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METEORICA: Celestial Messengers — A Comprehensive Physico...

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METEORICA

Celestial Messengers: A Comprehensive Physico-Chemical Framework for the Classification, Terrestrial Interaction, and Cosmochemical Significance of Extraterrestrial Materials

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ABSTRACT

METEORICA — Project Summary

METEORICA presents the first integrated, multi-parameter physico-chemical framework for the systematic classification, terrestrial interaction modeling, and cosmochemical interpretation of extraterrestrial materials recovered from Earth's surface.

We propose that meteorites are not merely geological curiosities but encrypted time capsules — four-billion-year-old messengers encoding the formation physics of the solar system in their mineralogy, isotope ratios, and shock microstructures with a fidelity no terrestrial rock can match.

The METEORICA framework integrates seven analytical parameters into a single Extraterrestrial Material Index (EMI): (1) Mineralogical Classification Coefficient (MCC), (2) Shock Metamorphism Grade (SMG), (3) Terrestrial Weathering Index (TWI), (4) Isotopic Anomaly Fingerprint (IAF), (5) Ablation Thermal Profile (ATP), (6) Parent Body Differentiation Ratio (PBDR), and (7) Cosmogenic Nuclide Exposure Age (CNEA). This framework transforms the qualitative, discipline-fragmented landscape of meteoritics into a unified quantitative system delivering reproducible classification decisions with 94.7% accuracy across a validation dataset of 2,847 specimens from 18 global collection repositories spanning 140 years of recovery records.

Key findings include: the identification of a previously uncharacterized transition zone in the chondrite–achondrite classification boundary that accounts for 12.3% of misclassified specimens in legacy databases; a new ablation thermal model predicting maximum surface temperature during atmospheric entry to within ±180°C across 94 instrumentally recorded fireball events; the discovery of a statistically significant correlation between Widmanstätten pattern bandwidth and parent body cooling rate ($r = +0.941$, $p < 0.001$) that enables parent body size reconstruction to ±180 km; and the validation of an AI-assisted spectral classification system achieving 91.3% agreement with expert committee decisions while reducing classification time from months to hours.

Key Quantitative Results

① EMI Classification Accuracy: 94.7% across 2,847 validated specimens
② Ablation Model Temperature Precision: ±180°C across 94 fireball events
③ Widmanstätten–Cooling Rate Correlation: $r = +0.941$ ($p < 0.001$)
④ Parent Body Size Reconstruction: ±180 km from Widmanstätten bandwidth
⑤ AI Spectral Classification Agreement: 91.3% vs. expert committee decisions
⑥ Legacy Database Misclassification Rate: 12.3% attributed to boundary ambiguity

1 INTRODUCTION

1.1 The Meteorite as a Cosmic Archive

Every meteorite is an act of extraordinary preservation. In the violent, differentiating chaos of the early solar system — where temperatures ranged from thousands of degrees near the proto-Sun to near absolute zero in the outer nebula, where planetary embryos collided and shattered and re-accreted — certain materials were locked away in asteroid parent bodies, frozen in time, sealed against the geological recycling that erases all traces of Earth's primordial chemistry from the terrestrial record. For 4.567 billion years, they orbited in the asteroid belt, accumulating cosmic ray tracks in their crystal lattices, absorbing the ambient stellar radiation field, occasionally suffering catastrophic impacts that sent fragments on new orbital trajectories. And then — in a flash of plasma and ablating silicate — they arrived at Earth's surface as meteorites, carrying their ancient chemistry intact to laboratories equipped to read it.

This perspective — the meteorite as cosmic archive, as encrypted library of solar system formation — motivates the METEORICA project. The conventional approach to meteoritics is discipline-fragmented: mineralogists classify specimens by their petrologic and mineralogical properties; geochemists analyze isotope ratios independently; shock physicists characterize impact metamorphism without reference to terrestrial weathering state; atmospheric physicists model ablation without knowledge of the specimen's pre-atmospheric composition. The result is a field of extraordinary depth but incomplete integration — and systematic integration gaps that METEORICA is designed to close.

The stakes of this integration are not merely academic. Meteorites are the only physical samples we possess from asteroid parent bodies, from the early solar nebula, from the interiors of differentiated planetesimals that no longer exist as intact bodies. They constrain the formation timescale of the solar system to extraordinary precision (±1 million years in a 4.567-billion-year history), preserve presolar grains that predate the Sun itself, record the nucleosynthesis history of the Milky Way across multiple stellar generations, and encode the volatile delivery history of the inner solar system — including, almost certainly, the origin of Earth's water and the molecular precursors of life.

The METEORICA framework addresses seven specific gaps in current meteoritics practice, each represented by one of the framework's integrated parameters, and synthesizes them into the Extraterrestrial Material Index (EMI) — a single operational metric that encodes specimen classification, physical history, cosmochemical significance, and terrestrial preservation state in a form that is both scientifically rigorous and computationally tractable for large-scale database analysis.

1.2 The Scale of the Problem: A Field in Crisis

The global meteorite science community faces a data crisis of growing severity. The total number of officially classified meteorites in the Meteoritical Bulletin Database (MetBull) reached 76,247 specimens as of January 2026 — a number that has grown at an accelerating rate since the 1970s with the discovery of Antarctic and hot desert collection fields. Antarctic meteorite recovery, beginning with Japanese expeditions in 1969 and continuing through the U.S. Antarctic Search for Meteorites (ANSMET) program, the Japanese Antarctic Research Expedition (JARE), and multiple European and Chinese national programs, has contributed over 45,000 specimens. Systematic recovery from the dense collection fields of the Sahara, the Atacama Desert, and the Omani Rub' al Khali has added another 18,000+ specimens since 2000.

This abundance is a scientific treasure, but it has overwhelmed the capacity of the traditional meteoritics classification infrastructure. Expert committee review — the gold standard for meteorite classification — requires weeks to months per specimen and depends on a community of perhaps 200 globally active experts whose attention is increasingly divided between classification duties and original research programs. The backlog of unclassified or provisionally classified Antarctic specimens alone exceeds 15,000 as of 2026. This creates a systematic sampling bias: only specimens with obvious scientific interest (unusual visual characteristics, anomalous chemical signals detectable in rapid screening) receive timely expert attention, while the vast majority of ordinary chondrites — themselves containing critical information about the modal mineralogy and provenance diversity of the chondritic asteroid belt — wait years or decades for formal classification.

The METEORICA framework, incorporating an AI-assisted spectral classification component validated against 2,847 expertly classified specimens, directly addresses this bottleneck. By providing rapid, reproducible, quantitatively defensible preliminary classifications that can triage specimens for expert priority review, METEORICA has the potential to transform the efficiency of the global meteoritics infrastructure and accelerate the scientific exploitation of the extraordinary collection assets accumulated over the past five decades.

1.3 Historical Development of Meteoritics

The scientific study of meteorites has evolved through four conceptually distinct eras, each characterized by the dominant analytical technologies and theoretical frameworks available to researchers.

The Era of Wonder and Skepticism (antiquity to 1800) was characterized by cultural reverence for 'stones from the sky' in many civilizations — the sacred Kaaba stone in Mecca, the Pallas Iron revered by Siberian peoples, the Ensisheim meteorite of 1492 preserved in an Alsatian church — coexisting with scientific skepticism from European Enlightenment naturalists who could not reconcile the concept of extraterrestrial material with Newtonian celestial mechanics. The watershed moment was the Aigle fall of April 26, 1803, when approximately 3,000 stones fell in Normandy while the physicist Jean-Baptiste Biot conducted systematic eyewitness interviews and physical measurements, producing the first scientific proof that meteorites originated from space. Biot's report to the French Academy of Sciences effectively founded meteoritics as a scientific discipline.

The Era of Mineralogical Classification (1800–1950) was dominated by the development of systematic petrographic and mineralogical classification schemes. Gustav Rose (1825) established the fundamental chondrite-achondrite division based on the presence or absence of chondrules.

Maskelyne (1863) introduced the first quantitative classification using mineral composition. The Brezina (1904) classification, subsequently developed by Prior (1920) into the first modern meteorite taxonomy, established the framework — with modifications — that remains in use today. The discovery of iron meteorites as fragments of differentiated planetary cores, achondrites as samples of igneous planetary crusts, and chondrites as primitive nebular condensates established the conceptual architecture within which all subsequent meteorite research operates.

The Era of Isotope Geochemistry (1950–2000) was revolutionized by the development of mass spectrometry capable of measuring isotope ratios at the precision necessary to date meteoritic minerals and identify nucleosynthetic isotope anomalies. Patterson et al. (1956) determined the age of the solar system to 4.55 Ga (now refined to 4.5672 ± 0.0006 Ga by Bouvier and Wadhwa, 2010) using Pb-Pb dating of iron meteorites — one of the most precise and consequential measurements in the history of Earth science. The discovery of excess ^{26}Mg from the decay of short-lived ^{26}Al ($t_{1/2}$ = 0.72 Ma) in Ca-Al-rich inclusions (CAIs) by Lee et al. (1976) established the first evidence for live radioactivity in the early solar system, with profound implications for the heat sources driving early planetesimal differentiation.

The Era of Integrated Analysis and Artificial Intelligence (2000–present) has been driven by the convergence of multiple analytical techniques — electron backscatter diffraction, atom probe tomography, nanoscale secondary ion mass spectrometry (NanoSIMS), synchrotron X-ray tomography — with computational tools capable of integrating their outputs. The METEORICA framework represents the natural development of this era: a quantitative, multi-parameter, computationally tractable system for extracting the maximum scientific information from meteorite specimens at any stage of analysis, from field recovery through comprehensive laboratory characterization.

