be defined as a ceramic is coal, due to its lack of a continuous covalent network. As a result, earthbenders can be thought of generally as ceramic benders, though obviously their abilities are not limited solely to this. Perhaps there is a component of earthbending which involves polymers like coal. In beginning to think about this question and the goal of defining earthbending, the complexity and difficulty in justifying and explaining metalbending may be perceived. In fact, it may be easier to explain the mechanism of metalbending due to its relatively small domain of materials compared to earthbending, which contains much more variety and depth to its observed action.

Debunking the Canon

With most of the pertinent facts collected, the process of examining the canon explanation for metalbending can begin. The "pieces of earth" referenced by canon sources clearly indicate that chemical impurities in the metal are the active component in bending. Though seemingly innocuous, this is a necessary term to explicitly define, as imperfections in the crystal structure of a metal may also be called "impurities" in certain fields of study. The similarity between the two is purely colloquial; only chemical impurities are referenced explicitly by the canon.

The canon explanation is adequate at rationalizing the ability for steels and other iron-carbon alloys to be bent. Steel is an iron alloy with a carbon content under 2%.[23] Bending of this alloy appears to be consistent with the canon explanation since inorganic carbon manipulation is predicted to be possible, and even most—if not all—earthbenders can easily bend coal. In the case of steel, the "pieces of earth" or "impurities" that metalbenders feel and manipulate are the inorganic carbon particles of the alloy. This satisfies the explanation and depiction of Toph's first time metalbending, assuming the cage she bent was made of steel or another iron-carbon alloy. She was able to sense the carbon particles in the alloy, then isolate and manipulate these (Figure 3). In sufficiently impure samples of metal, microscopic ceramic impurities like silicates, sulfides, and phosphates would fill the role of these carbon particles, enabling bending as well. This could explain why the "pieces of earth" explanation became commonplace; Toph had no experience bending other metals at this point and, as a result, generalized her experience with steel when describing metalbending as a whole.

The canon explanation quickly becomes nonsensical when other metals are examined. At its core, the reliance on platinum's purity as the standard for bending potential is flawed. Firstly, and most obviously, platinum is not inherently more or less pure than other processed metals, as its purity relies on the techniques with which it was produced. If purity is the sole defining characteristic that determines the bendability of a metal, why not simply produce—for example—high purity aluminum for a

[23] "Steel: Composition, Properties, Types, Grades, & Facts."

fraction of the cost of platinum?[24] Platinum is not miraculously easier to purify than any other given metal. Simply asserting that if a metal is pure it is immediately unbendable is inconsistent with the depiction of the abilities of metalbending in the world.

Even if purity was a determining factor in bendability, most of the platinum observed can be assumed to be alloyed. Pure platinum metal is fairly malleable and as such is unsuitable for use in supports and structurally integral components.[25] Most of the platinum metal seen in canon sources is part of heavy machinery or large structures which suggests that this platinum is alloyed with another metal, otherwise the machines would collapse under their own weight.[26] Alloying involves the combination of two different metals and, while this should still not permit bending on its own, seems to raise questions about the canon's overreliance on the purity of a metal. The canon explanation repeatedly states that the purity of platinum is the characteristic that determines its lack of bendability, so the fact that these presentations are not solely platinum indicates some level of inconsistency.

Furthermore, if purity is the sole defining characteristic of a metal's potential to be bent, mercury bending would likely be prohibited. Mercury is a metal that tends to be very pure once isolated since most solid contaminants are less dense than the metal and will float to and collect on the surface.[27] Other than these, the impurities detectable even in minute amounts in mercury are all other metals, with practically no organic, mineralogical, or otherwise solvated components.[28] This is categorically inconsistent with the notion that purity alone determines the potential for a metal to be bent.

Inadequacy of Existing Theories

When investigating the rules dictating metalbending, there are several tempting avenues to explore which are ultimately flawed in their justification or reasoning. First and foremost, one may be tempted to suggest that the abundance of a certain material in the Earth's crust determines its ability to be bent. While this is not a provably false claim, it provides a very geocentric definition to a question that requires a generalizable answer. It is also important to recall that terrestrial origin of a material is not required for it to be bendable. Relying on the composition of the planet as opposed to physical, structural, and chemical properties of the material makes the notion undesirable and unscientific. Doing so implies a philosophical reliance of bending capabilities on human concepts and definitions, which is unsuitable for this investigation and the subject as a whole.

Another initially attractive approach is to investigate the crystal structure of a material and search for any trend therein. While tempting on the surface, it quickly becomes apparent that this strategy is not a well-suited one for a multitude of reasons. In fact,

[24] Lindsay, "Very High Purity Aluminum."
[25] Lagowski, *Chemistry*.
[26] Ian and Hendrick, "Day of the Colossus."
[27] "Mercury (Metal): " Encyclopedia.Com.
[28] Cherrier and Nalbantoglu, "Determination of Trace Impurities in Mercury and Some High Purity Acids by Spark Source Mass Spectrometry"; Elliott and Wilkinson, "The Effect of Base-Metal Impurities on the Surface Tension of Mercury."

this explanation would only be adequate in investigating bending properties of regular crystalline minerals such as jennamite or quartz, as the vast majority of earth and metal observed to be bent are not regular in their crystalline structure.

