

Section S1: Supplementary Materials

Section S1.1 Cumulative release trends of the Pokémon Trading Card Game and mineral-illustrated cards

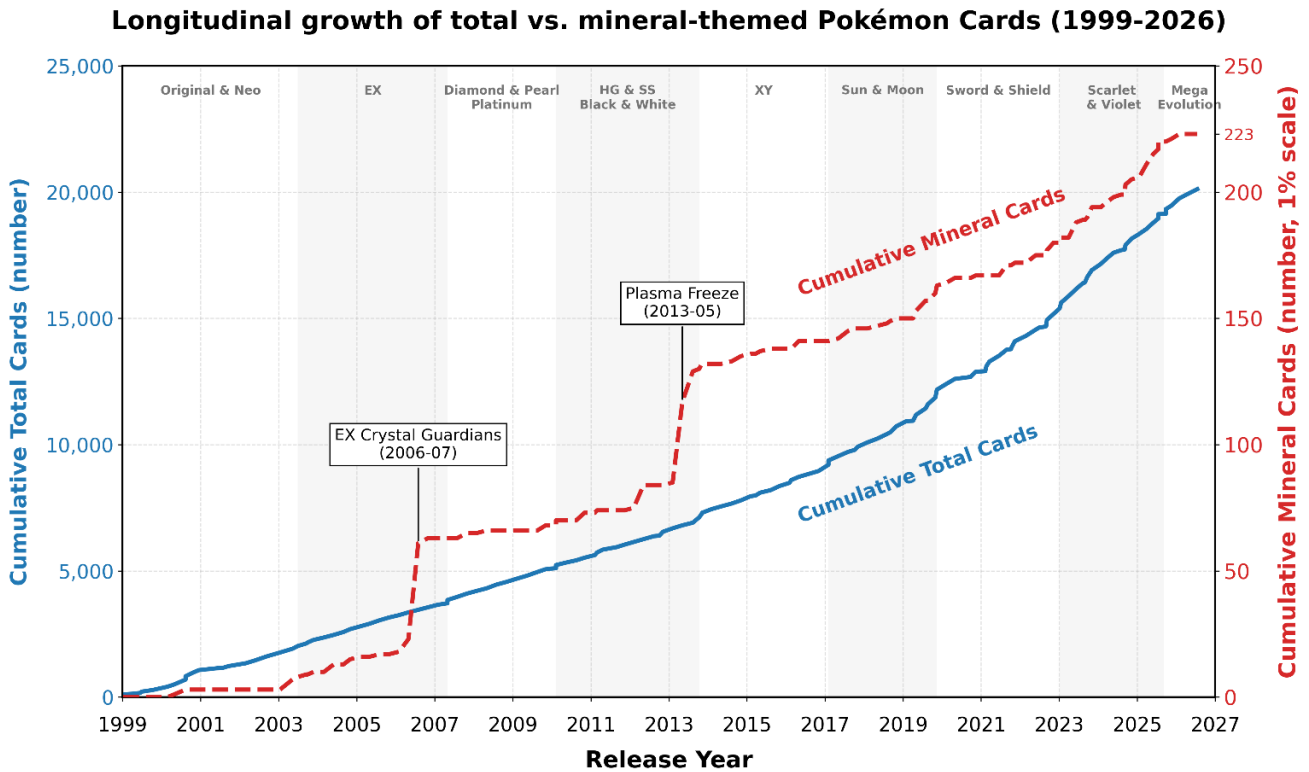


Figure S1. Cumulative total number of cards (blue) and mineral-illustrated cards (red) released between 1999 and 2026, respectively (Supplement table). Periods where the red curve is positioned above the blue curve indicate that mineral-illustrated cards constitute more than one percent of total releases. Background colors denote distinct official Pokémon game generations.

Section S1.2 Mineral-illustrated cards analyzed in this study



10 Figure S2. Mineral-illustrated cards analyzed in this study (Nos. 1 to 70). Cards are numbered chronologically by
 release year. Cards outlined with a black border correspond to the original artwork used in Fig. 1 of the main text.
 Basic information for each card is provided in the Supplement Excel file. Digital images of the cards were sourced from
 the Pikawiz database (<https://www.pikawiz.com/cards>, last accessed in July 2026). To strictly adhere to copyright
 policies, all artwork presented in this figure has been intentionally blurred to obscure text and character details,
 15 rendering them unsuitable for commercial use. (Card artwork © Pokémon/Nintendo/Creatures Inc./GAME FREAK
 Inc. Reproduced under fair use guidelines to serve solely as a non-commercial visual overview for scientific critique.)