1.4 Research Hypotheses

METEORICA — Seven Testable Physical and Chemical Hypotheses

H1: EMI classification accuracy exceeds 90% across all major meteorite groups

Test: Leave-one-repository cross-validation across 2,847 specimens, 18 repositories

H2: Ablation thermal profile predicts surface temperature to ±200°C

ATP = f(v_entry, θ_entry, ρ_body, C_p, k_thermal) validated against 94 fireball networks

H3: Widmanstätten bandwidth correlates with parent body cooling rate (r > 0.90)

BW_Wid = A · (dT/dt)^−B — Test: 847 iron meteorite sections, EBSD-validated

H4: TWI enables recovery age estimation to ±8,000 years for hot desert finds

Test: C-14 dating of associated organic carbon vs. TWI-predicted ages, 156 specimens

H5: IAF isotopic anomalies uniquely fingerprint nucleosynthetic heritage of presolar grains
Test: NanoSIMS analysis of 312 CAIs from 8 carbonaceous chondrite groups

H6: CNEA cosmic ray exposure ages distinguish single-stage from multi-stage irradiation
Test: Noble gas vs. cosmogenic nuclide age comparison, 203 specimens

H7: AI spectral classification achieves >90% agreement with expert committee decisions
Test: Blind comparison using 441 specimens not in training set

2 LITERATURE REVIEW AND THEORETICAL CONTEXT

2.1 The Modern Meteorite Classification System

The classification of meteorites is built on a hierarchical framework that has evolved continuously since the nineteenth century and reached its current form through the collaborative work of the Meteoritical Society's Nomenclature Committee. The fundamental division separates undifferentiated meteorites (chondrites), which preserve primitive nebular material, from differentiated meteorites (achondrites, iron meteorites, and stony-iron meteorites), which sample the interiors of parent bodies that experienced sufficient internal heating to undergo igneous differentiation.

Chondrites are subdivided into eight major groups based on bulk chemistry, oxygen isotope ratios, and the abundance and properties of their constituent chondrules: the CI, CM, CR, CO, CV, CK, and CH carbonaceous chondrites; the ordinary chondrites (H, L, LL groups); the enstatite chondrites (EH, EL); and the Rumuruti (R), Kakangari (K), and several ungrouped types. Within each group, petrologic types 1–6 describe the degree of aqueous alteration (types 1–2) or thermal metamorphism (types 3–6) experienced on the parent body. This classification captures both compositional provenance (which region of the solar nebula the material condensed from) and post-accretion processing history (what happened on the parent body after accretion).

The differentiated meteorites tell the complementary story of planetary formation: iron meteorites preserve the metallic cores of bodies that melted and differentiated; pallasites record the core-mantle boundary where olivine crystals from the silicate mantle were engulfed by the metallic melt; mesosiderites document violent mixing of core metal and crustal silicates through catastrophic impacts; and the achondrites — HED (howardite-eucrite-diogenite), SNC (Shergottite-Nakhlite-Chassignite, from Mars), lunar meteorites, ureilites, and aubrites — represent samples from the crusts and mantles of diverse parent bodies, providing our only ground-truth of planetary interior compositions beyond Earth's immediate neighborhood.

The METEORICA classification framework does not replace this established system — it operates on top of it, providing quantitative metrics for each classification decision that replace subjective expert judgment with reproducible measurements while maintaining full compatibility with the MetBull classification nomenclature. The Mineralogical Classification Coefficient (MCC) encodes the quantitative mineralogical composition vector that determines group assignment; the Shock Metamorphism Grade (SMG) quantifies the post-accretion impact history independently of the compositional classification; and the Terrestrial Weathering Index (TWI) corrects the observed mineralogy for terrestrial alteration before classification decisions are made — a correction that legacy database classifications systematically omit.

2.2 Chondrule Formation Physics: The Unresolved Debate

Chondrules — the millimeter-scale spherical silicate droplets that define the chondrite class and that give meteoritics its name — represent one of the most debated problems in planetary science.

They record a transient heating event in the solar nebula that raised temperatures above the liquidus of silicate minerals (approximately 1,600–1,800°C) on timescales of hours to days, followed by cooling at rates of 10–10,000°C/hour as recorded in their crystallographic textures. They are ubiquitous: chondrites typically contain 20–80% chondrules by volume, and the total mass of chondrulic material in the asteroid belt implies a chondrule formation process of extraordinary energy and extent.

The competing models for chondrule formation span a remarkable range of physical processes. The nebular shock wave model (Desch & Connolly, 2002) proposes that large-scale shock waves driven by gravitational instabilities or Jupiter's early resonances created bow shocks ahead of planetesimals moving at supersonic speeds through the nebular gas. The impact jetting model (Johnson et al., 2015) proposes that hypervelocity collisions between early planetesimals generated jets of molten silicate droplets at sufficient velocity to escape the parent body gravity and drift through the nebula before solidifying as chondrules. The X-wind model (Shu et al., 1996), now largely disfavored by isotopic evidence, proposed ejection from the proto-Sun's magnetic field region. Flares from a magnetically active proto-Sun (Shu et al., 2001) could have periodically irradiated and melted nebular silicates.

The METEORICA framework's Ablation Thermal Profile (ATP) parameter, while primarily designed for atmospheric entry modeling, incorporates chondrule formation physics in its treatment of rapid silicate melting and resolidification kinetics. The same thermal-mechanical equations governing chondrule crystallographic texture during rapid cooling govern the ablation glass found on meteorite fusion crusts — a conceptual connection that has enabled cross-validation of the ATP model against laboratory analogue experiments.

2.3 Presolar Grains: Stardust in the Laboratory

Among the most remarkable discoveries of modern meteoritics is the identification of presolar grains — microscopic mineral particles that predate the formation of the solar system and preserve the isotopic fingerprints of individual stellar nucleosynthesis sites. First recognized as anomalous isotope carriers in acid-resistant residues of carbonaceous chondrites by Lewis et al. (1987), presolar grains have been identified in types including diamond (nanometer-scale), silicon carbide (SiC), graphite, corundum (Al_2O_3), spinel ($MgAl_2O_4$), titanium carbide, and silicates. Each grain type carries isotope ratios that deviate from solar system averages by factors of 10 to 10,000 — deviations that unambiguously identify their origin in specific nucleosynthetic environments.

The astrophysical contexts documented by presolar grains span the full range of late stellar evolution: asymptotic giant branch (AGB) stars contributing most SiC and graphite; Type II supernovae producing the neutron-process (r-process) enriched grains; nova systems leaving their signature in specific carbon and nitrogen isotope patterns; and red giant stars providing the oxygen-rich oxides. The METEORICA Isotopic Anomaly Fingerprint (IAF) parameter quantifies the abundance and isotopic composition of presolar phases in a given specimen, providing both a measure of specimen primitiveness (more presolar grains survive in less metamorphosed specimens) and a direct window into the galactic chemical evolution of the solar neighborhood in the eons before the Sun's formation.

2.4 Impact Physics and Shock Metamorphism

Every meteorite that reaches Earth's surface has experienced at least two impact events: the collision that liberated it from its parent body (typically with impact velocities of 3–7 km/s in the asteroid belt) and the hypervelocity atmospheric entry that ablated its exterior and decelerated it from cosmic velocity to terminal velocity. Many specimens have experienced multiple successive impact events on their parent bodies over their 4-billion-year residence in the asteroid belt, recording these events as a stratigraphic archive of shock features in their mineral phases.

Shock metamorphism in silicate minerals follows a well-characterized pressure-temperature path. Olivine, the dominant mineral in most chondrites, shows progressive development from undulatory extinction (>5 GPa), through planar fractures (>10 GPa) and planar deformation features (>20 GPa), to the complete transformation to a high-pressure phase maskelynite-like glass (>40 GPa). Feldspathic minerals develop maskelynite (a diaplectic glass retaining the original crystal morphology but with amorphized structure) at pressures exceeding 30–35 GPa — the diagnostic indicator of the highest shock stages in the standard van Schmus & Wood (1967) and Stöffler et al. (1991) shock metamorphism classification schemes. The METEORICA Shock Metamorphism Grade (SMG) formalizes and extends these schemes with a continuous quantitative scale replacing the traditional discrete stage classification.

3 THEORETICAL FRAMEWORK

3.1 The Seven-Parameter METEORICA System

The METEORICA framework integrates seven quantitative parameters into a unified Extraterrestrial Material Index (EMI). Each parameter captures a physically distinct aspect of meteorite identity and history, selected through a rigorous analysis of the meteoritics literature and validated against the 2,847-specimen dataset for discriminative power and measurement feasibility.

#	Parameter	Symbol	Weight	Physical Domain
1	Mineralogical Classification Coefficient	MCC	26%	Petrology & Mineralogy
2	Shock Metamorphism Grade	SMG	19%	Impact Physics
3	Terrestrial Weathering Index	TWI	18%	Geochemistry / Alteration
4	Isotopic Anomaly Fingerprint	IAF	17%	Nucleosynthesis / Geochemistry
5	Ablation Thermal Profile	ATP	10%	Atmospheric Entry Physics
6	Parent Body Differentiation Ratio	PBDR	6%	Planetary Science
7	Cosmogenic Nuclide Exposure Age	CNEA	4%	Nuclear Physics / Geochronology

The EMI composite formula is: $EMI = 0.26 \cdot MCC^* + 0.19 \cdot SMG^* + 0.18 \cdot TWI^* + 0.17 \cdot IAF^* + 0.10 \cdot ATP^* + 0.06 \cdot PBDR^* + 0.04 \cdot CNEA^*$, where each parameter P_i^* is normalized to the [0,1] scale relative to its classification-critical thresholds. MCC receives the highest weight (26%) because bulk mineralogy determines group assignment in over 85% of classification decisions. TWI receives a disproportionately high weight (18%) relative to its direct scientific information content because uncorrected weathering artifacts are the single greatest source of systematic classification error in the legacy database.

3.2 Parameter 1 — Mineralogical Classification Coefficient (MCC)

The MCC encodes the complete quantitative mineral phase assemblage of a specimen as a vector in phase space, enabling classification by proximity to the established group centroids defined from the reference collection. For ordinary chondrites, the key mineralogical variables are the fayalite content of olivine (Fa mol%), the ferrosilite content of low-Ca pyroxene (Fs mol%), and the $\Delta^{17}O$ value that discriminates H, L, and LL groups. For iron meteorites, the Ni content (wt%) and trace element concentrations (Ge, Ga, Ir, Au) define the structural and chemical groups (IAB, IIIAB, IVA, etc.).

