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The Evolution of Mineral Hardness Reveals Both Changing Parageneses and Preservational Bias in the Mineralogical Record

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Abstract: A survey of the average Mohs hardness of minerals throughout Earth's history reveals a significant and systematic decrease from >6 in presolar grains to ~5 for Archean lithologies to <4 for Phanerozoic minerals. Two primary factors contribute to this temporal decrease in the average Mohs hardness. First, selective losses of softer minerals throughout billions of years of near-surface processing lead to preservational biases in the mineral record. Second, changes in the processes of mineral formation play a significant role because more ancient refractory stellar phases and primary igneous minerals of the Hadean/Archean Eon are intrinsically harder than more recently weathered products, especially following the Paleoproterozoic Great Oxidation Event and the production of Phanerozoic biominerals. Additionally, anthropogenic sampling biases resulting from the selective exploration and curation of the mineralogical record may be superimposed on these two factors.

Keywords: mineral evolution; Mohs hardness; preservational bias; anthropogenic bias

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1. Introduction

Biases arising both from differing preservation potentials and anthropogenic selection are inherent in the development and analysis of deep-time geodata resources. Consequently, a pervasive challenge in unravelling Earth's 4.567-billion-year-long evolution is teasing out legitimate historical trends from systematic natural- and human-induced distortions of the rock record. This concern may be especially relevant to understanding the history of Earth's evolving near-surface mineralogy.

Mineral evolution is the study of the changing diversity and distribution of minerals over more than 4.5 billion years of Earth's history [1–3]. Numerous studies have documented dramatic changes for minerals of varied chemical elements, for example, U [4], Hg [5], C [6], Be [7], Li [8], and P [9], as well as clay minerals [10] and igneous minerals [11]. These studies reveal both episodic mineralization associated with periods of supercontinent assembly (e.g., [12–15]) and systematic changes in oxidation states associated with Earth's evolving near-surface redox environment [16,17].

To what extent is this mineralogical record distorted by preservation and other biases? Are subsets of minerals selectively lost over time? Do these losses skew our interpretations? And is there any way to quantify such processes and, potentially, correct for them? In this study, we report one possible metric of systematic mineral loss—the variation of average mineral hardness throughout different stages of mineral evolution.

2. On the Nature of Biases in Deep-Time Data

Preservational and anthropogenic biases in the mineralogical record have received relatively minimal attention. However, important concepts and approaches have been devised by the paleobiological community, notably in their research on ancient ecosystems [18–23]. A brief survey of this paleobiological literature is, thus, informative. Every fossil ecosystem has "intrinsic and widespread missing data" [24]. Consequently, correcting the record for fossil species that are not preserved or underrepresented in collections remains a challenge for paleontologists, while providing lessons for deep-time studies of minerals.

The most obvious systematic losses occur with soft-bodied and/or microscopic fauna, which are only occasionally preserved, for example, in the so-called Lagerstätten, which include deposits with exceptional preservation that are most often found in fine-grained, anoxic sediments from the Cambrian and Jurassic Periods [25,26]. Soft-bodied organisms are best preserved through rapid burial, in situ mineralization (often via silicification, pyritization, or kerogenization), and "microbial sealing," which occurs commonly in anoxic environments and in the absence of bioturbation [27–30]. Such exceptional preservation of cellular- and even molecular-scale features provides high-resolution, though local, glimpses of ancient biodiversity.

Most fossil deposits display much more significant species loss compared to those of the Lagerstätten [31–33]. Field and laboratory studies reveal that selective losses result from several processes related to the nature of burial and lithification [20,34–36]. Shell preservation, in particular, depends on varied factors, including the rate of burial, local fluid chemistry, extent of disruptive environmental energy, and shell dissolution [37–39]. Additional biases may arise from differential surface exposures of fossil-bearing sedimentary lithologies [40,41].

In some instances, biases in fossil preservation are closely tied to mineralogy. For example, molluscs typically have calcium carbonate shells, which are made either of calcite or aragonite. Fossil assemblages from Paleozoic carbonate platforms often display the significant, preferential loss of aragonitic shells, thus resulting in the systematic underrepresentation of aragonite-based fauna [42–44]. This loss, which is amplified by burial in acidic, organic-rich sediments may vary with both depth and time, making corrections for preservational bias more challenging. Silicification typically provides a better picture of the proportional abundances of macrofauna; yet, it often fails to preserve microorganisms [35].