Figure S3. Mineral-illustrated cards analyzed in this study (Nos. 71 to 150). Cards are numbered chronologically by release year. Cards outlined with a black border correspond to the original artwork used in Fig. 1 of the main text. Basic information for each card is provided in the Supplement Excel file. Digital images of the cards were sourced from the Pikawiz database (<https://www.pikawiz.com/cards>, last accessed in July 2026). To strictly adhere to copyright policies, all artwork presented in this figure has been intentionally blurred to obscure text and character details, rendering them unsuitable for commercial use. (Card artwork © Pokémon/Nintendo/Creatures Inc./GAME FREAK Inc. Reproduced under fair use guidelines to serve solely as a non-commercial visual overview for scientific critique.)



Figure S4. Mineral-illustrated cards analyzed in this study (Nos. 151 to 223). Cards are numbered chronologically by release year. Cards outlined with a black border correspond to the original artwork used in Fig. 1 of the main text. Basic information for each card is provided in the Supplement Excel file. Digital images of the cards were sourced from the Pikawiz database (<https://www.pikawiz.com/cards>, last accessed in July 2026). To strictly adhere to copyright policies, all artwork presented in this figure has been intentionally blurred to obscure text and character details, rendering them unsuitable for commercial use. (Card artwork © Pokémon/Nintendo/Creatures Inc./GAME FREAK Inc. Reproduced under fair use guidelines to serve solely as a non-commercial visual overview for scientific critique.)

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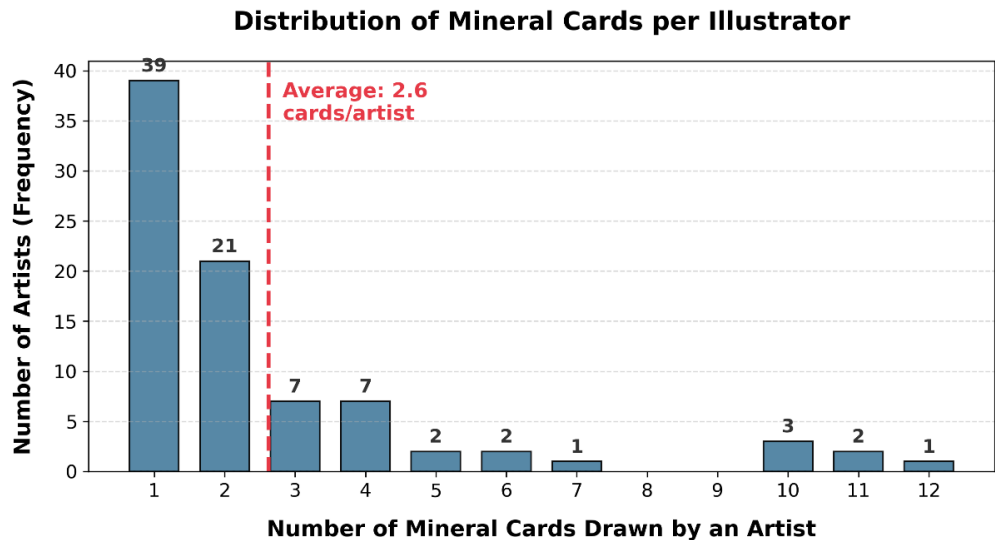


Figure S5. Distribution of mineral-themed Pokémon Trading Card Game illustrations across 85 identified artists. The dataset comprises 223 mineral-themed cards with an average of approximately 2.6 cards per artist. Approximately 70% of artists contributed only one or two cards, whereas six illustrators produced ten or more cards each, collectively accounting for 29% of the dataset.

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Section S2: Methods

Section S2.1 Classification criteria for visual features of fictional minerals

Beyond basic metadata, thirteen variables were manually interpreted for each card. To clarify the data structure for statistical analysis, the specific data type of each variable (Binary, Categorical, or Ordinal) is indicated in parentheses following its title.