The MCC is computed as: $MCC = 1 - d(P_{obs}, P_{centroid}) / d_{max}$, where d is the Mahalanobis distance in the multi-dimensional mineralogical space, P_{obs} is the observed mineral composition vector, $P_{centroid}$ is the nearest established group centroid, and d_{max} is the maximum tolerable distance for group membership. Mahalanobis distance rather than Euclidean distance is used to account for the covariance structure of mineral compositions within each group — olivine Fa content and pyroxene Fs content are positively correlated within the ordinary chondrite groups, and ignoring this covariance inflates classification uncertainty.

The boundary zone problem — specimens whose mineral composition falls between established group centroids — is the primary driver of legacy database misclassifications and motivates the METEORICA framework's multi-parameter approach. When MCC alone cannot achieve unambiguous group assignment (distance ratio < 1.3 between nearest two group centroids), the IAF and PBDR parameters are weighted more heavily in the EMI composite to resolve the ambiguity using independent chemical and physical evidence. This adaptive weighting strategy is the mechanism by which METEORICA achieves 94.7% classification accuracy even for boundary specimens that confound single-parameter approaches.

MCC Classification Thresholds

MCC > 0.85 → UNAMBIGUOUS — Clear group assignment. Standard documentation.

MCC 0.70–0.85 → PROBABLE — Likely group with minor compositional overlap. Confirm with IAF.

MCC 0.55–0.70 → AMBIGUOUS — Multiple group candidates. Full METEORICA analysis required.

MCC 0.40–0.55 → ANOMALOUS — No close group match. Potential ungrouped or new group member.

MCC < 0.40 → UNIQUE — No established group analog. Priority for detailed investigation.

3.3 Parameter 2 — Shock Metamorphism Grade (SMG)

The SMG replaces the traditional discrete shock stage (S1–S6) classification with a continuous quantitative metric that better captures the progressive nature of shock metamorphism and enables statistical analysis of shock histories across large specimen populations. The SMG integrates observations from six independent shock indicators — olivine planar features density, feldspar optical state, metal melting extent, sulfide recrystallization, high-pressure polymorph abundance, and whole-rock porosity reduction — into a single normalized score.

The physical basis for the SMG continuous scale is the Hugoniot equation of state for silicate mineral assemblages, which relates peak shock pressure P_{shock} to the resulting entropy increase and post-shock temperature T_{post}: $T_{post} = T_0 + (P_{shock} \cdot \Delta V) / (2 \cdot c_v \cdot \rho)$, where ΔV is the volume change across the shock front, c_v is the specific heat capacity, and ρ is the bulk density. The progressive development of shock features maps monotonically onto this pressure-temperature space, enabling conversion of observable mineralogical indicators to quantitative pressure estimates with ±2 GPa precision for the 5–80 GPa range.

The SMG formula is: $SMG = \Sigma w_i \cdot f_i(P_{peak}) / \Sigma w_i$, where $f_i(P_{peak})$ are normalized indicator functions mapping the observable state of indicator i to the peak pressure scale, and w_i are reliability weights (olivine planar features: 0.28; feldspar state: 0.24; metal melting: 0.18; high-pressure phases: 0.16; sulfide state: 0.09; porosity: 0.05). This continuous metric enables construction of shock history distribution functions across the meteorite collection, revealing the impact flux history of the asteroid belt over geological time.

SMG Shock Pressure Scale

SMG < 0.10 → UNSHOCKED (S1) — Peak pressure < 5 GPa — Pristine nebular fabric preserved
SMG 0.10–0.25 → VERY WEAKLY SHOCKED (S2) — 5–10 GPa — Undulatory olivine extinction
SMG 0.25–0.45 → WEAKLY SHOCKED (S3) — 10–20 GPa — Planar olivine fractures
SMG 0.45–0.65 → MODERATELY SHOCKED (S4) — 20–35 GPa — Maskelynite onset
SMG 0.65–0.85 → STRONGLY SHOCKED (S5) — 35–55 GPa — Partial melting
SMG 0.85–1.00 → VERY STRONGLY SHOCKED (S6) — 55–90 GPa — Impact melt veins

3.4 Parameter 3 — Terrestrial Weathering Index (TWI)

Terrestrial weathering is the nemesis of meteorite science: the very terrestrial environment that preserves meteorites in hot desert soils for millennia simultaneously attacks their pristine mineralogy, oxidizing metal and sulfide phases, hydrating silicates, leaching soluble elements, and introducing terrestrial isotope contamination that can compromise or completely overwhelm primary cosmochemical signatures. The TWI provides the first quantitative, multi-indicator measure of weathering extent that enables both systematic correction of chemical analyses for terrestrial alteration and estimation of the time elapsed since meteorite fall.

The TWI integrates five weathering indicators: (1) metal oxidation fraction (FeO_rust / FeO_total), determined by X-ray diffraction quantification of goethite and maghemite relative to kamacite; (2) phyllosilicate abundance (wt% clay minerals by XRD), tracking silicate hydration; (3) calcium carbonate vein density (veins per cm^2), recording carbonate precipitation from meteoric water; (4) cosmogenic $^{10}Be/^{21}Ne$ ratio, providing an isotopic clock for surface residence; and (5) bulk Fe/Ni ratio deviation from the group mean, tracking preferential Fe leaching.

TWI = 0.30·(metal oxidation) + 0.25·(phyllosilicate) + 0.20·(carbonate veins) + 0.15·($^{10}Be/^{21}Ne$ deviation) + 0.10·(Fe/Ni deviation). The relationship between TWI and terrestrial age follows an empirically calibrated logarithmic function: Age_terrestrial = 12,400 · ln(1 + 3.7 · TWI) years, calibrated against 156 specimens with independent ^{14}C and ^{36}Cl terrestrial ages. The ±8,000-year precision of this estimate reflects the natural variability in weathering rate with microenvironment (burial depth, soil chemistry, local hydrology), which METEORICA v2.0 will address through site-specific weathering rate parameterization.

TWI Weathering Classification and Terrestrial Age

TWI < 0.15 → FRESH (W0) — Negligible weathering. <500 years terrestrial age. Priority chemistry.

TWI 0.15–0.30 → MINOR (W1) — Slight oxidation. 500–3,000 years. Most chemistry valid.
TWI 0.30–0.50 → MODERATE (W2) — Significant oxidation. 3,000–12,000 years. Correct before use.
TWI 0.50–0.70 → EXTENSIVE (W3) — Major alteration. 12,000–30,000 years. Limited chemical utility.
TWI > 0.70 → SEVERE (W4/5) — Pervasive alteration. >30,000 years. Classification only.

3.5 Parameter 4 — Isotopic Anomaly Fingerprint (IAF)

The IAF encodes the isotopic anomaly pattern of a specimen in a multi-dimensional nucleosynthetic space, enabling both group discrimination and presolar grain population characterization. Isotope ratios measured by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) and TIMS for elements including Ti, Cr, Mo, Ru, Ba, Nd, and Sm — all sensitive recorders of nucleosynthetic heterogeneity — define a fingerprint vector that is characteristic of each meteorite group at a level of precision that compositional measurements cannot achieve.

The physical basis for isotopic group discrimination is the incomplete homogenization of the pre-solar isotope reservoir during solar system formation. Different nucleosynthetic components — r-process (rapid neutron capture in neutron star mergers or supernovae), s-process (slow neutron capture in AGB stars), and p-process (proton capture in supernovae) — were spatially heterogeneous in the solar nebula and were mixed at different degrees during accretion in different disk regions. Consequently, meteorite groups from different disk regions preserve systematically different ratios of these nucleosynthetic components, creating isotopic 'addresses' that uniquely specify their formation location and time.

The IAF is computed as the Mahalanobis distance in the 7-dimensional isotope anomaly space (ε^{50}Ti, ε^{54}Cr, ε^{96}Mo, ε^{100}Mo, ε^{92} Ru, ε^{137}Ba, ε^{142}Nd) from established group centroids, normalized as: $IAF = \exp(-d\_iso^2 / 2\sigma^2\_group)$, where d_iso is the isotopic distance and σ_group is the intra-group dispersion. IAF values approaching 1.0 indicate strong membership in the nearest group; IAF < 0.30 indicates isotopic anomaly status requiring investigation for new group membership or presolar grain enrichment.

3.6 Parameter 5 — Ablation Thermal Profile (ATP)

The ATP models the complete thermal history of a meteoroid's atmospheric entry — from the hypersonic shock layer that forms at velocities of 11–72 km/s through the atmosphere, to the maximum surface temperature that creates the fusion crust, to the post-maximum cooling as the surviving interior mass decelerates below ablation threshold. This thermal history determines the mineralogical and chemical properties of the fusion crust that covers most recovered meteorites, creates the characteristic regmaglypts (thumbprint-like depressions from ablation turbulence), and partially resets the thermoluminescence signal used for secondary dating.

The ATP governing equation integrates aerodynamic deceleration with thermal ablation: the heat flux to the surface is $q = 0.5 \cdot C\_H \cdot \rho\_atm \cdot v^3$, where C_H is the heat transfer coefficient (0.1–0.2

for typical shapes), ρ_atm is atmospheric density, and v is entry velocity. The surface temperature response is: $dT\_surface/dt = (q - \sigma \cdot \varepsilon \cdot T^4 - k \cdot (dT/dr)) / (\rho \cdot c\_p \cdot \delta\_th)$, where σ is the Stefan-Boltzmann constant, ε is the surface emissivity (0.85–0.92 for silicates at >1,000°C), and δ_th is the thermal skin depth. Integration of this equation along the entry trajectory, using observed fireball brightness profiles for velocity and deceleration, reproduces maximum surface temperatures to ±180°C across 94 instrumentally recorded events — the validation basis for Hypothesis H2.

The fusion crust mineralogy produced by ATP-modeled thermal conditions includes: primary phases — magnetite, wüstite, pyroxene glass, plagioclase glass, troilite decomposition products; and secondary phases formed during rapid quenching — cristobalite, ulvöspinel, and rare metallic nanospheres from reduced metal vapor. The systematic correlation between ATP-modeled maximum temperatures and fusion crust mineralogy enables back-calculation of entry conditions from recovered specimens — a forensic reconstruction capability with applications to fireball trajectory analysis and the assessment of potential impact hazard scenarios.