In addition to these inevitable physically and chemically induced losses in the fossil record, a number of potentially avoidable anthropogenic biases exist (e.g., [22,45], and the references therein). Among the many pitfalls that may contribute to non-random collections in the field are the tendency to avoid large and bulky specimens, the difficulty in extracting specimens from the hardest lithologies, and the challenge in identifying and collecting microscopic species [34,37,46–48]. All types of natural history collections may also be biased by geography: deposits near wealthier populated areas, especially in proximity to research institutions, are typically more extensively sampled [49–51]. Such potential sources of the bias may be compounded by curatorial decisions to retain and prepare only relatively complete specimens of convenient sizes.

Compared to paleontologists' extensive literature on biases in the fossil record, mineralogists have devoted relatively minimal attention to biases in the selective preservation and/or collection of minerals. Nevertheless, evidence exists for both preservational and anthropogenic biases in the mineral record. For example, the differential preservation of minerals may arise as a consequence of variable rates of erosion [52], sorting during dynamic sedimentation [53], selective dissolution [42], and the loss of metamict phases [54]. Mineral discoveries are shown to depend on the geography, population, economic development of the region, and general interest in the science linking positive anomalies during discoveries and explorations shown in publications of mineralogical encyclopedias and classifications [55].

Much of the research on preservational bias in the mineral record pertains to studies of the temporal distribution of zircon throughout Earth's history. Cawood and Hawkesworth [56] summarize the roles of tectonic processes in the selective formation and preservation of minerals during supercontinent assembly as "a process that encases the deposit within the assembled supercontinent and isolates it from subsequent removal and recycling at plate margins". The record of zircon ages over the past three billion years, documented via measurements of hundreds of thousands of individual grains, reveals five distinct pulses of zircon formation, each synchronous with an interval of supercontinent formation [56–60]. Cawood and Hawkesworth [56] conclude that the episodic zircon record arises via a combination of supercontinent assembly and removal via erosion and recycling: "The implication for mineral deposits is that those generated in near-surface environments in zones of active uplift have young mean ages".

This interpretation of the episodic zircon record is reinforced in studies of 100,000 detrital monazite grains, which display a strikingly similar age distribution to that of zircon over the past three Gya [61]. The authors conclude that "the detrital zircon record has been biased by the selective preservation of crust associated with the collisional assembly of supercontinents since 3000 Ma".

It should be noted that these mineralogical studies are not immune to anthropogenic biases. Dröllner et al. [62] demonstrate that handpicking zircon grains, which tends to favor a more brightly colored and euhedral population, adds a bias to detrital age signatures. Statistically significant differences between the handpicked and bulk-mounted age distributions are found; though, they are not so large an effect as to negate the findings of preservational biases in the ancient mineral record. Biases are also introduced in most museum and private mineral collections due to the factors of economic value, beauty, and rarity. Minerals with economic worth, such as concentrated ores or showy crystalline specimens, are far more likely to be collected and recorded in databases than are bland examples of scant commercial value, including most rock-forming minerals that collectively represent more than 99% of Earth's crustal volume [63,64]. At the same time, because most mineral species are rare, reported in fewer than five localities [65,66], mineral databases typically over-represent rarities that are volumetrically insignificant.

3. Results

The Evolution of Mineral Hardness

In this study, we consider the hypothesis that mineral hardness, as documented via the Mohs hardness scale, has the potential to elucidate one source of preservational bias: the selective loss of softer minerals over time. To test this hypothesis, we employed the Mineral Evolution Database, which records the ages of almost 200,000 mineral–locality pairs, representing 5788 localities with their associated metadata (MED [67]; https://rruff.info/evolution, accessed 21 March 2023). These data incorporate significant biases associated with geochronological surveys, notably the preferential focus on the ages of the ore deposits, as well as a focus on localities with anomalously large mineral diversity. Nevertheless, the MED includes a wide range of minerals spanning most of Earth's history and all stages of mineral evolution.

For each MED entry, we recorded the age and the Mohs hardness of that mineral species [68]. Furthermore, each mineral was assigned several attributes, such as paragenetic modes of its formation ([69]; their Table 1 and Table OM1), its mineral evolution stage [2], whether it can be formed by biotic or abiotic processes, and if it is hydrous or anhydrous. These attributes were used to separate the hydrous, anhydrous, and biotic minerals present in each stage of mineral evolution and to calculate their respective average Mohs hardness (Table 1).