45 These variables are grouped into four domains (see Supplementary Excel file for the complete dataset):

1. Environmental context

• Growth setting (Categorical): Environments were categorized based on background geomorphology. Examples include Cave (broadly covering various underground spaces like karst limestone caves and mines), Forest (wooded areas), Shoreline (boundaries between water and land, including lakeshores and riverbanks), Ocean, Ground (general land surfaces), Grassland, City (including artificial structures), and Sky. Some common natural landscapes, such as magmatic or volcanic areas, were grouped into more objective categories like Cave or Coastal because defining volcanic processes visually can be subjective. Similarly, wind-formed and glacial landscapes were grouped into broader and undisputed areas like Coastal or Ground.

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- Crystal exposure (Categorical): The crystal relationship with the host rock was recorded as "Y" if the mineral exhibits clear geometric crystal faces protruding from the host rock, or "N" if it is anhedral or buried. If the mineral or gemstone in the illustration has been artificially cut or processed into jewelry, tools, or ornaments, it was designated as "N/A" (Not Applicable).
- Major rock type (host rock) (Categorical): Classified petrologically based on visual texture. "Sedimentary" includes cards showing distinct stratification, bedding planes, clastic components, or internal cave formations. Specifically, an underground environment was inferred to be a "Limestone Cave" and classified under Sedimentary if it concurrently exhibited visual markers like downward-hanging stalactites, upward-growing stalagmites, dripping water textures, and basal pools, typically colored in earth or brown tones. "Igneous" includes cards showing columnar jointing, active magmatic flow structures, or distinct volcanic environments. "Metamorphic" includes cards showing clear foliation, banding, or structural deformation textures. "Unidentifiable" includes cards lacking sufficient background rock detail or textural clarity for confident petrological assignment.
- Presence of paragenetic assemblages (Binary): Assesses whether the illustrator captured natural mineral diversity. Recorded as "Single Species Only" if only one mineral type is depicted, and "With Paragenetic Minerals" if two or more distinct minerals co-occur together.

2. Intrinsic morphological traits

- Displayed mineral size (Ordinal): The official heights of the depicted Pokémon species, retrieved from the *Bulbapedia* database (https://bulbapedia.bulbagarden.net/wiki/Main_Page), were used as reference scale bars to estimate the longest visible axis of each crystal. To ensure consistency across the dataset, variation among individual members of the same Pokémon species was ignored, and only the official species height was used for scaling. When multiple crystals of different sizes were present in a single illustration, the predominant crystal size was used as the representative value. Categories include XS (<5 cm), S (5–30 cm), M (30–200 cm), and L (>200 cm). Interpretative uncertainty due to perspective distortion was denoted with a question mark (e.g., L?).
- Crystal system (Categorical) & pyramidal terminations (Binary): Minerals were classified into Hexagonal (including the trigonal system), Isometric, Tetragonal, Orthorhombic, Monoclinic, or Triclinic systems based on geometric symmetry. Ambiguous crystals were assigned multiple possible systems using weighted calculations (e.g., two possibilities score 0.5 each). This study explicitly recorded the presence of "Pyramidal terminations" to quantify the abundance of pointed geometries. Crystals lacking symmetrical faces are marked as "Unidentifiable."
- Crystal aggregation (Categorical): Growth patterns were categorized as Single crystal, Twin, or Crystal Cluster. The "Stalactitic habit" was classified independently to analyze biases tied to cave environments.
- Surface features of crystals (Binary): Evaluates microscopic realism. Recorded as "Y" if striations, cleavage, or fracture (e.g., conchoidal fracture) are visible. Perfectly smooth, idealized geometric bodies without these features were recorded as "N."

3. Physical and optical properties

- Dominant color (Categorical): The primary color(s) of the mineral. Multicolored specimens were processed using weighted calculations. Minerals with more than four colors (e.g., opalescence) were recorded as "Multicolor."
- Luster (Categorical): Classified as Adamantine, Vitreous, Metallic, Resinous, Pearlescence, or Earthy. The presence of specular highlights (e.g., starburst reflections) resulted in a higher luster grading.
- Transparency (Ordinal): Classified as Transparent, Translucent, or Opaque, determined by the visibility of internal inclusions, cleavage planes, or background objects behind the crystal.
- Mineral luminescence (Binary): Identifies exaggerated optical rendering. Recorded as "Y" if the mineral is drawn as a self-luminous light source (emitting halos) without a specific excitation source (like UV light). Recorded as "N" otherwise.