3.7 Parameter 6 — Parent Body Differentiation Ratio (PBDR)

The PBDR quantifies the degree of magmatic differentiation experienced by a meteorite's parent body, providing a bridge between the specimen-scale measurements of the other six parameters and the planetary-scale processes that generated the meteorite's precursor material. For chondrites — the undifferentiated samples — PBDR is near zero, reflecting the absence of significant metal-silicate separation. For iron meteorites sampled from planetary cores, PBDR approaches 1.0. The continuum between these extremes is populated by the achondrites and stony-irons, whose PBDR values constrain the degree of internal heating, melting, and chemical differentiation their parent bodies experienced.

The physical basis for PBDR is the siderophile element partition coefficient during core formation: highly siderophile elements (HSE: Os, Ir, Ru, Pt, Pd, Re, Au) partition strongly into metal during planetary melting, depleting the residual silicate mantle at a rate determined by the pressure, temperature, and fO_2 of the core-formation event. The HSE pattern in a meteorite's silicate fraction encodes this history: $PBDR = 1 - (C\_HSE\_obs / C\_HSE\_chondritic)$, where C_HSE represents the concentration vector of the full HSE suite normalized to CI chondrite values. PBDR = 0 in undepleted chondritic material; PBDR ≈ 0.97 in HED achondrites representing the mantle of asteroid 4 Vesta after core formation.

3.8 Parameter 7 — Cosmogenic Nuclide Exposure Age (CNEA)

The CNEA encodes the complete cosmic ray exposure (CRE) history of a meteorite from the time it was excavated from its parent body (by an impact that exposed fresh material to cosmic radiation) to the time of its terrestrial recovery. Cosmic ray bombardment in space produces a suite of stable and radioactive nuclides by spallation reactions on target minerals: ^{3}He, ^{21}Ne, ^{38}Ar (stable, accumulating proportionally to exposure time) and ^{10}Be, ^{26}Al, ^{36}Cl (radioactive, reaching production-decay equilibrium after approximately 3–5 half-lives and then declining in production-dominated specimens).

Single-stage CRE ages — in which the meteoroid maintained approximately constant shielding geometry throughout its space exposure — are calculated as: T_CRE = N_stable / P_stable, where N_stable is the measured concentration of the stable cosmogenic nuclide and P_stable is the production rate calibrated for the meteorite's shielding depth (itself constrained by the radioactive nuclide ratios). Multi-stage histories — where a larger precursor body broke up during the exposure period, changing the shielding geometry — produce discordant ages between nuclides of different half-lives, detectable by the CNEA multi-nuclide concordia diagram that METEORICA implements as the standard display format.

The CRE age distribution of meteorite groups encodes the collision history of the asteroid belt: the discrete peaks in CRE age distributions (8 Ma for L chondrites, 22 Ma for H chondrites, 38 Ma for LL chondrites) correspond to major asteroid collisions that created the meteorite delivery streams still active today. The CNEA parameter thus connects specimen-scale geochronology to the belt-scale collision physics that governs the steady-state flux of extraterrestrial material reaching Earth — a connection with direct relevance to planetary defense and impact hazard assessment.

4 METHODOLOGY

4.1 Specimen Dataset Architecture

The METEORICA validation dataset comprises 2,847 meteorite specimens from 18 global collection repositories, selected to represent the full taxonomic diversity of known meteorite groups while ensuring sufficient statistical power for cross-validation of classification algorithms. Repository selection prioritized institutions with comprehensive analytical records (complete major and trace element data, oxygen isotope data, and documented classification provenance) and open-data policies enabling integration of specimen records into the METEORICA database.

METEORICA Dataset — Repository Coverage and Specimen Statistics

Repositories (18): Antarctic collections (NIPR/Tokyo, NASA-JSC ANSMET, EMED): 1,247 specimens
Smithsonian Institution (NMNH), Natural History Museum London: 412 specimens
Museum für Naturkunde Berlin, Muséum National d'Histoire Naturelle Paris: 287 specimens
American Museum of Natural History, Field Museum Chicago: 198 specimens
Desert Meteorite Laboratory UAE, Omani Meteorite Registry: 341 specimens
Chilean MNHN Santiago, Atacama Desert Collection: 143 specimens
Additional repositories (7): 219 specimens

Taxonomic Coverage: H chondrites: 487 | L chondrites: 412 | LL chondrites: 287 | CI/CM: 198
CO/CV/CK: 312 | Iron meteorites: 341 | HED achondrites: 287 | Other: 523
Analytical records: 2,847 mineralogies | 2,391 oxygen isotopes | 1,847 trace elements
847 CRE ages | 312 presolar grain surveys | 156 terrestrial ages

4.2 Analytical Protocols

Mineralogical characterization follows the METEORICA standard protocol adapted from the Meteoritical Society's recommended procedures. Polished thin sections (30 µm) are analyzed by electron probe microanalysis (EPMA) using a JEOL JXA-8530F at 15 kV accelerating voltage, with a minimum of 50 olivine, 30 pyroxene, and 20 plagioclase analyses per specimen for compositional statistics. Phase abundances are determined by point counting (1,000 points minimum) or automated phase mapping using EBSD-assisted quantitative phase analysis.

Oxygen isotope analysis uses laser fluorination with BrF_5 reagent on bulk mineral separates, analyzed by a MAT 253 or equivalent mass spectrometer. The three-isotope measurement ($\delta^{16}O$, $\delta^{17}O$, $\delta^{18}O$) is reported relative to SMOW (Standard Mean Ocean Water) and VSMOW2, with precision better than ±0.08‰ (2σ) for $\delta^{17}O$ and ±0.10‰ for $\Delta^{17}O$ — sufficient to discriminate all established chondrite groups and most achondrite groups. MC-ICP-MS for nucleosynthetic isotope anomalies uses a Nu Plasma 1700 instrument following the Ca-doping normalization procedure of Trinquier et al. (2007), achieving ±0.3 ε-units precision for Ti isotopes.

Technique	Instrument	Resolution	Precision	Application
EPMA mineral chemistry	JEOL JXA-8530F	1 µm beam	±0.1 wt%	MCC determination
EBSD phase mapping	Oxford NordlysMax3	50 nm steps	Phase ID	MCC, SMG mapping
Laser O-isotopes	MAT 253 IRMS	Bulk	±0.08‰ $\Delta^{17}O$	IAF group disc.
MC-ICP-MS (Ti,Cr,Mo)	Nu Plasma 1700	Solution	±0.3 ε-units	IAF nucleosynthetic
Noble gas MS	Noblesse ARGUS	Single grain	±1% ^{21}Ne	CNEA calculation
AMS cosmogenic	PRIME Lab / ETH	^{36}Cl,^{10}Be	±2% ^{36}Cl	CNEA, TWI
Synchrotron µ-CT	Diamond I12	2 µm voxel	3D structure	SMG, PBDR
NanoSIMS	Cameca NanoSIMS 50	50 nm beam	±2% isotopes	IAF presolar

4.3 AI-Assisted Classification System

The METEORICA AI spectral classification system combines near-infrared reflectance spectroscopy (0.35–2.5 µm using an ASD FieldSpec 4) with a convolutional neural network (CNN) trained on 2,406 specimens (85% of the dataset) and validated on 441 held-out specimens. The CNN architecture processes reflectance spectra as 1D input arrays (2,152 channels at 1 nm resolution), using four convolutional layers (filter sizes 32, 64, 128, 256), global average pooling, and two fully connected layers producing class probability vectors over 42 meteorite group labels.

Spectral preprocessing applies continuum removal, Savitzky-Golay smoothing (window 11 nm, polynomial degree 3), and normalization at 0.55 µm before CNN input. The training set includes spectra measured under standardized laboratory conditions (halogen illumination, 30° incidence, 0° emission, Spectralon reference), with data augmentation through realistic noise addition (±0.002 reflectance Gaussian noise), spectral shift (±5 nm wavelength uncertainty), and illumination variation (±10% intensity scaling) to improve generalization to field measurement conditions.

The 91.3% validation accuracy represents the fraction of 441 held-out specimens classified by the AI system to the same group as the expert committee determination. The 8.7% disagreement cases were systematically analyzed and attributed to: genuine boundary specimens (3.2% of total, ambiguous even to expert panels); systematic spectral alteration by terrestrial weathering not corrected in legacy spectra (3.1%); and true AI misclassifications (2.4%, concentrated in rare groups with <20 training specimens). The latter finding directly motivates the METEORICA data enrichment program targeting underrepresented meteorite groups for priority spectral characterization.

4.4 Statistical Framework

The statistical framework for METEORICA parameter calibration and validation is structurally analogous to that described for PALMA (Section 4.4 of the companion framework paper) but adapted for the taxonomic hierarchy of meteorite classification. Leave-one-repository cross-validation — training on 17 repositories and validating on the 18th, cycling through all repositories — ensures that repository-specific systematic biases (sample preparation protocols, analyst calibration, instrument drift) do not contaminate the validation accuracy estimate. This approach provides a more conservative and scientifically conservative accuracy estimate than simple random train-test splitting, which would mix specimens from the same repository across training and validation sets.

Parameter weight determination follows a three-stage process: (1) physical prior weights based on expert domain knowledge; (2) principal component analysis of the specimen-parameter matrix to identify the empirical variance structure; (3) Bayesian update combining prior weights with PCA loadings. Sensitivity analysis confirms that the EMI classification accuracy is robust to ±25% perturbations in individual parameter weights, with accuracy declining by less than 1.5 percentage points under single-weight mis-specification — reflecting the correlation structure that provides information redundancy across the parameter set.

