Revista Científica TecnoHumanismo
https://tecnohumanismo.online
Julio - Septiembre 2026
Volumen 6 / No. 3
ISSN: 2710-2394
pp. 168 - 167

The Martian Gold Frontier: Geochemical Potential, Extraction Technologies, and Techno-Economic Pathways for Precious-Metal Mining in the Inner Solar System

La frontera del oro marciano: potencial geoquímico, tecnologías de extracción y vías técnico-económicas para la minería de metales preciosos en el sistema solar interior.

A Fronteira do Ouro em Marte: Potencial Geoquímico, Tecnologias de Extração e Caminhos Tecnoeconômicos para a Mineração de Metais Preciosos no Sistema Solar Interno

ARTÍCULO ORIGINAL

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Recibido 25 de Junio 2026 | Arbitrado y aceptado 12 de Julio 2026 | Publicado el 16 de Septiembre 2026

RESUMEN

Human expansion beyond Earth requires a transition from supply architectures dominated by terrestrial launch to systems capable of identifying, extracting, and transforming extraterrestrial resources. This article critically evaluates the potential for gold (Au), platinum-group elements (PGEs), and strategic metals on Mars, placing the Red Planet at the center of a possible inner-Solar-System mineral economy. An integrative review of 40 scientific sources with verifiable DOIs covers Martian geochemistry, meteorites, highly siderophile elements, magmatic and hydrothermal metallogenesis, impacts, water and ice, in-situ resource utilization (ISRU), drilling, regolith processing, asteroids, the Martian moons, and space economics. Evidence confirms Au and other HSEs in Martian materials, while plausible concentration mechanisms include sulfide segregation, hydrothermal activity, impact systems, and sedimentary processes. No direct evidence, however, demonstrates a Martian gold deposit with grade, tonnage, and continuity sufficient for classification as an exploitable resource. A Space Gold Prospectivity Index (SGPI) is proposed to prioritize exploration targets by integrating geology, accessibility, water, energy, technology maturity, and uncertainty. The analysis concludes that water, oxygen, propellants, and structural materials are likely to precede Au as economically relevant products; at later stages Mars could evolve into an industrial and logistical node linked to Phobos, Deimos, asteroids, and volatile-rich bodies. The Martian gold frontier should therefore be understood as a planetary economic-geology research program rather than as a demonstrated mineral reserve.

Keywords: Mars; space mining; gold; precious metals; platinum-group elements; ISRU; Phobos; Deimos; asteroids; planetary economic geology.

ABSTRACT

La expansión humana más allá de la Tierra exige transitar desde arquitecturas dependientes de suministros terrestres hacia sistemas capaces de identificar, extraer y transformar recursos extraterrestres. Este artículo evalúa críticamente el potencial del oro (Au), elementos del grupo del platino (PGE) y metales estratégicos en Marte, con el planeta rojo como núcleo de una posible economía mineral del Sistema Solar interior. Se realizó una revisión integrativa de 40 fuentes científicas con DOI verificable sobre geoquímica marciana, meteoritos, elementos altamente siderófilos, metalogénesis magmática e hidrotermal, impactos, agua y hielo, utilización de recursos in situ (ISRU), perforación, procesamiento de regolito, asteroides, lunas marcianas y economía espacial. La evidencia confirma Au y otros HSE en materiales marcianos, y existen mecanismos plausibles para su concentración mediante segregación de sulfuros, actividad hidrotermal, impactos y procesos sedimentarios. Sin embargo, no existe evidencia directa de un yacimiento aurífero marciano con ley, tonelaje y continuidad suficientes para ser clasificado como recurso explotable. Se propone un Space Gold Prospectivity Index (SGPI) para priorizar objetivos de exploración integrando geología, accesibilidad, agua, energía, madurez tecnológica e incertidumbre. El análisis concluye que agua, oxígeno, propelentes y materiales estructurales probablemente antecederán al Au como productos económicamente relevantes; en fases posteriores, Marte podría evolucionar hacia un nodo industrial y logístico conectado con Fobos, Deimos, asteroides y cuerpos ricos en volátiles. La frontera del oro marciano debe entenderse, por tanto, como un programa de geología económica planetaria y no como una reserva mineral ya demostrada.

Palabras clave: Marte; minería espacial; oro; metales preciosos; elementos del grupo del platino; ISRU; Fobos; Deimos; asteroides; geología económica planetaria.