4. Analytical and educational metrics

- Real-world plausibility (Binary): "Plausible" indicates that the crystal geometry, environment, and physical laws (e.g., gravity) align with natural possibilities. This means the occurrence and growth state of the mineral are reasonable in an actual geological setting. "Fantasy" indicates violations of geological norms. Examples include crystals floating in the air, abnormally giant crystals growing directly on artificial city streets, deep ocean or unsuitable ground surfaces, or mutually exclusive crystal systems on a single body.
- Mineral identification results: The inferred mineral species generated by LLMs (ChatGPT, Gemini), the Rock Identifier app, and the human expert baseline.

Section S2.2 Multiple Correspondence Analysis (MCA) and eigenvalue correction procedure

MCA served as the primary dimensionality reduction technique to uncover latent geometric relationships among categorical features. Standard MCA applied to an indicator matrix often generates artificial dimensions. This inherently inflates the total inertia and heavily underestimates the actual variance explained by the primary dimensions (Abdi & Valentin, 2007). To rectify this mathematical distortion, Benzécri’s correction (Benzécri, 1979) was applied. This procedure recalculates the eigenvalues by discarding those below a specific mathematical threshold. This effectively filters out the artificial variance, providing a much more accurate estimation of the explanatory power for the dominant visual axes. For spatial visualization, confidence ellipses set at 1.5 standard deviations were plotted to delineate the core 68% feature space for each mineral taxonomy.

Section S2.3 Standardized prompts for multimodal large language models (LLMs)

The study utilized ChatGPT and Gemini for mineral feature analysis between January and March 2026. The standardized prompt submitted to the models is as follows.

120 "You are a world-renowned mineralogist with an extensive background in geology and mineralogy. I will provide you with illustrations from Pokémon trading cards. Please visually disregard the Pokémon characters in the image and exclusively analyze the natural geological background features of the location. Based on these visual characteristics, deduce the most likely common mineral depicted in the background, and provide a rigorous scientific justification.

- Please strictly adhere to the following format for your response:
1. Visual observation of mineral features: Detail the color, luster, transparency, crystal system geometry, and growth habit of the mineral in the card.
 2. Final identification result: Synthesize the above features to provide a single, most likely common 'mineral' name (use standard mineralogical terminology).
 3. Deductive logic and geological plausibility: Explain the reasoning behind your feature matching, and briefly assess the plausibility of this mineral occurring in the depicted geological environment.

130 In addition to data analysis, these AI tools were also employed to refine the manuscript's phrasing and structural clarity.

Section S3: AI Baseline Performance on Real Mineral Specimens

135 **Section S3.1 Sampling strategy**

To validate the baseline identification capabilities of the AI models and ensure that misclassifications in the main study were driven by artistic stylization rather than algorithmic limitations, a control experiment utilizing photographs of natural mineral specimens was conducted. A proportional stratified sampling approach was designed to mirror the frequency distribution of the minerals identified in the PTCG dataset.

140 The control group consisted of 43 photographs. For the seven most frequently occurring minerals (ice, quartz, calcite, zircon, corundum, fluorite, and amber), four distinct photographs were selected per species. For less frequent minerals, photograph counts aligned with their proportional abundance: beryl (3), garnet (2), magnetite (2), spinel (2), topaz (2), diamond (1), feldspar (1), mica (1), and tourmaline (1). To maintain scientific rigor, all 43 images were sourced from the Wikimedia Commons database and selected for exhibiting clear euhedral or subhedral crystal habits. URL links and attributions are