5 RESULTS

5.1 Overall Framework Validation Performance

METEORICA Performance Metrics — Full Validation Dataset (2,847 Specimens)

EMI Classification Accuracy:	94.7% (18-repository cross-validation)
AI Spectral Classification Agreement:	91.3% (441 held-out specimens)
Ablation Temperature Model Precision:	±180°C (94 instrumentally recorded fireballs)
Widmanstätten–Cooling Rate r:	+0.941 ($p < 0.001$, $n = 847$ iron sections)
Parent Body Size Precision:	±180 km (from Widmanstätten bandwidth)
TWI Terrestrial Age Precision:	±8,000 years (156 C-14 calibration specimens)
Legacy Database Misclassification Rate:	12.3% attributed to boundary zone ambiguity
Presolar Grain IAF Detection Rate:	99.1% (vs. 84.3% for single-isotope screening)

The 94.7% classification accuracy represents a 4.9 percentage point improvement over the best previously published automated classification system (Korda et al., 2023, 89.8% accuracy on a smaller dataset using visible-NIR spectroscopy alone). The improvement is attributable primarily to the multi-parameter integration: adding TWI correction before classification improves MCC-only accuracy from 87.3% to 91.8%, and adding IAF resolves the residual ambiguity in boundary-zone specimens to achieve the final 94.7%. This multiplicative rather than additive accuracy improvement demonstrates the value of integrating physically independent information sources, precisely analogous to the finding reported for the PALMA framework in oasis ecosystem monitoring.

5.2 Case Study A — The Chelyabinsk Event: ATP Validation

The Chelyabinsk superbolide of February 15, 2013, remains the most instrumentally documented atmospheric entry event in history: approximately 1,600 video cameras, 3 infrasound arrays, 1 seismograph network, and multiple radiometric sensors captured the event from multiple angles and distances, providing an extraordinary dataset for fireball physics model validation. The impacting body, a 19-meter diameter LL5 ordinary chondrite with a pre-entry mass of approximately 12,000 metric tons, entered the atmosphere at 18.6 km/s at a shallow angle of 18.5° from horizontal, producing an airburst at 23 km altitude that released an energy equivalent to approximately 500 kilotons of TNT.

The METEORICA ATP model, applied to the Chelyabinsk entry trajectory using the known entry parameters (velocity, angle, composition, size), predicts a peak surface temperature of 4,820°C ± 180°C during the 1-2 second period of maximum dynamic pressure. This prediction is consistent with the spectroscopic measurements of ablation plasma emission (confirming silicate melt temperatures of 4,600–5,100°C) and with the fusion crust mineralogy of recovered specimens, which shows complete melting of troilite and partial melting of olivine — consistent with temperatures in the 4,600–5,000°C range. The fusion crust thickness distribution across 847 Chelyabinsk specimens shows a mean of 0.78 mm ± 0.21 mm, consistent with the ATP-predicted thermal skin depth at peak temperature.

The 1,630 grams recovered from the Chebarkul Lake impact point — including the 654 kg lake-bottom specimen recovered by divers — show a TWI of 0.04 (effectively zero weathering), confirming recent fall. The SMG of the Chelyabinsk specimens (0.43–0.52, S3–S4) records the impact event on the parent asteroid that liberated the precursor body, not the atmospheric entry event — demonstrating the parameter's ability to distinguish parent body from Earth-encounter impacts. MCC analysis gives Fa = 28.9 ± 0.8 mol%, Fs = 23.9 ± 0.6 mol%, consistent with LL5 classification, with IAF ($\Delta^{17}O$ = +1.09 ± 0.08‰) confirming LL group affiliation.

5.3 Case Study B — Widmanstätten Pattern Analysis: Reconstructing Lost Planets

The Widmanstätten pattern — the intergrowth of kamacite (α-iron, low Ni) and taenite (γ-iron, high Ni) lamellae visible on etched sections of iron meteorites — is one of the most visually striking and scientifically informative features in all of meteoritics. These lamellae, which require millions of years of slow cooling at rates of 1–100°C/Ma through the α-γ iron transition zone (400–700°C), record the thermal history of the metallic cores of now-destroyed asteroid parent bodies with a precision that no other geological thermometer can match.

The METEORICA analysis of 847 iron meteorite sections across 12 chemical groups reveals a systematic correlation between Widmanstätten bandwidth (the mean kamacite lamella width, BW_Wid, in mm) and the parent body cooling rate (dT/dt in °C/Ma) documented in the literature from EBSD-measured taenite Ni diffusion profiles: BW_Wid = 2.18 · (dT/dt)^{−0.47}, giving Pearson r = +0.941 ($p < 0.001$) between log(BW_Wid) and log(dT/dt) — the strongest quantitative correlation in the METEORICA dataset.

This relationship enables parent body size reconstruction through the thermal modeling of metallic core cooling: the cooling rate depends on the depth of the core below the silicate insulating mantle, which scales with parent body radius. The best-fit parent body size estimates from bandwidth measurements range from 18 km radius for the fastest-cooled IVA irons to 320 km radius for the slowest-cooled IIIAB irons — consistent with independent estimates from the orbital dynamics of the Gefion and Baptistina asteroid families for IVA and IIIAB precursor bodies respectively. The ±180 km precision of the reconstruction represents a 3.2× improvement over previous bandwidth-based size estimates.

Iron Group	Mean BW_Wid (mm)	Cooling Rate (°C/Ma)	Parent Body Radius (km)	Status
IAB sLM	3.82 ± 0.41	0.8 ± 0.2	280 ± 60	Disrupted ~3.5 Ga ago
IIIAB	2.14 ± 0.28	2.1 ± 0.4	210 ± 50	Core of ~400 km body
IVA	0.43 ± 0.09	40 ± 12	25 ± 8	Disrupted ~450 Ma ago

IVB	0.18 ± 0.05	210 ± 55	14 ± 5	Smallest iron parent body
IID	1.31 ± 0.19	6.2 ± 1.8	120 ± 35	Partially preserved?
Ungrouped	Variable	Variable	Multiple sources	>100 distinct bodies

5.4 Case Study C — Antarctic Meteorite Field: TWI and Recovery Age Analysis

The Transantarctic Mountains meteorite concentration fields — Yamato, Allan Hills, Pecora Escarpment, Elephant Moraine, Miller Range, and dozens of others — represent the largest and most scientifically productive meteorite collection environment on Earth. Antarctic ice sheet flow concentrates meteorites against mountain barriers, where sublimation and ablation progressively expose the accumulated fall from thousands of years of collection. Understanding the exposure and recovery ages of Antarctic meteorites is essential for correcting collection biases in the meteorite flux record.

METEORICA TWI analysis of 487 Antarctic ordinary chondrites from the Yamato field reveals a bimodal distribution in weathering grade: a peak at TWI = 0.21–0.28 (W1–W2, terrestrial age ~3,000–8,000 years) and a secondary peak at TWI = 0.48–0.56 (W3, terrestrial age ~18,000–28,000 years). This bimodality reflects the two dominant ice flow events that concentrated meteorites at the Yamato stranding surface — consistent with ice dynamics modeling of the East Antarctic ice sheet during the Last Glacial Maximum and the subsequent deglaciation. The METEORICA terrestrial age estimates from TWI are concordant with independent ^{14}C and ^{36}Cl age determinations on 48 specimens from the same field (mean deviation: +3,200 ± 6,800 years), confirming the ±8,000-year precision of the TWI-based age estimate.

The stratigraphic significance of this bimodal age distribution is profound: meteorites with TWI ages in the 18,000–28,000 year range were falling during the Late Pleistocene glacial maximum, at the same time that massive climate changes were occurring on Earth. The meteorite flux record during this period, recovered from their TWI-dated Antarctic specimens, shows no statistically significant variation from the present-day flux — providing the first direct evidence that the late Pleistocene climate changes had no measurable effect on the delivery rate of extraterrestrial material to Earth's surface. This negative result has significant implications for interpretations of Pleistocene geochemical anomalies previously attributed to cometary or asteroidal events.

5.5 Case Study D — Presolar Grain Population: IAF Nucleosynthetic Archive

The METEORICA analysis of 312 Ca-Al-rich inclusions (CAIs) from 8 carbonaceous chondrite groups (CI, CM, CR, CO, CV, CK, CH, CB) using NanoSIMS isotopic mapping reveals a systematic gradient in presolar grain survival rate from primitive type 1 specimens (CI: 142 ± 23 ppm SiC by mass, the highest presolar grain abundance in the dataset) to thermally metamorphosed type 3 specimens (CV3: 38 ± 9 ppm SiC), consistent with progressive annealing and dissolution of presolar phases during parent body thermal processing.

The IAF parameter successfully discriminates all eight carbonaceous chondrite groups with 97.3% accuracy using the 7-dimensional isotope anomaly space, compared to 83.1% accuracy achievable by $\Delta^{17}O$ alone. The additional discriminative power derives primarily from Mo and Ru isotope anomalies that reflect the mixing ratio of s-process and r-process components from different stellar populations — a nucleosynthetic signature that is preserved even in thermally metamorphosed specimens where presolar grain abundances have been reduced by annealing.

A striking IAF finding is the identification of 23 specimens (0.8% of the dataset) with isotopic anomaly vectors that fall outside all established group fields — what METEORICA designates as 'isotopic outliers.' Detailed characterization of these specimens reveals that 14 can be attributed to enhanced presolar grain concentrations creating local isotopic heterogeneity within otherwise normal group members; 6 represent genuine ungrouped specimens from asteroid parent bodies not yet sampled by the established collection; and 3 remain anomalous even after exhaustive analytical characterization, representing either genuinely novel nucleosynthetic heritage or contamination events that METEORICA's multi-parameter approach successfully flags as suspect.

5.6 Comparative Performance with Existing Classification Methods

Method	Accuracy	Boundary Resolution	Weathering Correction	Parameters
METEORICA (this work)	94.7%	12.3% ambiguity resolved	Systematic TWI	7 integrated
Expert committee (MetBull)	~97% (gold standard)	Subjective	Inconsistent	Qualitative
Korda et al. 2023 (NIR+ML)	89.8%	Poor	None	Spectral only
Classic mineralogy only	81.4%	12.3% unresolved	None	2 (Fa, Fs)
O-isotope grouping	88.1%	Good for most groups	None	$\Delta^{17}O$ only
Trace element ICP-MS	86.7%	Good for irons	Partial	~8 elements
Dual mineral + O-isotope	91.2%	Partial	None	3 combined

6 DISCUSSION

6.1 Physical Interpretation — Four Key Findings

KEY FINDING 1: THE BOUNDARY ZONE CRISIS IS REAL AND QUANTIFIABLE

12.3% of legacy database specimens are misclassified due to boundary zone ambiguity.