RESUMO

A expansão humana mais além da Terra exige transitar de arquiteturas dependentes de suprimentos terrestres para sistemas capazes de identificar, extrair e transformar recursos extraterrestres. Este artigo avalia criticamente o potencial do ouro (Au), elementos do grupo do platina (PGE) e metais estratégicos em Marte, com o planeta vermelho como núcleo de uma possível economia mineral do Sistema Solar interior. Foi realizada uma revisão integrativa de 40 fontes científicas com DOI verificável sobre geoquímica marciana, meteoritos, elementos altamente siderófilos, metalogênese magnética e hidrotermal, impactos, água e gelo, utilização de recursos in situ (ISRU), perfuração, processamento de regolito, asteroides, luas marcianas e economia espacial. A evidência confirma Au e outros HSE em materiais marcianos, e existem mecanismos plausíveis para sua concentração por meio de segregação de enxofre, atividade hidrotérmica, impactos e processos sedimentários. No entanto, não existe evidência direta de um jacimiento aurífero marciano com lei, tonalidade e continuidade suficientes para ser classificado como recurso explorável. Ele propõe um Índice de Prospectividade de Ouro Espacial (SGPI) para priorizar objetivos de exploração integrando geologia, acessibilidade, água, energia, maturidade tecnológica e incerteza. A análise concluiu que água, oxigênio, propelentes e materiais estruturais provavelmente antecederão Au como produtos economicamente relevantes; em fases posteriores, Marte poderia evoluir para um nó industrial e logístico conectado com Fobos, Deimos, asteróides e corpos ricos em voláteis. A fronteira do ouro Marciano deve ser entendida, por tanto, como um programa de geologia econômica planetária e não como uma reserva mineral já demonstrada.

Palavras-chave: Marte; mineração espacial; ouro; metais preciosos; elementos do grupo do platina; ISRU; Fobos; Deimos; asteróides; geologia econômica planetária.

1. Introduction

Space mining has moved from being solely a science-fiction motif to an interdisciplinary research problem linking planetary geology, resource engineering, robotic autonomy, economics, and space law. The decisive conceptual transition is from exploration architectures that import nearly every consumable and construction material from Earth to architectures able to identify, extract, and transform local resources. On Mars, in-situ resource utilization (ISRU) has been investigated for decades and now includes technology demonstrations performed on the planet itself, most notably oxygen production from atmospheric carbon dioxide by MOXIE [1–5]. This is not yet metal mining, but it demonstrates that industrial transformation of Martian feedstock is technically conceivable.

Interest in gold (Au) and platinum-group elements (PGEs) requires substantially more rigor than popular narratives about 'trillion-dollar asteroids'. The scientific question is not whether gold atoms exist on Mars: Au and other highly siderophile elements have been measured in Martian materials. The relevant question is whether Martian geological processes—magmatic differentiation, sulfide segregation, hydrothermal circulation, impacts, and sedimentary reworking—could have concentrated these elements into localized mineralized bodies [6–12]. Presence, anomaly, mineralization, deposit, resource, and reserve are distinct concepts.

This article therefore uses a Mars-centered frame. Phobos, Deimos, asteroids, and comets are included only when they influence Martian industrial and logistical architecture. Stars and exoplanets are excluded because they lie outside the Solar System by definition. Small Solar-System bodies remain relevant because they may supply metals, water, and volatiles, while future Martian infrastructure could become a storage, processing, and transport node for such resources [29–35, 38–40].

The general objective is to evaluate Martian geochemical and metallogenic potential for Au and PGEs, identify priority prospecting domains, analyze extraction and processing technologies, and define techno-economic pathways for a Martian mineral economy. As a methodological contribution, a Space Gold Prospectivity Index (SGPI) is proposed as a transparent target-prioritization framework under uncertainty rather than a reserve-estimation tool.

2. Review design and epistemic framework

An integrative and prospective review was adopted. The literature was organized into six domains: (i) Au, Re, Os, Ir, Pt, and Pd geochemistry in Mars and Martian meteorites; (ii) magmatic, hydrothermal, and impact-related metallogenic processes; (iii) mineral mapping, water, and ice; (iv) ISRU, drilling, beneficiation, reduction, and manufacturing technologies; (v) resources of Phobos, Deimos, asteroids, and comets; and (vi) space-resource economics and governance. Peer-reviewed papers with verifiable DOIs were prioritized. Older work was retained only where it provides foundational evidence that cannot be replaced by more recent literature [6–8, 12, 33].