The bulk of rock is an inhomogeneous mixture of aggregated mineral particles, and even highly processed metals are not uniform in their crystal structure.[29] Metals are comprised of grains (Figure 4) which can vary in size from a few micrometers to over a millimeter depending on the metal identity, purity, and methods of preparation, casting, and annealing.[30] The lack of a single crystalline structure in metals prohibits examination of the crystal structure as a primary source of physical properties. Grain size has a significant effect on material properties in refined metals and, beyond this, the physical properties of a metal vary a great deal based on its environment, even if the morphology remains unchanged.[31]

Since metalbending is ultimately a macroscopic physical process, perhaps investigating characteristics of a metal such as tensile strength and yield strength could net useful information? Again, this is a tempting and logical idea. If bending is a mechanical act that follows the same rules as conventional physical processes in the classical sense, the strength of a material should determine—at least in part—how difficult it is to bend.

When considering tensile and yield strengths of metals pertinent to the discussion, (Table 1) it is important to note that these strength figures are extremely generalized and will vary greatly based on the preparation, casting, and working of the metal in question. Tensile strength is the maximum tensional force a material is able to withstand before forming permanent local deformations and is likely the less important of the two for this consideration.[32] Yield strength is the point at which a material begins to exhibit plastic deformation.[33] This is more likely than tensile strength to be important in the alterations that commonly result from bending. As outlined in the table, platinum is a fairly malleable metal, on par with cast iron and much more malleable than steel—both of which are bent extensively. Even stronger platinum alloys only have yield points in the mid-200s MPa, whereas properly treated steels can possess strength figures in the 1000s of MPa.[34] If tensile or yield strength were an important factor in determining bendability, platinum should be one of the easier metals to manipulate. Thus, it can be concluded that, although material strength may or may not play a role in the difficulty with which a material can be bent, it definitely cannot be the sole determining factor in a metal's *ability* to be bent. There is obviously a remaining factor or set of factors that are much more influential in that regard.

[29] Cipriani, *The Encyclopedia of Rocks and Minerals*.
[30] E04 Committee, "ASTM E112-13, Test Methods for Determining Average Grain Size"; Res et al., *Grain Size in Cast Gold Alloys*.
[31] Wright, "Materials Science and Engineering. An Introduction, " 2d ed.

[32] "Tensile Strength: Definition, Unit, & Facts."
[33] Dieter, *Mechanical Metallurgy*.
[34] "The PGM Database"; "Online Materials Information Resource - MatWeb."

Proposal of New Theories

I. Oxidation and the Passive Layer Theory

To develop a new set of theories regarding natural rules which regulate metalbending and earthbending, it is important to search for any correlations between observations made and existing data. The most important observation of metalbending that requires explanation is platinum's inability to be bent. In attempting to define what makes platinum unique, there is one key characteristic that immediately stands out: Its inertness. Platinum is a remarkably unreactive metal, even relative to other precious metals such as gold. Although the reactivity series of elements is inconsistently defined and lacks standardization between sources, platinum is universally ranked as the least reactive metal.[35] For the purposes of this paper, the most important application of this information is that platinum will oxidize at a much lower rate than even gold or silver. Platinum oxide does exist and is used as a catalyst in many hydrogenation and dehydrogenation reactions.[36] Despite this, the formation of natural platinum oxide on metal is more complicated, and the line between bound and free oxygen molecules is often blurry.[37] It can only be formed reliably on solid platinum metal under close to atmospheric conditions if given a timescale on the order of hours to react.[38] By comparison, steel and iron will both begin to oxidize the moment they are exposed to oxygen, even at atmospheric pressure. Even aluminum, which notably resists corrosion, readily forms an oxide layer upon exposure to the atmosphere.[39]

Before proceeding further, it is necessary to define the requisite vocabulary. When referring to platinum, gold, and other metals and alloys, "oxidation" and "corrosion" cannot be used interchangeably. Many metals and alloys such as iron and steel oxidize and corrode, while others such as chromium and aluminum oxidize but are strikingly resistant to corrosion. Oxidation is a purely chemical transformation in which a metal undergoes a chemical reaction with an oxidizing species—most commonly oxygen gas in the atmosphere. Corrosion is the physical weakening and change in other properties which results from oxidation. Oxidation is a change at the chemical level, whereas corrosion is a macroscopic physical process that may or may not result from this chemical change depending on the system in question.

Corrosion prevention can commonly be achieved through the formation of a "passive layer" in a process called passivation.[40] The formation of a passive layer is a common technique employed in corrosion-resistant alloys. One common type of passivation relies on a naturally formed surface oxide layer to protect the pure metal underneath

[35] Greenwood et al., *Chemistry of the Elements*.
[36] Nishimura, *Handbook of Heterogeneous Catalytic Hydrogenation for Organic Synthesis*.
[37] McCabe, Wong, and Woo, "The Passivating Oxidation of Platinum."
[38] Fantauzzi et al., "Growth of Stable Surface Oxides on ^{111}Pt at Near-Ambient Pressures."
[39] Agarwala and Fort, "Nature of the Stable Oxide Layer Formed on an Aluminum Surface by Work Function Measurements."
[40] "Surface Passivation - an Overview," ScienceDirect Topics.