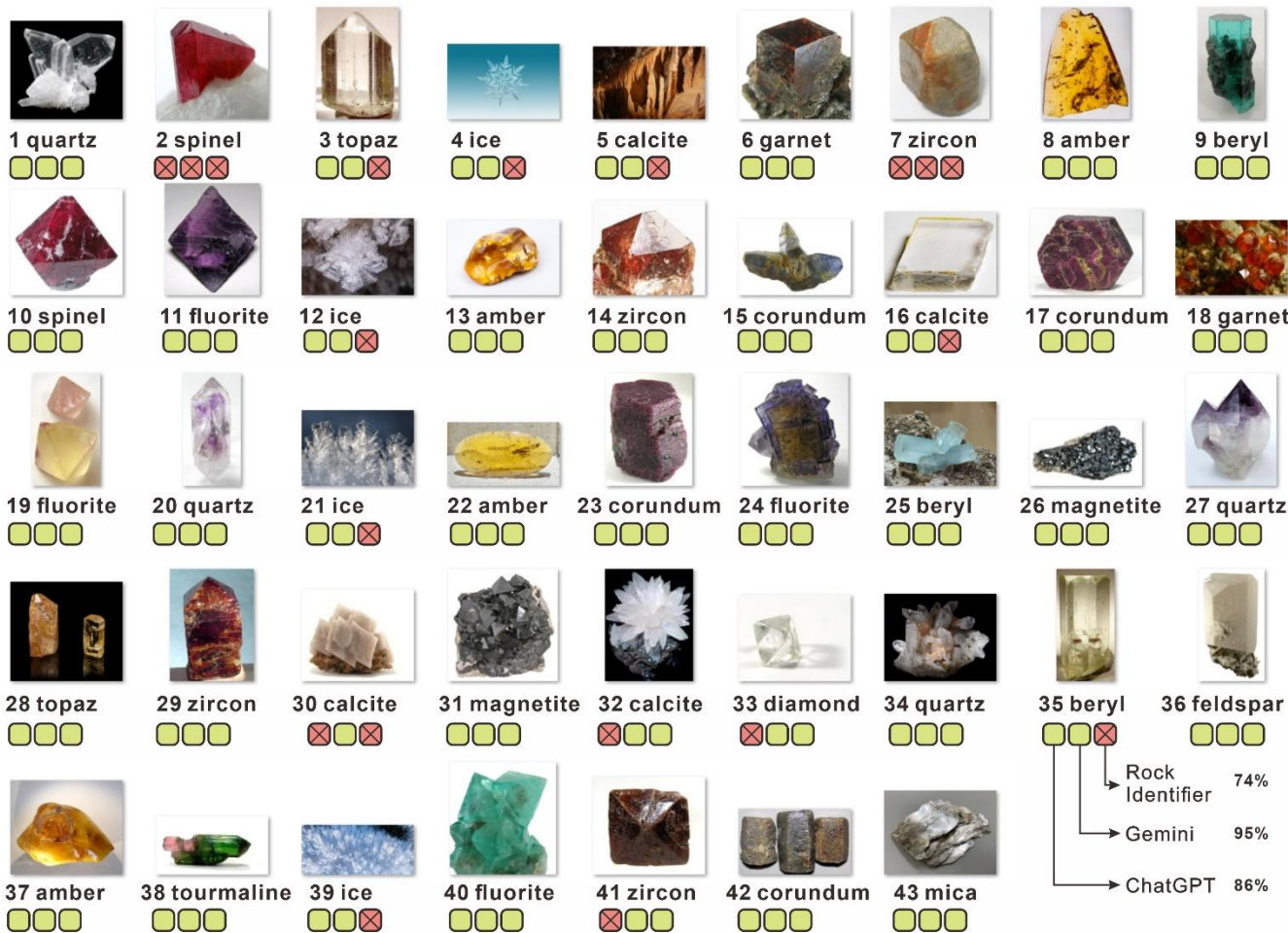
145 detailed in the Supplementary Excel file.

Section S3.2 Testing procedure and results

The 43 photographs were randomized to prevent sequential bias. Each image was processed by three AI tools (ChatGPT 5.3, Gemini 3.0, and Rock Identifier v2.19.2) using the identical standardized prompts applied to the card illustrations. Each

150 photograph was tested twice per software application, and the response most accurately identifying the correct species was recorded as the model's optimal capability.

The baseline experiment confirmed that all three tools possess high proficiency in natural geological pattern recognition. Gemini achieved the highest accuracy at 95%, followed by ChatGPT at 86%, and Rock Identifier at 74%. Rock Identifier's relatively lower success rate was attributed to the absence of ice crystals and limestone cave formations in its training database; excluding these materials raised its accuracy above 80%. Given the small sample size, these percentages serve strictly as a general baseline reference. The complete evaluation matrix is provided in the Supplementary Excel file and summarized in Fig. S6.



160 **Figure S6. Performance evaluation of three AI tools (ChatGPT, Gemini, and Rock Identifier) on 43 real mineral photographs used in the control experiment. Photographs of actual mineral specimens were sourced from Wikimedia**

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