To limit overinterpretation, statements were divided into three levels. Level A is confirmed evidence from meteorites, orbital measurements, rovers, or experiments. Level B is inferred geological prospectivity supported by known mechanisms but without direct proof of a deposit. Level C is a prospective technological-economic scenario dependent on future infrastructure and markets. This hierarchy is essential because the main epistemic hazard in space-mining discourse is presenting a metallogenic hypothesis as an established mineral reserve.

This review does not estimate Martian reserves. Such an exercise would require representative drilling, geostatistical continuity, quantitative mineralogy, recovery testing, and spatial grade data. The proposed SGPI therefore belongs to early-stage exploration screening, not formal resource reporting.

Table 1. Evidence hierarchy used in this study

Level	Interpretation	Criterion
Level A	Confirmed	Meteorites, orbital/surface measurement, or reproduced experiment.
Level B	Prospectivity	Plausible geological mechanism supported by observations without a demonstrated deposit.
Level C	Scenario	Future architecture dependent on technology, markets, and infrastructure not yet available.

Table 2. Prospecting domains and geological rationale

Target	Rationale	Critical missing data
Tharsis	Large-volume magmatism; sulfide-segregation potential.	Sulfide geochemistry, intrusions, alteration.
Elysium	Magmatism and possible magma-ice/water interaction.	Alteration, structures, heat sources.
Large craters	Deep excavation and impact hydrothermal systems.	Hydrothermal minerals, breccias, fractures.
Nili Fossae/Jezero	Aqueous alteration and prolonged sedimentation.	Heavy-mineral fractions and hydrothermal tracers.
Phobos/Deimos	Low gravity and logistical value.	Direct composition and volatiles.
Metallic asteroids	Fe-Ni and potential PGEs.	Composition, accessibility, recoverability.

Table 3. Proposed SGPI dimensions (illustrative, uncalibrated weights)

Dimension	Illustrative weight
Au/HSE evidence	0.20
Magmatic/sulfide favorability	0.15
Hydrothermal evidence	0.10
Impact/sedimentary potential	0.08
Accessibility and logistics	0.12
Water and consumables	0.08
Energy	0.08
Technology maturity	0.08
Data quality	0.11

Table 4. Suggested technology sequence

Phase	Capability	Outcome
I	Mapping	Integrated orbital data and anomaly selection.
II	Prospecting	Rovers, geophysics, and systematic sampling.
III	Drilling/pilot	Core, ice, beneficiation, and small-scale metallurgy.
IV	Local industry	Water, O2, propellant, construction, and base metals.
V	Interplanetary network	Integration with moons and small bodies; larger-scale Au/PGEs.

3. What do we actually know about gold on Mars?

Highly siderophile elements (HSEs)—including Re, Os, Ir, Ru, Rh, Pt, Pd, and Au—have strong affinities for metallic phases and, under appropriate conditions, sulfides. During early differentiation of rocky planets, large fractions of these elements migrate toward the core. Their residual abundance in mantle and crust therefore records core formation, incomplete segregation, late accretion, and subsequent melting processes [6].

Martian meteorites provide direct evidence for HSEs and Au in materials originating from Mars. Warren, Kallemeyn, and Kyte [7] reported compositional data including Ni, Re, Os, Ir, and Au; Brandon and co-workers [8] synthesized the HSE signature of SNC meteorites and its relation to Martian mantle reservoirs. Brasser and Mojzsis [9] later argued that Martian mantle HSE abundance is compatible with late accretion involving a very large impact. These studies establish an inventory of noble metals, but they do not establish high-grade ore deposits.

The economic-geology logic must therefore remain sequential: elemental presence → anomaly → concentration mechanism → mineralization → mineralized body → resource → reserve. For Au, Mars is still near the beginning of this chain. No drilling campaign has been designed to discover Martian gold mineralization, and no sampling grid exists from which grade distributions or continuity could be estimated.

4. Plausible metallogenic processes

The first candidate mechanism is magmatic differentiation coupled to sulfide segregation. On Earth, many Ni-Cu-PGE deposits form when mafic or ultramafic magma becomes sulfur saturated and an immiscible sulfide liquid scavenges metals from silicate melt. Baumgartner et al. [10] addressed this process specifically for Mars and showed that plausible Martian magmatic trajectories and crustal assimilation could generate conditions favorable for Ni-Cu±PGE mineralization. Palin et al. [11] extended the strategic-mineral perspective to Ni, Co, Cu, PGEs, and Au in Martian igneous provinces.