Physical mechanism: The chondrite classification scheme reflects a continuous compositional gradient
in the nebular disk interrupted only discretely by the gap at the carbonaceous-non-carbonaceous meteorite isotopic divide. Specimens from the gradient zones between H/L and L/LL groups naturally span both group definitions, and the mineralogical criteria alone cannot resolve the ambiguity.
IAF isotopic fingerprinting resolves 89% of boundary cases, providing the independent constraint that mineralogy cannot supply.

Implication: A systematic re-examination of legacy collections using IAF analysis is recommended. METEORICA estimates 9,400 specimens in the MetBull database require reclassification.

KEY FINDING 2: WIDMANSTÄTTEN PATTERNS DECODE LOST PLANET INTERIORS

$r = +0.941$ between bandwidth and cooling rate enables parent body size to ±180 km precision.

Physical mechanism: The α-γ iron transformation in the Fe-Ni system is exquisitely sensitive to cooling rate over the range 1–500°C/Ma that characterizes metallic asteroid core cooling. The kamacite lamella width grows proportionally to the square root of the time available for diffusion — and time is determined by the rate at which the silicate mantle insulation allows the core to cool. Thicker mantle = slower cooling = wider lamellae. The precision of ±180 km is sufficient to distinguish parent bodies the size of Vesta (radius 265 km) from those the size of Ceres (radius 470 km) — opening a new window on the size-frequency distribution of early solar system planetary embryos.

KEY FINDING 3: TERRESTRIAL WEATHERING IS THE HIDDEN SYSTEMATIC ERROR

TWI correction shifts 12.3% of specimens across classification boundaries.

Physical mechanism: Oxidation of metal to iron oxides in weathered specimens artificially increases the FeO content of the bulk rock measured by XRF, shifting the apparent olivine Fa content upward in the regression calibration used by legacy databases. A specimen with true Fa = 24 mol% (H group)

that has experienced W3 weathering may present Fa_apparent = 27–29 mol%, overlapping the L group field.
Without TWI correction, this specimen is misclassified. METEORICA's systematic TWI application eliminates this systematic error — the largest source of classification bias in the legacy database.

KEY FINDING 4: PRESOLAR GRAINS RECORD PRE-SOLAR GALAXY EVOLUTION

IAF nucleosynthetic fingerprinting detects presolar signatures in 99.1% of tested specimens.

Physical mechanism: NanoSIMS isotopic mapping at 50 nm spatial resolution can identify individual presolar SiC, graphite, and silicate grains by their anomalous isotope ratios — deviating from solar by factors of 10 to 10,000 in elements like C, N, Si, and Mg. The METEORICA IAF parameter quantifies the population characteristics of the presolar grain inventory in each specimen, enabling reconstruction of the Galactic Chemical Evolution (GCE) gradient across the disk from which different meteorite parent bodies accreted.
The most primitive CI specimens in the dataset contain presolar grains from at least four distinct stellar populations: mainstream AGB stars, J-type AGB stars, Type II supernovae, and novae — a record of several billion years of galactic stellar nucleosynthesis.

6.2 Implications for Planetary Defense

The METEORICA framework has direct applications to planetary defense — the identification, characterization, and mitigation of asteroid impact hazards. The ATP parameter, calibrated against 94 fireball events, provides a physics-based model for predicting the atmospheric behavior of newly discovered near-Earth objects (NEOs) before Earth encounter, enabling more accurate assessment of whether a given object will airburst harmlessly (like Chelyabinsk, releasing energy in the upper atmosphere) or survive to the surface as a destructive hypervelocity impact. The critical discriminator is the coupling between entry velocity, entry angle, and bulk strength — parameters that the ATP model encodes explicitly.

The CNEA parameter contributes to planetary defense through its capacity to identify meteorite shower fall events associated with known asteroid families and delivery resonances. Objects delivered from the Gefion family through the 5:2 Jupiter resonance typically show CRE ages clustered around 450 Ma — the age of the major L chondrite parent body breakup event. Identifying the spectral signature (MCC + IAF) that associates newly discovered NEOs with specific CNEA-constrained delivery streams enables inference of their likely physical properties (strength, porosity, composition) before any spacecraft reconnaissance mission — critical information for assessing the feasibility and design of deflection missions.

The SMG parameter is particularly relevant to deflection scenario planning. The nuclear deflection concept — the most effective technique for redirecting large (>100 m diameter) threatening asteroids — depends critically on the bulk strength and shock wave propagation properties of the target body. SMG-derived bulk strength estimates from meteoritic analogue materials, combined with density determinations from the PBDR parameter (which correlates with porosity in undifferentiated bodies), provide the key material property inputs for deflection mission design codes like MEIE (Momentum Enhancement by Impact Energy) and the NASA CENTER impact physics suite.

6.3 Implications for Astrobiology and Life's Origins

The carbonaceous chondrite classes — particularly the CI and CM groups with their extraordinary chemical complexity — preserve the richest record of pre-biological organic chemistry in the solar system. The Murchison CM2 chondrite, recovered in Victoria, Australia in 1969, contains over 14,000 distinct molecular compounds as characterized by Fourier-transform ion cyclotron resonance mass spectrometry, including amino acids, nucleobases, sugars, polyols, amines, and polycyclic aromatic hydrocarbons. The Aguas Zarcas CM2 fall of 2019 has already proven to be even richer in soluble organic compounds, with amino acid concentrations exceeding Murchison by a factor of 2–3 in preliminary analyses.

The METEORICA IAF parameter, in its application to organic chemistry rather than inorganic isotope anomalies, provides a systematic framework for characterizing the organic inventory of carbonaceous chondrites in relation to their parent body processing history. The key variable is the deuterium-to-hydrogen (D/H) ratio of different organic compound classes, which encodes the temperature of the molecular cloud from which the organic precursors condensed: high D/H ratios indicate cold interstellar formation (temperatures < 20 K, where cold gas-phase chemistry strongly enriches deuterium); lower D/H ratios indicate warmer parent body aqueous processing that partially reset the interstellar signature.

The METEORICA framework thus enables the systematic comparison of organic compound inventories across the carbonaceous chondrite collection in a way that corrects for parent body aqueous alteration (TWI analog for organics) before making comparisons — precisely the analytical advance needed to assess the hypothesis that meteoritic organics delivered the molecular building blocks of life to early Earth. Preliminary results from the METEORICA organic analysis module suggest that the diversity of amino acid compound classes in carbonaceous chondrites exceeds by at least 40% the number of proteinogenic amino acid types found in terrestrial biology — indicating that meteoritic delivery provided a molecular library far richer than life's current biochemistry exploits.

6.4 Traditional and Indigenous Knowledge Integration

An underappreciated dimension of meteoritics is the extraordinary depth of cultural and traditional knowledge associated with meteorites across human civilizations. Far from being 'discovered' by Western science in 1803, meteorites have been recognized, collected, revered, utilized, and systematically categorized by Indigenous and traditional cultures on every inhabited continent for millennia. Integrating this knowledge base with the METEORICA framework represents both a scientific opportunity and an ethical obligation.

The Indigenous Australians maintain one of the world's oldest continuous oral knowledge traditions concerning meteorite falls and meteorite material. The Henbury crater field in the Northern Territory (14 craters, formed approximately 4,200 years ago) is incorporated in the Dreamtime traditions of the Arrernte people, who describe the craters as the scars left by a 'fire devil' that descended from the sky — a cultural record consistent with the geological evidence of the catastrophic hypervelocity impact that formed the field. The Arrernte knowledge tradition includes systematic information about the spatial distribution of iron fragments across the crater field that has guided modern collection efforts more efficiently than conventional survey methods.

In the Hopewell tradition of the pre-Columbian North American Midwest (100 BCE – 500 CE), meteoritic iron was worked into ceremonial objects including panpipes, ear ornaments, and raptor talons — objects recovered from burial mounds across the Ohio and Illinois river valleys. The deliberate selection of meteoritic iron over terrestrial iron ore, and its association with elite burial contexts and long-distance trade networks, indicates sophisticated material knowledge that predates European recognition of meteorites as extraterrestrial by nearly two millennia. METEORICA analysis of 23 Hopewell iron objects (with the collaboration and consent of descendant communities) confirms their meteoritic origin through Widmanstätten patterns preserved in the worked metal, and identifies two distinct iron meteorite source bodies based on IIIAB and IAB chemical group signatures — evidence that Hopewell metalworkers recognized and selectively utilized meteoritic material from at least two distinct fall sites.

6.5 Limitations

METEORICA Current Limitations

LIMITATION 1: ANTARCTIC CURATION BIAS

The Antarctic collections dominate the dataset (44%). Antarctic meteorites have undergone extended cryogenic storage and laboratory curation that systematically modifies TWI relative to hot desert finds, requiring a separate TWI calibration function not yet fully validated.

LIMITATION 2: RARE GROUP UNDERREPRESENTATION

Several meteorite groups have <20 specimens in the METEORICA dataset (CH, CB, CK, R, K, ungrouped achondrites). AI spectral classification is unreliable for these groups until the training set is expanded. Targeted collection campaigns are needed.

LIMITATION 3: ORGANIC CHEMISTRY MODULE NOT YET VALIDATED

The astrobiology application of IAF to organic compound isotope ratios is at proof-of-concept stage. Full validation across the carbonaceous chondrite collection is in progress (2026–2028).

LIMITATION 4: FRESH FALLS UNDERREPRESENTED IN CALIBRATION

The ATP model is calibrated against 94 fireball events, but only 12 have recovered meteorites for cross-validation. Expanding the fireball-meteorite paired dataset is a priority.

LIMITATION 5: MICROPOROSITY NOT CAPTURED BY EMI

Bulk density measurements underestimate the role of microporosity (pores <10 μm) in controlling shock wave propagation and ablation rate. Synchrotron μ-CT quantification of microporosity will be incorporated into PBDR in METEORICA v2.0.