from reacting with the atmosphere (Figure 5). For platinum and gold, this passive layer is slow to form at normal atmospheric conditions, and even then is essentially limited to the outer layer of atoms exclusively.[41] As such it is extremely thin, generally on the order of one to three Angstroms regardless of oxygen pressure or temperature, and does not grow any larger under extended timescales.[42] This is compared to stainless steels, which almost immediately form passive layers between 10-30 Å, and aluminum, which will form an oxide layer of up to 50 Å.[43]

If metal oxides are able to be bent by metalbenders, which seems likely, then the "bending active" portion of a processed metal may simply be these oxides present on the surface. This would explain why platinum cannot be bent: Its passive layer of platinum oxide is simply too small or entirely nonexistent, and as such cannot be effectively utilized to bend the bulk metal. Definitive knowledge of gold's bendability would be useful in evaluating this theory; gold is another remarkably unreactive metal, only marginally more reactive than platinum. Although it does form oxides, there is currently evidence that this only occurs in appreciable quantities at atmospheric pressure and temperature when ozone is present.[44] As a result, even though gold is thought to have a passive layer, the bulk metal should most likely be unbendable according to this Passive Layer Theory due to its low thickness, much like platinum.[45] Silver oxidizes to a considerably higher degree than either gold or platinum, and as such should most likely be bendable.

It may seem logical to conflate this theory with the canon explanation criticized previously, however, there are many key differences. A small but meaningful distinction is that this layer of metal oxide is on the outside of the metal, rather than dispersed throughout. Due to this, it does not rely on metal purity as a defining factor in bendability. This is the main sticking point where the original explanation goes wrong. According to the canon, a slightly impure sample of platinum would be bendable while an extremely pure sample of iron would not. With this new explanation, even the purest sample of iron or copper or aluminum should be bendable by extremely gifted earthbenders due to its unavoidable oxide layer. This is more in line with the behavior and logic presented in canon sources. It successfully explains the phenomenon of both pure platinum and derived alloys being unbendable without relying solely on purity as an explanation. One noteworthy complication that arises from this theory is the implication of dependence on surface area to volume ratio if bending is thought to be described by traditional mechanics. Without a clear sampling of the relative difficulties inherent in bending samples of differing geometries, evaluating the validity of this prediction is impossible.

[41] Cuff, "Passivation Layer on Noble Metals."

[42] Fehlner, "Low Temperature Oxidation, the Role of Vitreous Oxides."

[43] Olsson and Landolt, "Passive Films on Stainless Steels - Chemistry, Structure and Growth."

[44] Cuff, "Passivation Layer on Noble Metals."

[45] Müller and Löw, "Passivity of Gold."

II. Dependence on Macroscopic and Microscopic Heterogeneity

One of the major shortcomings of the Passive Layer Theory in isolation is the lack of an explanation for the relative ease with which metal meteorites are bent. Even if there were high levels of silicates or other bendable impurities in these meteorites, that could not singlehandedly account for the superlative ease with which metal meteorites are able to be bent compared to steels and cast iron. In addition to the Passive Layer Theory, there must be other factors governing the act of metalbending. One theory which seems to adequately explain this phenomenon while also tying into existing knowledge about earthbending is that sample heterogeneity on both the atomic and macroscopic level reduces the difficulty of earthbending and metalbending. In other words, material identity determines if bending is possible, and the heterogeneity of a sample plays a role in how difficult the bending is. This proposal not only provides a rationale for the increased bendability of metal meteorites compared to other metals, but is also compatible with the Passive Layer Theory, and the two work in complement to fill in gaps that exist in isolation.

Metal meteorites are almost exclusively composed of a metal known as meteoric iron, an iron alloy which generally possesses a low cobalt content and a nickel content between 5% and 25% by mass.[46] Structurally speaking, they are extremely easy to recognize and classify thanks to distinctive Widmanstätten patterns in the metal (Figure 6). These well-defined phase boundaries in the bulk meteorite arise from the propensity for iron-nickel alloys to form different mineral phases depending on deposition conditions and cooling timescale, as well as the nickel content of the sample.[47] The different phases are most commonly the minerals kamacite and taenite, along with other trace minerals such as the sulfur-containing schreibersite and troilite.[48] These different phases can have dimensions ranging in size from under 200 μm to over 3.3 mm.[49] If sample heterogeneity is a parameter that affects bendability, then meteorites should certainly be easier to bend due to their extensive irregularity in crystalline and chemical structure; in this regard, they are similar to bulk earth and rocks.

Application of this theory may also aid in explaining the bendability of coal. As stated previously, coal bending is the sole occasion on which manipulation of organic carbon is observed. Coal is a polymer but is nonregular in its structure due to its biological origin.[50] It is possible that the irregularity in coal's structure explains its ability to be bent; it is much less uniform than most minerals and is considered a sedimentary rock by the ASTM.[51] This nonregularity of the polymer and lack of structural heterogeneity could explain coal's

[46] Wasson, *Meteorites*.

[47] Goldstein, Scott, and Chabot, "Iron Meteorites."
[48] Paneth, "The Discovery and Earliest Reproductions of the Widmanstätten Figures"; Burke, *Cosmic Debris*.
[49] Shirley and Fairbridge, *Encyclopedia of Planetary Sciences*.
[50] Chadwick, Highton, and Lindman, "6 - Coal Conversion Technologies."
[51] Malvadkar, Forbes, and McGurl, "Coal Resources, Formation of."

apparent ease of bending despite its organic nature.