Figure 1 plots Mohs hardness versus age for minerals in the MED, with dashed, dotted, and solid lines indicating averages for anhydrous, hydrous, and all of the minerals, respectively. In each of these three cases, we observe significant decreases in the average hardness of minerals over more than four billion years. The slopes of these lines represent 0.23 ± 0.03 hardness units per billion years.

Table 1. Average hardness of minerals versus stage of mineral evolution [a].

Stage	Age (Ga)	C	Hydrous	Biotic	All Minerals
0 Stellar minerals	>4.57	6.6	2.5		6.4
1 Chondrites	4.56	5.8	2.5		5.8
2 Achondrites	>4.56	5.2	2.8		4.9
3a Earliest Hadean crust	>4.0	5.1	4.3		4.8
3b Earliest hydrosphere	>4.0	4.0	3.5		3.8
4a Earliest continental crust	3.0	4.3	3.9		4.1
4b Evolved igneous rocks	<3.0	5.1	4.5		4.8
5 Plate tectonics	<3.0	5.7	4.4		4.8
6 Anoxic microbial	>2.5	4.4	-		4.4
7 Great oxidation event	<2.5	3.6	3.1	3.2	3.2
10a Terrestrial biosphere	<0.54	4.3	2.9	3.6	3.6
10b Anthropogenic	0.0	3.9	2.8	3.3	3.3

[a] Stages of mineral evolution from [1,2]; associated minerals from each stage are tabulated by Hazen and Morrison ([69]; their Table 1 and Table OM1).

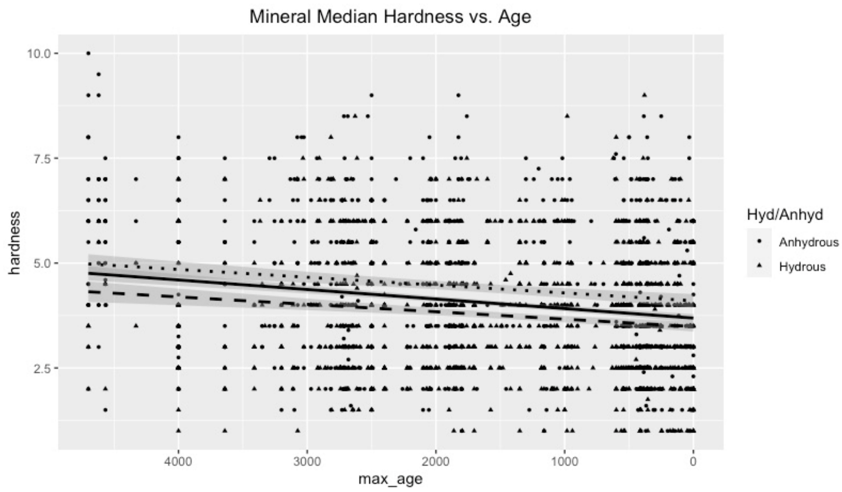

Figure 1. A graph of the average Mohs hardness of minerals versus their maximum known ages (in Ma) reveals a significant decrease in average mineral hardness over 4.5 billion years. Dashed, dotted, and solid lines indicate averages for anhydrous, hydrous, and all minerals, respectively. Hydrous minerals are systematically softer than are anhydrous minerals. Age data are from the Mineral Evolution Database [67], available at https://rruff.info/evolution (accessed on 8 March 2023). Hardness data are from [68].

A significant temporal decrease in the average Mohs hardness of the preserved minerals throughout Earth's history is particularly evident in comparisons of the primary and secondary minerals from the successive stages of mineral evolution [1,2], as recorded in Table 1. The earliest three mineral-forming intervals represent presolar stardust (Stage 0; >4.567 Ga), primary chondrite minerals (Stage 1; ~4.565 Ga), and achondrite minerals, and their alteration due to shock effects, as well as thermal and aqueous processes (Stage 2; >4.55 Ga), respectively. Stages 3a and 3b (>4 Ga) include the postulated earliest minerals of this terrestrial planet, both primary and secondary, without and with active hydrospheres, respectively. Stage 4a (~3 Ga) represents Earth's earliest continental crust, and Stage 4b (<3 Ga) demonstrates highly evolved igneous rocks, such as complex pegmatites and agpaitic lithologies, as well as their near-surface weathering products. Stage 5 (<3 Ga) focuses on varied minerals associated with plate tectonics, including a variety of volcanogenic deposits, massive sulfide ores, and regional metamorphic minerals. Stages 6 and 7 include minerals associated with anoxic (>2.5 Ga) and oxic (<2.5 Ga) microbial biospheres, respectively. Stage 10a (<540 Ma) represents minerals associated with Phanerozoic biomineralization and the terrestrial biosphere, while Stage 10b includes anthropogenic minerals from the past 2000 years.