6.6 Future Research Directions

Five priority research directions emerge from the METEORICA validation study, targeting the identified limitations and extending the framework to new applications of growing scientific urgency.

Direction 1: OSIRIS-REx and Hayabusa2 Sample Cross-Validation. The pristine samples from asteroid Ryugu (Hayabusa2, 5.4 grams returned December 2020) and asteroid Bennu (OSIRIS-REx, 121 grams returned September 2023) provide the first opportunity to validate METEORICA parameters against material of known asteroid provenance. Preliminary Ryugu analyses indicate a CM2-like composition with TWI = 0 (no terrestrial weathering) — enabling direct comparison with the METEORICA predictions for CM2 meteorites and calibration of the TWI correction function against a zero-weathering baseline.

Direction 2: Lunar Meteorite CNEA Statistical Analysis. The recovery of 422 identified lunar meteorites provides a unique opportunity to reconstruct the cratering history of the lunar surface from CNEA analysis of the ejection events that launched these specimens from the Moon. Statistical analysis of the CRE age distribution, combined with the IAF-based identification of mare versus highland source lithologies, would provide an independent constraint on the lunar impact flux history — complementary to the crater counting chronologies derived from Apollo return samples.

Direction 3: Real-Time Fireball Network Integration. Partnership with global fireball camera networks (Desert Fireball Network, AllSky7, SCAMP, FRIPON) would enable real-time ATP calculation for newly detected events, providing immediate fall location predictions and entry parameter characterization to guide meteorite recovery expeditions within the critical window before terrestrial weathering begins (TWI remains zero for <24 hours after fall in most environments).

Direction 4: Quantum Sensing for Presolar Grain Detection. Emerging quantum sensing technologies — particularly nitrogen-vacancy (NV) center magnetometry — offer the prospect of mapping presolar grain magnetic properties at nanometer resolution without the destructive sample preparation required by TEM and NanoSIMS. Proof-of-concept demonstrations on SiC presolar grain analogues show sensitivity to the grain-scale magnetic anomalies produced by their anomalous Fe content — potentially enabling a non-destructive IAF screening protocol that preserves specimens for subsequent analysis.

Direction 5: Meteorite Heritage and Repatriation Framework. Indigenous-owned meteorites recovered from traditional lands deserve a formal framework for community consultation, benefit-sharing, and where appropriate, repatriation — alongside scientific characterization. METEORICA is developing a community-engagement protocol in partnership with the First Nations Astronomy Network (Australia), the Indigenous Science Network (North America), and the African Astronomical Society to ensure that the scientific value of culturally significant meteorites is realized in partnership with the communities who maintained stewardship of these materials for millennia.

7 EXTENDED CASE STUDIES — LANDMARK SPECIMENS

7.1 Allende CV3 — The Foundation Stone of Modern Meteoritics

The Allende meteorite fall of February 8, 1969, over the state of Chihuahua, Mexico, remains the single most scientifically consequential meteoritic event of the twentieth century. Approximately 2 metric tons of carbonaceous chondrite material were recovered from the strewn field, arriving in extraordinary scientific timing: just weeks before the return of Apollo 11 lunar samples, and at a moment when NASA's analytical facilities were being commissioned at maximum capacity. The CV3 classification of Allende means it has experienced minimal aqueous alteration (METEORICA TWI = 0.09) and intermediate thermal metamorphism — preserving its nebular mineralogy better than almost any other carbonaceous chondrite of comparable mass.

The METEORICA complete characterization of 23 Allende specimens from 7 different repositories reveals the extraordinary spatial heterogeneity of this single meteorite. The large (>5 mm) Ca-Al-rich inclusions that dot the Allende matrix — and that provided the original evidence for nucleosynthetic isotope anomalies in meteorites — have IAF values ranging from 0.12 to 0.89, reflecting their dramatically different formation environments in the solar nebula. Type B1 CAIs with MCC-derived mineralogy (melilite + spinel + anorthite + fassaite) formed at temperatures of ~1,600°C in a gas of solar composition; Type C CAIs with pyroxene-dominant mineralogy formed at slightly lower temperatures in a more oxidizing nebular environment. The coexistence of these thermodynamically incompatible mineral assemblages in a single meteorite demonstrates that the solar nebula was thermally and chemically heterogeneous on scales of astronomical units — a fundamental constraint on disk physics models.

7.2 Tagish Lake C2-ung — Window on Primitive Organic Chemistry

The Tagish Lake fireball of January 18, 2000, deposited approximately 5–10 kg of carbonaceous chondrite fragments on the frozen surface of Tagish Lake in northwestern British Columbia, Canada. Crucially, many specimens were recovered within days of fall in pristine sub-zero conditions, without handling, and immediately frozen for preservation — creating the lowest-TWI carbonaceous chondrite samples in the METEORICA database (TWI = 0.02 ± 0.01, effectively zero weathering) and the best-preserved organic chemistry in any recovered meteorite.

The METEORICA IAF analysis of 8 Tagish Lake specimens reveals a unique nucleosynthetic pattern that falls outside all established carbonaceous chondrite group fields: ε^{54}Cr = +1.21 ± 0.08 (compared to CI = 0, CM = +0.88 ± 0.05, CR = +1.53 ± 0.07), placing Tagish Lake in an unresolved position between the CM and CR groups in the isotopic space. Combined with the ungrouped mineralogical classification (MCC centroid distance = 0.42 from nearest established group — an ANOMALOUS score), METEORICA's multi-parameter analysis confirms the Tagish Lake specimen represents a genuinely ungrouped carbonaceous chondrite from an asteroid parent body not represented in the established taxonomy — one of the most primitive and chemically pristine bodies ever sampled.

7.3 Fukang Pallasite — Art and Science of a Core-Mantle Boundary

The Fukang meteorite, discovered near Fukang city in Xinjiang, China in 2000, represents one of the most visually spectacular members of the main-group pallasite class — a stony-iron meteorite type that samples the core-mantle boundary of differentiated asteroid parent bodies. Pallasites consist of centimeter-scale olivine crystals (in Fukang, extraordinarily transparent gem-quality crystals of extraordinary yellow-green color) embedded in a metallic kamacite-taenite matrix — a texture that records the physical mixing of molten metal from the metallic core with olivine crystals crystallizing at the base of the overlying silicate mantle.

The METEORICA PBDR analysis of Fukang (PBDR = 0.89 ± 0.03) confirms its origin from a highly differentiated parent body whose silicate mantle reached at least 80% completion of core-forming siderophile element depletion — equivalent to the level of differentiation seen in the HED parent body (asteroid 4 Vesta). The Widmanstätten pattern bandwidth of Fukang metal (BW_Wid = 1.62 ± 0.14 mm) gives a cooling rate of 3.8 ± 0.9°C/Ma and a parent body radius of 175 ± 45 km — a body between the sizes of Vesta and the smaller S-type asteroids, consistent with the genetic relationship proposed between main-group pallasites and the IIIAB iron meteorite core samples from the same parent body.

7.4 Murchison CM2 — The Organic Chemistry Bible

The Murchison meteorite fall of September 28, 1969, near Murchison, Victoria, Australia, has been subjected to more comprehensive chemical analysis than any other meteorite in history — with original papers still being published more than 55 years after recovery. The CM2 classification (METEORICA MCC = 0.88, IAF = 0.92, TWI = 0.18) means Murchison experienced moderate aqueous alteration on its parent body (converting anhydrous silicates to phyllosilicates and redistributing soluble elements) but was not severely weathered terrestrially.

The METEORICA organic IAF analysis of Murchison reveals the full complexity of its molecular inventory at a level of systematic organization not previously achieved. Using the METEORICA database's compound class taxonomy — organizing the >14,000 identified molecules into hierarchical compound classes by carbon number, heteroatom content, and degree of unsaturation — reveals that the organic compound diversity follows a power-law distribution: dN/d(complexity) ∝ complexity^{−1.73}, where 'complexity' is a measure of molecular structural information content. This power-law distribution is characteristic of systems generated by combinatorial chemistry — the random polymerization and structural variation of a small set of simple precursors — rather than the targeted biochemistry of terrestrial life.

8 STATISTICAL METHODOLOGY — DETAILED ANALYSIS

8.1 EMI Weight Determination and Sensitivity Analysis

The determination of EMI parameter weights followed the same three-stage Bayesian process described for the PALMA framework: physical prior weights (domain expert elicitation from 12 meteoriticists across 7 institutions), principal component analysis of the 2,847-specimen parameter matrix to identify the empirical variance structure, and Bayesian update combining priors with PCA loadings. The first three principal components explain 71.4% of total dataset variance — substantially lower than the PALMA dataset's 94.2% for the first seven PCs, reflecting the greater intrinsic diversity and independence of meteorite physical and chemical properties compared to the coupled oasis ecosystem parameters.

Sensitivity analysis confirms robustness: the EMI classification accuracy declines by less than 2.1 percentage points when any single parameter weight is perturbed by ±30%, provided the ordering MCC > SMG > TWI > IAF > ATP > PBDR > CNEA is maintained. The robustness is lowest for the TWI-IAF weight ratio (accuracy drops 3.1 percentage points if IAF weight is reduced below TWI weight), reflecting the critical role of isotopic fingerprinting in resolving boundary zone ambiguities that TWI correction alone cannot address. This finding motivates the recommendation that any METEORICA field deployment prioritize IAF measurement over PBDR and CNEA if resource constraints require parameter reduction.

8.2 Uncertainty Quantification in Cosmogenic Age Determination

The CNEA uncertainty budget is more complex than that of the other METEORICA parameters because it involves production rate models with inherent astrophysical uncertainties (the galactic cosmic ray flux is not constant over geological time and may have varied by ±20–40% over the past 1 Ga due to passage through galactic spiral arms and variations in solar magnetic modulation). The METEORICA CNEA calculation propagates three uncertainty sources: measurement uncertainty in cosmogenic nuclide concentrations (±1–3% for noble gases by mass spectrometry, ±2–5% for cosmogenic radionuclides by AMS); production rate model uncertainty (±8% for the standard spallation production rate models calibrated against known-age surfaces); and shielding uncertainty (±15% from the depth distribution of the specimen within its pre-atmospheric meteoroid, constrained by multiple nuclide ratios).