In defining this theory, it is necessary to also define the notion of heterogeneity. In this case, both chemical heterogeneity as well as a compositional heterogeneity on the macroscopic level are important. Most generic earth and rocks as well as metal meteorites would be considered macroscopically heterogeneous since they are comprised of different minerals and grains compacted together. On the other hand, a material like glass would be considered homogenous compositionally, but heterogeneous on the level of chemical structure. A pure sample of silica glass is a silicon dioxide network solid which is not crystalline and has an amorphous nonregular crystal structure. It is all the same chemical formula, SiO_2, but there is no regular pattern with which the structure is repeated over in 3D space. If this heterogeneity theory is correct, the bending of a sample of pure silica glass would be expected to be easier than an equivalent sample of quartz even though the chemical composition is the same in both. Similar to silica glass, refined metals should be mostly homogenous compositionally but will not have an entirely regular crystal structure. There will be differences in the crystal structure and orientation of grains, but the metals will still be far more regular when compared to rocks or ores.

It is necessary to acknowledge that this theory is incomplete, and in fact, seems to be directly contradicted by the existence and depictions of crystalbending. On multiple occasions, earthbenders are seen manipulating what appear to be solid mineral crystals.[52] In these depictions, it appears that crystalbending is not significantly more difficult than generic earthbending, as Avatar Aang was able to manipulate crystals while still a novice earthbender. This is not at all consistent with the predictions made by the heterogeneity theory. Pure crystals are the ultimate standard in chemical and structural homogeneity, and thus would be predicted by the heterogeneity theory to be more difficult to bend. If they can be manipulated by earthbenders who do not seem overly skilled such as a novice Aang and Jargala Omo, then the heterogeneity theory conflicts with the facts as presented.[53] Currently, this discrepancy remains unresolved. Although unsatisfying, this working model is subject to change—as all theories are—and requires more refining before it is consistent with all the facts presented. At this point, there is simply not enough information to either explain the counterintuitive bendability of crystals or to refine the theory to allow for this behavior. Any number of other factors such as crystal composition, doping, or lattice structure could play a role, but without concrete proof and knowledge of the crystals' identity, these proposals will remain as speculation.

The two theories presented thus far are by no means mutually exclusive and can be applied in tandem to describe the behavior observed and recorded regarding metalbending. When considering the effect that heterogeneity has on bending characteristics, most of the distinctions made

[52] Di Martino and Ehasz, "The Crossroads of Destiny"; Lioi and O'Bryan, "The King of Omashu."
[53] Di Martino, *The Legend of Korra*, 2017.

regarding metals and alloys already cited would be relatively unaffected by the application of this new theory. Grain size in refined metals varies greatly based on small differences in the preparation and working of the sample but remains more or less consistent from metal to metal. Edge cases with excessively small or extremely large grains may—or may not—be significantly affected by the application of this theory; without a testable hypothesis it is not possible to weight the two theories and pinpoint an empirical point where one overtakes the other in importance. Even with these small caveats and unknown quanta, it is expected that the heterogeneity theory should not play a very important role in the distinctions between metals, but will have a much more pronounced effect when considering materials whose grains are more distinct in composition such as meteorites, or materials which are completely homogenous throughout, like crystals.

The two models presented can and should be applied in a complementary manner, where the impacts of passivation and oxidation are more important when used to define refined metalbending interactions and the homogeneity proposal is more applicable to explaining specific behavior observed in other materials such as meteorites. Although both are ideally generalizable and should be universally applicable, they are most useful when applied in the manner described which should adequately explain recorded phenomena and not conflict with each other while maintaining a simple enough model to be useful.

III. Regarding Aqueous and Chelated Metal Ions: The Mercury Problem

One remaining action of metalbending which is not addressed satisfactorily by application of either theory presented thus far is the ability for metalbenders to remove mercury from a person's body. Suyin Beifong and Avatar Korra are shown accomplishing this feat in 171 AG and 174 AG respectively, and it has implications that are unexpectedly complicating.[54] Unfortunately, many of the questions raised by and regarding this feat are unable to be answered without the ability to collect more information on the subject; there is simply not enough evidence regarding this incident or the bending of mercury as a whole presented in canon sources. As such, any hypotheses presented including those below must in part be manufactured of educated guesswork and will unavoidably leave gaps in their explanation.

When introduced to the circulatory system and other bodily tissues either via inhalation or absorption through the skin, metallic mercury is quickly oxidized to the considerably more soluble Hg^{2+} ion by enzymatic action.[55] Once dissolved within the body, the mercuric ion may be bound by any strong enough nucleophiles due to its small hydrostatic radius. One particular interaction that is responsible for much of the damage associated with mercury poisoning is the affinity of the ion for thiol groups and selenols, specifically those in the class of proteins known as thioredoxin

[54] Zwyer, Hendrick, and Hamilton, "Venom of the Red Lotus"; Heck and Mattila, "The Calling."
[55] "Toxicological Profile for Mercury."

reductases (TrxR).[56] The selenocysteine residue in TrxR lends the enzyme a significantly higher reactivity with its preferred substrates, but also induces a higher affinity for mercuric ions compared to thiols alone.[57] Through its binding to these residues (Figure 7), the mercuric ion inhibits TrxR, which is responsible for (among other things) the reduction of antioxidant molecules back into their active forms.[58] Without the continuous renewal of these antioxidant compounds, oxidative damage to cells is more prevalent. This damage is particularly concentrated in the brain, where oxygen consumption is high. The subsequent oxidative damage to the brain causes many of the neurological symptoms associated with mercury poisoning. Luckily for Avatar Korra, the sheer volume of mercury administered may have played a role in hindering its own absorption into the bloodstream, as a similar effect is known to occur when elemental mercury is administered intravenously.[59] This may have been a contributing factor that enabled her survival for a long enough time before emergency aid could be administered by Suyin.