The most obvious trend in Table 1 is that older mineral assemblages are systematically harder, on average, than are the younger assemblages. The earliest stellar and meteorite minerals average > 6.0 in terms of Mohs hardness, which is significantly greater than those of Precambrian minerals (average > 4.5) and Phanerozoic minerals (average < 3.5).

Systematic compositional and paragenetic trends are included in these changes ([70]; their Supplementary Table S1). For example, Table 1 reveals that the hydrous minerals from every stage are softer, on average, than are anhydrous minerals. Note that biogenic minerals from Stages 7, 10a, and 10b are intermediate in terms of hardness between anhydrous and hydrous minerals, with the average values being identical to the average for all the minerals in those stages. Hazen et al. [70] also record that the hardnesses of minerals formed by ephemeral near-surface processes, such as evaporation (average Mohs hardness = 3.7), volcanic fumaroles (3.2), soils (3.8), plant decay (3.2), guano (2.7), and secondary minerals associated with anthropogenic mining (3.2), are systematically softer than are igneous (ultramafic/mafic = 5.5; granitic = 5.7; alkaline = 5.5) and metamorphic (contact = 5.2; regional = 6.1; high pressure = 5.5) lithologies.

The details of mineral hardness are revealed in violin plots (Figures 2 and 3A,B), which underscore and amplify the findings of Table 1. In particular, these plots point to significant trends in the distribution of the mineral hardness values during different stages of mineral evolution. For example, while all stages of mineral evolution display a range of hardness, the earlier stages (0, 1, 2, and 3a) are strongly skewed towards minerals with greater hardness, i.e., the majority of minerals in these group are significantly harder than the midpoint value of the violin figure. By contrast, the most recent stages (6, 7, and 10), which are all biomineralized, are significantly skewed toward being less hard; the majority of these minerals are significantly softer than the plots' midpoints. We suggest that these trends point to systematic losses of softer minerals in older deposits. In addition, these differences create a strong visual impression of decreasing average hardness versus age in Figures 2 and 3A. However, Figure 3B, which represents hydrous minerals in Stages 2 through 10, reveals a relatively uniform average Mohs hardness from ~3 to 4. We conclude that hydrous minerals have been consistently softer than anhydrous minerals on average throughout Earth's history.

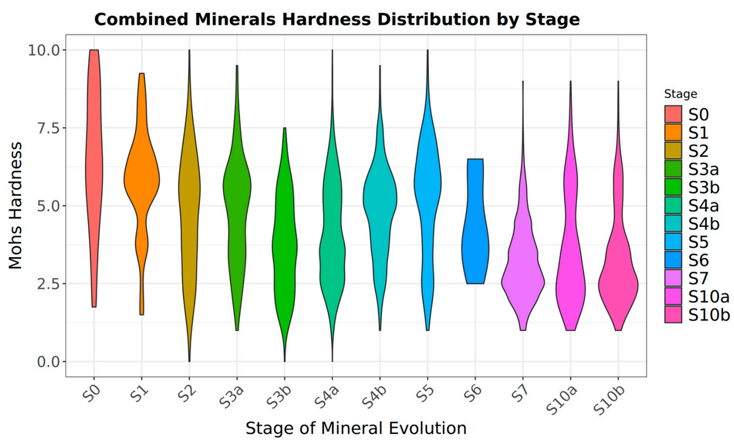

Figure 2. A violin plot of the Mohs hardness of all minerals versus stage of mineral evolution. Each violin figure is truncated at the top and bottom because individual extreme values are not plotted. This effect is more pronounced in Stage 6 because of the small sample size. Stages of mineral evolution from [1,2]; associated minerals from each stage are tabulated by Hazen and Morrison ([69]; their Table 1 and Table OM1).