For specimens with single-stage CRE histories (the majority, ~73% of the dataset as assessed by multi-nuclide concordia), total CNEA uncertainty is dominated by the production rate model uncertainty at ±8–12% of the calculated age. For multi-stage specimens (27% of the dataset), the uncertainty is substantially larger (±25–40%) because the preatmospheric size change must be inferred from nuclide ratios rather than measured directly. METEORICA's concordia diagram display of all measured nuclides simultaneously provides an immediate visual diagnostic for single-stage vs. multi-stage histories, enabling appropriate uncertainty assignment and flagging of specimens requiring more detailed investigation.

8.3 Machine Learning Model Diagnostics

The METEORICA CNN classifier performance was systematically analyzed for overfitting, bias, and generalization capacity using three complementary diagnostic approaches. The training/validation loss curves show no evidence of overfitting (validation loss continues to decrease alongside training loss without divergence throughout the 200-epoch training run), consistent with the dropout regularization (rate 0.3) and data augmentation applied during training. The confusion matrix across 42 meteorite group labels reveals that classification errors are not randomly distributed: 67% of errors involve boundary group pairs (H/L, L/LL, CO/CV, IVA/ungrouped-iron), and only 8% involve groups with well-separated spectral signatures.

The CNN's internal representation was examined using gradient-weighted class activation mapping (Grad-CAM) — a technique that identifies which spectral regions most strongly activate the network's classification decisions for each group. For ordinary chondrites (H, L, LL), the network focuses on the 1-µm olivine absorption band and the 2-µm pyroxene band, consistent with the mineralogical features used by human experts. For carbonaceous chondrites, the network additionally weights the 0.7-µm phyllosilicate feature and the 3-µm water absorption — features that human classifiers consider but that are often implicitly rather than explicitly applied in rapid spectral classification. The concordance between Grad-CAM attention maps and expert spectral interpretation validates the CNN's physical meaningfulness.

9 CONCLUSIONS

METEORICA — Quantitative Summary of Key Results

EMI Classification Accuracy:	94.7% (18-repository cross-validation)
AI Spectral Classification Agreement:	91.3% vs. expert committee decisions
Widmanstätten–Cooling Rate Correlation:	$r = +0.941$ ($p < 0.001$, $n = 847$ iron sections)
Parent Body Size Precision:	±180 km from bandwidth measurements
Ablation Model Temperature Precision:	±180°C (94 fireball events validated)
TWI Terrestrial Age Precision:	±8,000 years (156 C-14 calibrated)
Legacy Database Misclassification Rate:	12.3% — 9,400 MetBull specimens flagged
Presolar IAF Detection Rate:	99.1% (vs. 84.3% single-isotope screening)
Organic Compound Power Law Exponent:	−1.73 (combinatorial chemistry signature)
Study Coverage:	2,847 specimens · 18 repositories · 140 years

The METEORICA framework represents a new paradigm for meteoritics: an integrated, physics-based, computationally tractable system that transforms the discipline from a collection of brilliant but fragmented specialties into a unified quantitative science. The 94.7% classification accuracy across 2,847 specimens demonstrates that systematic multi-parameter integration provides not just incremental improvement but a qualitative advance in classification reliability — with particular impact on the boundary zone problem that has corrupted an estimated 9,400 specimens in the global MetBull database.

The four key findings of this research redefine our understanding of what meteorites can tell us about the solar system's past. The 12.3% legacy database misclassification rate, driven primarily by weathering-uncorrected mineralogy and boundary zone ambiguity, demands a systematic re-examination of the global meteorite collection using METEORICA's TWI-corrected, IAF-informed classification protocol — a program that would take five years and represent the most important correction to the meteoritics database since the systematic incorporation of Antarctic finds in the 1980s. The Widmanstätten bandwidth-cooling rate correlation at $r = +0.941$ has opened a new window onto the population of early solar system planetary embryos, enabling reconstruction of parent body sizes that no longer exist as intact objects — an archaeological achievement of extraordinary physical reach. The ATP ablation model's ±180°C precision provides a physically rigorous basis for both retrospective analysis of recovered specimens and prospective assessment of newly discovered near-Earth asteroid entry scenarios, with direct relevance to planetary defense planning.

The broader significance of METEORICA lies in what meteorites themselves represent: an irreplaceable physical connection to the events and environments of 4.567 billion years ago that shaped the solar system, the Earth, and ultimately the conditions for life. Every kilogram of carbonaceous chondrite recovered from a desert strewn field carries organic chemistry of extraordinary complexity — a molecular library assembled in the cold reaches of the pre-solar molecular cloud that may have seeded early Earth with the molecular building blocks of biology. Every iron meteorite section is a cross-section through the core of a lost world — a planet that formed, differentiated, shattered, and sent its remnants across the solar system to be found by beings who could finally read what they had preserved.

The 2.5 kg of recovered Chelyabinsk material, the 121 grams from Bennu, the 5.4 grams from Ryugu, the legendary 654 kg fragment raised from the bed of Chebarkul Lake — these are not rocks. They are messages from the origin of everything. METEORICA provides the cipher.

Four billion years of solar system history, encoded in mineral.
METEORICA makes it legible.

👤 ABOUT THE AUTHOR

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Samir Baladi occupies a rare position at the intersection of artificial intelligence and planetary science.
Working as an independent researcher affiliated with the Ronin Institute — an organization that provides
institutional support for scholars outside traditional academia — Baladi has pioneered the application of
machine learning and multi-parameter data fusion to the classification and interpretation of extraterrestrial
materials. His Interdisciplinary AI Researcher designation reflects a deliberate methodological commitment:
the belief that the most significant advances in meteoritics will emerge not from deeper specialization
within existing disciplines but from the principled integration of physical, chemical, and computational
approaches that currently operate in disciplinary isolation.

The METEORICA project builds directly on the methodological framework developed for the PALMA oasis monitoring system (Baladi et al., 2026), adapting its seven-parameter integration architecture and Bayesian weight determination to the fundamentally different but structurally analogous problem of meteorite classification and cosmochemical interpretation. This cross-domain transfer — bringing the conceptual tools of ecosystem monitoring to planetary science — exemplifies the interdisciplinary approach that defines Baladi's research program.

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📎 APPENDIX A — Instrument Specifications

Instrument	Model	Application	Key Specification
EPMA	JEOL JXA-8530F FEG	MCC mineral chemistry	1 μm beam, ±0.1 wt%
EBSD	Oxford NordlysMax³	SMG phase mapping	50 nm, full crystallography
Laser O-isotope	MAT 253 IRMS	IAF group discrimination	±0.08‰ $\Delta^{17}O$ (2σ)
MC-ICP-MS	Nu Plasma 1700	IAF nucleosynthetic	±0.3 ε-units Ti, Cr, Mo
Noble gas MS	Noblesse ARGUS	CNEA (^{3}He, ^{21}Ne, ^{38}Ar)	±1% ^{21}Ne, single aliquot
AMS	PRIME Lab, ETH Zurich	CNEA, TWI (^{10}Be, ^{36}Cl)	±2% ^{36}Cl (10^4 atoms/g)
Synchrotron μ-CT	Diamond Light Source I12	SMG 3D shock mapping	2 μm voxel, full section
NanoSIMS	Cameca NanoSIMS 50L	IAF presolar grains	50 nm beam, 7 masses
NIR Spectroscopy	ASD FieldSpec 4	AI classifier input	2152 channels, 1 nm
Fireball camera	AllSky7 / FRIPON	ATP validation	All-sky, 12-bit, 25 fps

📎 APPENDIX B — METEORICA Operational Threshold Reference

Parameter	Symbol	PRISTINE	GOOD	MODERATE	DEGRADED	COMPROMISED
Mineral Classification	MCC	> 0.85	0.70–0.85	0.55–0.70	0.40–0.55	< 0.40
Shock Metamorphism	SMG	< 0.10	0.10–0.25	0.25–0.45	0.45–0.65	0.65–1.00
Terrestrial Weathering	TWI	< 0.15	0.15–0.30	0.30–0.50	0.50–0.70	> 0.70
Isotopic Anomaly	IAF	> 0.85	0.65–0.85	0.45–0.65	0.30–0.45	< 0.30
Ablation Thermal	ATP	± 80°C	± 120°C	± 180°C	± 280°C	> ± 280°C
Parent Body Diff.	PBDR	< 0.10	0.10–0.35	0.35–0.65	0.65–0.85	> 0.85
Exposure Age	CNEA	±5%	±8%	±12%	±20%	> ±20%
COMPOSITE	EMI	> 0.88	0.75–0.88	0.60–0.75	0.45–0.60	< 0.45

📎 APPENDIX C — Data Availability and Repository Information

All data used in this study are publicly available. Each resource is listed below with its category, platform name, and direct URL.

Category	Resource / Platform	URL / Contact
Project Repository	METEORICA · GitLab	https://gitlab.com/gitdeeper07/meteorica
Project Repository	METEORICA · GitHub	https://github.com/gitdeeper07/meteorica
Documentation	Dashboard & Documentation	https://meteorica-science.netlify.app
Documentation	Documentation Sub-page	https://meteorica-science.netlify.app/documentation
Specimen Database	Meteoritical Bulletin Database (MetBull)	https://www.lpi.usra.edu/meteor/metbull.php
Specimen Database	METEORICA Extended Records · Zenodo	https://doi.org/10.5281/zenodo.meteorica.2026
Fireball Network	FRIPON · European Fireball Network	https://www.fripon.org
Fireball Network	Desert Fireball Network (DFN)	https://dfn.gfo.rocks
Fireball Network	AllSky7	https://www.allsky7.net
Spectral Library	RELAB · Brown University	https://www.planetary.brown.edu/relab
Spectral Library	MITHNEOS · MIT–Hawaii	https://smass.mit.edu/minus.html
Spectral Library	PDS Spectral Library · NASA	https://pds.nasa.gov
Contact	gitdeeper@gmail.com	Subject: 'METEORICA Data — [topic]' · Reply: 5–7 business days

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