Percutaneous absorption of metallic mercury is normally limited to a very slow rate.[60] As such, there is little in the way of scientific literature regarding high volume mercury administration through the skin. Without any conclusive scientific data on the matter, definitively predicting the behavior of the mercury is impossible; however, it is reasonable to assume that the quantity of mercury seen introduced to Korra's system could not possibly be totally oxidized and dissolved in a timescale under an hour.[61] This is important to note since it means that both metallic mercury and metal ions were present for Suyin's aid.

It is theorized that Suyin was only able to detect this unoxidized mercury metal, not the dissolved metal ions; in fact, the only person ever shown capable of this latter feat without tutoring was her mother, Toph.[62] If the mercury which Suyin was able to remove in 171 AG had not yet been oxidized and dissolved into Korra's bloodstream or chelated by any biomolecules, this means that any and all of the dissolved metal ions which had already been oxidized remained in the Avatar's body. Perplexingly, the sheer quantity of metal which remained should have been effortless to detect for such a proficient metalbender even when dispersed throughout a volume as large as a body, yet neither Suyin nor Korra could detect the metal at any point in the next three years, even though the Avatar's body obviously still contained several kilograms of mercury ions. Thus, evidence seems to indicate that detecting—let alone bending—metal ions is extremely difficult, even in comparison to other feats in the already advanced school of metalbending.

Avatar Korra performed her own metalbending bioremediation in 174 AG

56 Carvalho et al., "Inhibition of the Human Thioredoxin System: A Molecular Mechanism of Mercury Toxicity."

57 Gromer et al., "Active Sites of Thioredoxin Reductases."

58 Linster and Schaftingen, "Vitamin C Biosynthesis, Recycling and Degradation in Mammals."

59 Clarkson and Magos, "The Toxicology of Mercury and Its Chemical Compounds."

60 Hursh et al., "Percutaneous Absorption of Mercury Vapor by Man."

61 Sigel and Sigel, *Metal Ions in Biological Systems*.

62 Heck and Mattila, "The Calling."

and, in the process, finally proved that aqueous and chelated metal ions can be bent by sufficiently strong metalbenders. Even if Suyin had left minute traces of metallic mercury behind in 171 AG it would all have been oxidized and dissolved within the body over the next 3 years, so all of the mercury removed in 174 AG certainly originated in the form of the mercuric ion. Though this manipulation of aqueous and chelated metal ions is apparently extremely difficult even for very skilled metalbenders it must be possible as demonstrated in this instance. Since Avatar Korra and Toph are the sole known practitioners, it seems that bending metal ions in solution or in one's body is a technique that approaches but does not equal or surpass the difficulty of plate tectonics manipulation, which is an Avatar level feat of earthbending.[63]

The implications of this ability are broad, far-reaching, and could likely fill a separate paper multiple times the size of this one. As of right now, the focus will be on gleaning any possible facts about the technique. It is possible that a metal ion's hydrostatic radius and the ease with which it is manipulated are inversely correlated. In aqueous solution, a larger hydrostatic radius makes ions significantly less mobile and, as a heavy metal, mercury ions have a much smaller hydrostatic radius than common metal ions like potassium, magnesium, and sodium.[64] This could explain why bending of these common biological ions is never observed; their large hydrated radii may impede or prohibit manipulation, and as a result this metalbending form may only be possible with heavier metal ions with smaller hydrostatic radii which are rarely present in biological systems or everyday life.

It is currently unclear how exactly the Avatar was able to remove the mercury from the chelated biomolecules but it appears that in the process she reduced it back to its oxidation state of 0, as the mercury removed from her body is clearly in its metallic unoxidized form (Figure 8). Normally, mercury ions can be converted back to their metallic form through oxidation-reduction reactions, but it is unclear what exact chemical process occurred during the mercury's removal from the Avatar. The only occasion on which any school of bending is seen to be capable of controlling electrochemical change is the firebending sub-school of lightningbending, which deals with ionization and movement of electrons within materials to induce charge separation.[65] If charge manipulation is a skill exclusive to firebenders, perhaps only the Avatar is capable of the observed reduction of mercury to its metallic form because of their ability to manipulate metal ions as well as ability in firebending. Even though Korra is not a lightningbender, she may still have been able to control the charge flow due to the small scale, and especially because it was within her own body. This prediction could be tested if Toph was seen extracting the metal from Korra's body. However, since she never actually removed the mercury, it cannot be determined whether she was capable of this conversion back to

[63] Di Martino, Konietzko, and Yang, *The Promise*, Part Three; MacMullan and O'Bryan, "Avatar Day."
[64] Tansel et al., "Significance of Hydrated Radius and Hydration Shells on Ionic Permeability during Nanofiltration in Dead End and Cross Flow Modes."
[65] Spaulding and Ehasz, "Bitter Work."

the metallic form or not. The physical and electrochemical implications of effectively becoming a human capacitor are most certainly outside the scope of this paper but may very well hold the key to explaining this phenomenon observed in Korra's mercury bending, assuming finely tuned control of charge manipulation is attainable.