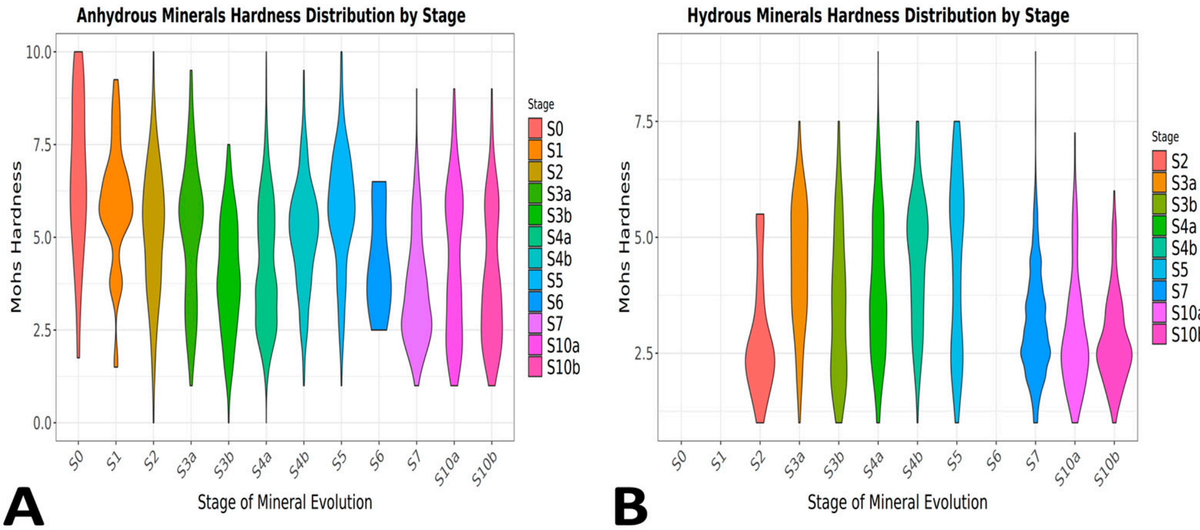

Figure 3. Violin plots of the Mohs hardness of (**A**) anhydrous minerals and (**B**) hydrous minerals versus stage of mineral evolution. Anhydrous minerals display a significant decrease in average hardness with stage of mineral evolution. Hydrous minerals are on average significantly softer than are anhydrous minerals from the same stage, but they do not show the same degree of systematic variation as the stages increase. Stages of mineral evolution from [1,2]; associated minerals from each stage are tabulated by Hazen and Morrison ([69]; their Table 1 and Table OM1).

4. Discussion

The results of this study suggest that a complex combination of preservational and paragenetic factors contribute to the observed decrease in the average hardness of minerals throughout time. On the one hand, the changing modes of mineral formation throughout Earth's history are important factors [69,70]. Pre-terrestrial, high-temperature refractory phases of Stages 0 and 1 (average Mohs hardness > 6) are inherently harder on average than are the minerals formed during the Archean and Proterozoic Eons (~5), which are in turn harder, on average, than are the biogenic minerals of the Phanerozoic Eon (<4). In addition, formation modes that produce hydrous phases, such as aqueous alteration and near-surface weathering, result in minerals that are, on average, more than one point softer on the Mohs scale than are those that underwent anhydrous processes; this is a finding that echoes the distinctive crystal chemistry of many hydrogen-bearing minerals [71]. Minerals formed by life (Stages 6–10) tend to be less hard than are minerals formed abiotically. We speculate that the relative softness of biogenic minerals might reflect a selection pressure to create minerals that are easily weathered, promoting the recycling of key inorganic nutrients in the biosphere.

On the other hand, paragenesis alone cannot explain the significant temporal changes in observed average mineral hardness over the past 4.5 billion years. The shapes of the violin plots in Figures 2 and 3, with systematic downward shifts in the positions of bulges at younger ages, suggest that softer minerals have been selectively lost from older formations.

Future studies of preservational bias in the mineral record should also focus on solubility and other factors influencing mineral stability [72]. For example, Royce et al. [73] estimate that more than 10% of specimens in museum collections are susceptible to alteration due to temperature, moisture, light, or pollutants. It follows that thermally unstable, water-soluble, or light-sensitive minerals have likely been selectively removed from older formations. The detailed documentation of these and other systematic losses will facilitate a clearer understanding of mineral evolution on Earth and other worlds.

Finally, we cannot rule out the important potential influences of anthropogenic biases in the reported mineralogical record. Museum and private collections often favor larger, colorful, and well crystallized specimens; these are understandable biases that may significantly under-represent softer, mineral groups originating in soils and other near-surface environments, notably hydroxides, clay minerals, and a wide range of fine-grained secondary minerals. Nevertheless, the two primary factors contributing to the observed decrease in average mineral hardness over more than 4.5 billion years of Earth's history are changes in the modes of mineral formation coupled with the selective loss of softer minerals, which appear to be intrinsic to the evolution of any Earth-like planet.

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