If this interpretation of the mercury remediation events in 171 and 174 AG is correct and only extremely capable metalbenders can manipulate metal ions in solution, is it consistent with the already proposed theories? For the most part, the answer to this question is yes, but there are some areas of doubt involved. The Passive Layer Theory mainly details the necessity for a metal to be in an oxidized compound in order for it to be bendable, which the already oxidized mercury in the body would at least be arguably consistent with. The Passive Layer Theory does not make any predictions on the bendability of metal ions; its only major stipulation is that a metal must be part of an oxidized compound. In all technicality the mercury ions are consistent with this description; they are simply solvated or chelated as opposed to being confined in a solid lattice. However, the unoxidized metal Suyin removed initially from Korra in 171 AG as well as the metallic mercury which Korra herself removed in 174 AG would not be predicted to be bendable by the passive layer theory or any other mechanism discussed. This mercury should be elemental, and thus far it has been assumed that pure metals in oxidation state 0 are themselves unbendable and are only able to be manipulated by the actions of small amounts of oxides or other additives present.

Currently, there is no way to reconcile these two theories. That is not to say that one or both are wrong, there is simply such little information from which to draw that any number of factors could be responsible for the apparent bendability of the metal mercury. For instance, it could simply be caused by oxidized mercury species which are not dissolved in the blood or tissue but are instead still incorporated into the liquid metal. This solution has no immediate mechanism by which it may be rationalized, it is simply one of many hypotheses which could be posited to explain this lack of agreement. Forming more accurate or specific justifications for the apparent bendability of supposedly pure mercury would require the ability to experiment and gather new data. Perhaps liquid metal behaves differently and is for some reason more bendable than solid metal, even when lacking metal oxides or other bendable components. This proposition may hold slightly more proverbial water, as it could be justified using the predictions of the heterogeneity theory on the basis that liquid mercury lacks an ordered crystalline structure due to its liquid state of matter.

Conclusion

The investigation of earthbending and its sub-discipline of metalbending has revealed a set of theories which may be applied in discussion and analysis of metalbending abilities, and which are consistent and scientific in their application. First and foremost, most of the refined metals known to be bendable are able to be manipulated due to the unavoidable layer of oxidation which forms upon exposure to the atmosphere. The mechanism of action for metalbending pure metals and alloys involves the manipulation of this oxide layer. Platinum reacts slowly if at all with oxygen under atmospheric conditions and as a result is predicted by this theory to be unbendable if purified or slightly alloyed. Gold is similarly unreactive in the atmosphere and is hypothesized to be unbendable as well. Sample homogeneity also appears to play a role in the relative difficulty with which a material may be bent. Evidence indicates that samples which are more heterogenous on the structural and chemical level are easier for earthbenders to manipulate. Although it is unlikely to be a major factor with regards to bending refined metals, this theory can be applied in justification of the relative ease with which metal meteorites are observed to be acted upon in comparison. It is, however, notably inconsistent with depictions of crystalbending, a seemingly novice-level earthbending sub-discipline of a very homogenous material. Finally, it appears that the manipulation of metal ions either free in solution or chelated by ligands is possible, but only for the most advanced metalbenders. This technique is surrounded by uncertainty due to the infrequency of its use and scarcity of its practitioners but is evidenced to be possible all the same, and the ability may be inversely correlated to an ion's hydrated radius. Its application by Avatar Korra in the removal of mercury ions from her own body presents the discussion of a new Avatar level application of metalbending: control of oxidation and reduction of metals—at least in one's own body. These theories are for the most part consistent and may be applied without conflicting. The few areas in which they may lack agreement stem primarily from an absence of supporting information and should not be used in isolation to justify dismissing the validity of a component.

Additional Information

The following section is a collection of miscellaneous side notes and applications of research that do not necessarily fit in the scope of the main paper but are valuable to explore nonetheless. Some lack sufficient facts to yield any useful discussion and thus are not quite fitting for a paper of this type, and others require such a degree of expansion and elaboration that placing them in the same category as the theories which are the main focus of the paper would jeopardize the scope of an already long and sprawling document. While sources will continue to be cited, this section can be considered an extraneous portion of the paper which contains observations and questions which are not necessarily pertinent to the main discussion at hand but may be useful as appendices to it.

Jennamite is described as "rock candy" by King Bumi of Omashu and accordingly is usually inferred to be some sort of saccharine crystal.[66] Notably, it is never described this way again despite being depicted many times. Organic crystals are neither ceramic nor polymeric and thus, if this "candy" description is accurate, it would

[66] Lioi and O'Bryan, "The King of Omashu."

be the only occasion on which organic carbon is observed to be bendable outside of coal manipulation. This seems highly improbable and raises three distinct possibilities. In the unlikely case that the crystal really is composed of sugars, then it suggests organic compounds can be bent if in a crystalline phase. If the crystal is not made of sugars, this either casts doubt on the notoriously eccentric king's "rock candy" description, or indicates that the crystal is a relatively non-toxic inorganic salt or mineral which tastes sweet to humans.[67] Beyond these speculations, definitive elucidation of jennamite's composition is impossible.

One note which is useful to consider regarding mercury bending is that the Passive Layer Theory can be applied to the first time mercury is seen being bent. When Ghazan initially oversees the administration of mercury metal to Korra it is presented in an uncovered bowl.[68] Even in dry air and at room temperature, metallic mercury will dull as oxides are formed on its surface. This occurs regardless of purity and the oxides concentrate on the surface of the liquid due to surface tension.[69] This explanation becomes more difficult to apply to all the other times mercury is seen being manipulated, as on these occasions it is being freshly exposed to the atmosphere. In those cases, the oxidation implied to be present would be required to originate from another source such as trace mercury ions still unreduced back to their metallic state, or other bendable contamination from the body they are extracted from.

The mercury left in Korra's body after Suyin's initial aid would be expected to gradually be excreted over the next 3 years with a half-life of approximately 30 to 60 days.[70] Judging by these figures Korra's body should have already remediated practically 100% of the mercury that had been dissolved as the mercuric ion in her body. Even when assuming a half-life of 60 days, only 0.001% of the original ions should remain in her body after 1000 days. The mercury ions which were deposited in the brain have a very different story, however. Mercury remains in the brain for much longer, with an estimated half-life of up to 20 years.[71] Using this figure, approximately 91% of the mercury in Korra's brain would remain unremediated after 1000 days. Thus, when she bent the remainder of the metal out from her body in 174 AG, practically all of it should have come from her brain. Judging purely by the volume of mercury which was removed, it seems impossible for this to be true. That much mercury solely in Korra's brain would surely be fatal. This implies that somehow the process of mercury remediation and excretion from the body must have been slowed. Perhaps the subsequent paralysis which resulted from her poisoning impacted blood flow or other anatomical parameters that impeded the remediation of mercury from her body? Judging by Toph's bending motions during her attempt to extract the mercury herself, there seems to be a high

[67] Basbaum et al., *The Senses*.
[68] Zwyer, Hendrick, and Hamilton, "Venom of the Red Lotus."
[69] Elliott and Wilkinson, "The Effect of Base-Metal Impurities on the Surface Tension of Mercury."
[70] Park and Zheng, "Human Exposure and Health Effects of Inorganic and Elemental Mercury."
[71] Ibid.

amount of mercury remaining in Korra's legs—which were paralyzed for a time. This could be interpreted to lend support to this hypothesis.

It is difficult to write a paper of this nature without talking about platinum abundance in some way. On the surface, platinum appears to be much more abundant in the canon universe; Zaofu alone was protected by domes which likely contained more platinum than has been mined in the history of our earth.[72] Where did all this platinum come from? Simply stating that platinum is naturally more abundant in the canon universe may answer the question but is a vague and impossible to support hypothesis. There is another, more specific explanation that fits neatly into the history, geography, and lore of the Earth Kingdom. Zaofu is located fairly close to the Chin peninsula and Kyoshi island (Figure 9). In 270 BG, this was the site of Avatar Kyoshi's manipulation of plate tectonics to separate the island from the mainland.[73] There is evidence that most of the large platinum deposits in the earth's crust originated in the mantle due to platinum's siderophilicity which caused it to "sink" in the early stages of planetary formation.[74] It the author's theory that in the process of moving the continental plates, a large section of previously buried mantle was exposed in the Kyoshi Strait. This new mantle material—if rich in platinum—would have provided the raw material necessary for Zaofu's construction and would explain the city's proximity to the strait, as well as the apparent high abundance of platinum in the world.

Finally, this paper would be incomplete if it did not briefly mention the application of these theories to the mystery of Avatar Kyoshi and Lao Ge's long lives. Avatar Kyoshi's extremely long lifespan of 230 years is noteworthy and is shrouded in mystery. The sparse information regarding it is taught to her by Lao Ge, an earthbender who served as her spiritual mentor. In his teachings to Kyoshi, he states that:

> Aging is really just your body falling apart, on the smallest, most invisible levels, and neglecting to put itself back together. With the right mental focus, you could take an inventory of your own body and place each little piece that's not where it should be back into the correct order.[75]

This vague explanation of the aging process could be interpreted as a less scientific description of the process of oxidative damage to the body, which is a common theory regarding the causes of aging.[74] It hypothesizes that symptoms of aging are due largely to oxidative damage to an organism's cells and biomolecules which accumulates throughout an organism's lifetime. If this interpretation of Lao Ge's wisdom is accepted, it could be construed that control of the oxidation in one's own body as predicted from Korra's mercury bending is responsible at least in part for Kyoshi's long life. While this connection is

[72] Anderson, "How Much Platinum Is in the World?"; Di Martino, *The Legend of Korra*, 2015.
[73] MacMullan and O'Bryan, "Avatar Day."
[74] Richardson and Shirey, "Continental Mantle Signature of Bushveld Magmas and Coeval Diamonds"; Albarede, "Siderophile Elements"; Anderson, "Chemical Composition of the Mantle."

[75] Yee and Di Martino, *Avatar, The Last Airbender*.

tempting to make, the truth is most likely significantly more complicated than that. Firstly, it was hypothesized that an ability in firebending is required to achieve precise control of the charge flow required in oxidative control, and Lao Ge is an earthbender. Secondly, the assertion that oxidative damage to the body's macromolecules is the sole cause of age-related physiological changes is a bold assertion and one which is not supported by the bulk of scientific literature. Aging is a vastly complicated process that is nowhere close to being fully understood. It is the culmination of chemical and biological mistakes, dysfunctions, design limitations, and a host of yet undiscovered root causes that accumulate over the course of a lifetime.[76] It is simply not a process which may be simplified to this degree. Finally, neither Lao Ge nor Kyoshi were metalbenders, which eliminates the possibility of controlling the metals within the nervous system or in the active sites of proteins, which would presumably be an important part of monitoring and reversing oxidative damage to the body.

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[76] Mc Auley et al., "Modelling the Molecular Mechanisms of Aging."

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Figure 1: Shown is the catacomb crystal armor (top) utilized by Avatar Aang in the catacombs below Ba Sing Se and the covering of jennamite (bottom) that immobilized Sokka and Katara upon meeting King Bumi.

Figure 2: A sample of hematite, a common iron oxide mineral. Oxides of iron and other metals are extremely common constituents of minerals in all rock types.

Figure 3: When successfully metalbending for the first time, Toph was able to visualize the chemical impurities and/or carbon particles within the metal of the cage. Manipulation of these allowed her to bend the bulk metal.

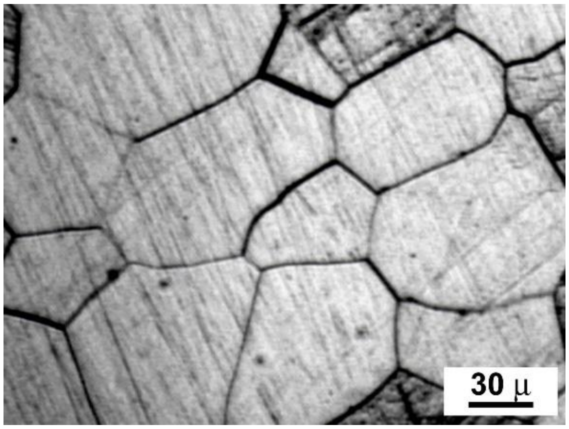

Figure 4: Micrograph of a quenched titanium wrought alloy after acid etching to accentuate grain boundaries. Clearly visible are the cross-sections of individual grains, each with a uniquely oriented crystal structure relative to one another.

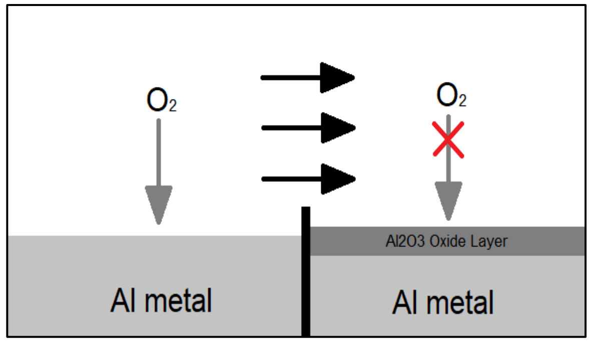

Figure 5: Diagram of the passivation process. In this case, the aluminum metal is protected from further oxidation by the barrier of aluminum oxide which forms from contact with oxygen in the air. Not every metal's oxide layer is passivating.

Figure 6: Etched cross-section of a metal meteorite found in Namibia displaying a fine Widmanstätten pattern. In this image the average phase width is 0.3 mm.

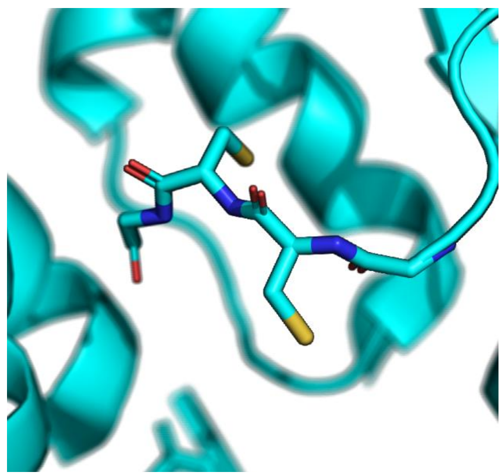

Figure 7: Section of the crystal structure for rat TrxR (PDB 1H6V) showing one of the conserved C-terminal Gly-Cys-SeCys-Gly sequences which are responsible for the binding of mercury. Figure generated with PyMOL.

Figure 8: The mercury that Korra removed from her body was reduced back to its elemental metallic form in the process. The volume suggests that around a kilogram of metal was removed. This amount should be a fraction of the total that was left behind in 171 AG.

Figure 9: Map of the Earth Kingdom overlaid with the relative locations of Zaofu (northeast point) and the Chin peninsula (southwest point). The proximity of the two is apparent. Original image used with permission of Reddit u/YellowPudding.

Tensile and Yield Strengths of Relevant Metals

Howatson, Lund, and Todd, "Engineering Tables and Data."

Metal	Tensile Strength (MPa)	Yield Strength (MPa)
Structural Steel	400-500	250
Cast Iron	200	150
Copper	220	70
Platinum	125-240	185

Table 1: Tensile and Yield Strengths of Relevant Metals.