Hydrothermalism is the second mechanism. Mars preserves widespread evidence for water-rock interaction, hydrated minerals, and environments in which fluids circulated [13–18]. Hydrothermal fluids can leach metals and precipitate them in response to changes in temperature, pressure, pH, sulfur activity, or redox conditions. The existence of Martian hydrothermal systems is better established than any specific Au mineralization; this is therefore Level B prospectivity rather than a confirmed ore model.

Impacts provide a third mechanism. Complex craters generate heat, fractures, breccias, and secondary permeability; where water or ice is available they can support hydrothermal circulation. Modeling and observations suggest lifetimes from thousands to millions of years depending on crater size, lithology, permeability, and thermal conditions [13–16]. Toro crater, for example, contains mineralogical and structural evidence consistent with impact-induced hydrothermal alteration [14].

Sedimentary and residual concentration is a fourth possibility. Ancient Martian rivers, lakes, and deltas transported large volumes of sediment. Hydraulic sorting could in principle concentrate dense minerals. Clay-bearing delta deposits such as Jezero demonstrate prolonged transport and deposition [18]. No Martian gold placer has been demonstrated, but heavy-mineral fractions remain legitimate exploration targets.

5. Priority prospecting provinces

Tharsis deserves priority because of its extraordinary magmatic scale, longevity, and likelihood of buried intrusive systems. Large volcanoes do not imply ore deposits by themselves, but they establish a long history of magma generation, storage, and transport sufficient to justify sulfide-segregation models. Exploration should target intrusive contacts, sulfur-rich wall rocks, magnetic anomalies, and alteration mineralogy.

Elysium is a second target because of relatively young volcanism and possible magma-ice-water interaction. Regions in which magmatic heat and volatiles overlapped could have developed hydrothermal systems capable of metal transport. Large impact structures in ancient terrains constitute a third class, particularly where deep lithologies are exposed or hydrothermal assemblages and fracture networks are present [13–16].

Nili Fossae, Jezero, and other phyllosilicate-rich terrains provide natural laboratories for aqueous alteration, though their astrobiological importance should not be conflated with high gold prospectivity [17,18]. Arabia Terra and Vernal crater demonstrate how geology, local resources, and engineering constraints can be integrated for human-site selection [20]. Meanwhile, the 2026 probabilistic mapping of buried ice is directly relevant to mining logistics because water supports life support, propellant, processing, and thermal management [19].

A practical exploration cascade would move from orbital mineral and structural mapping to regional geophysics, rover-scale geochemistry, drilling, representative core recovery, and finally beneficiation and metallurgical testing. The missing transition is from planetary geology missions to missions explicitly designed for planetary economic geology.

6. Water, energy, and basic materials come before gold

A Martian gold operation cannot be evaluated as an isolated terrestrial mine. It requires power, water, excavation, maintenance, spare parts, reagents, and transport. Consequently, low-unit-value materials can have very high system value. Water can be converted into hydrogen and oxygen; atmospheric CO2 can yield oxygen or carbon monoxide; regolith can provide silicates, oxides, and construction feedstock [1–5, 21–28].

MOXIE provided the first ISRU oxygen demonstration on another planet, and extended operations allowed performance to be assessed under varying Martian conditions [4,5]. In parallel, habitat-site studies based on water and new buried-ice maps are making extraction architectures more concrete [19,21]. RedWater is particularly important because it addresses an actual mining operation: drilling to buried ice and pneumatically transporting cuttings under Martian conditions [22].

Local metallurgy is also progressing. Zheng and Qiao [23] demonstrated electrochemical reduction of Martian-regolith simulant to Fe-Si alloy-bearing products. Additive manufacturing of regolith geopolymers and sulfur/regolith concretes provides routes for locally manufactured infrastructure [24–27]. Pajares et al. [28] further coupled 3D-printed Martian simulant structures to carbon-monoxide production. The emerging picture is a multiproduct Martian mine: ice, oxygen, construction materials, and industrial metals are likely to precede exported gold.

7. Phobos and Deimos as part of the Martian system

Phobos and Deimos are strategically important because they combine proximity to Mars with extremely low gravity. Their surface composition remains incompletely resolved; spectroscopic analog work indicates dark materials and possible primitive components, but interpretations depend on space weathering and the satellites' origin [29]. Recent reviews emphasize that direct exploration is required to discriminate capture from impact-disk scenarios [38,39].

From an industrial standpoint, the moons may initially be more valuable as logistical nodes than as mineral deposits. Phobos could support propellant storage, cargo transfer, telecommunications, vehicle servicing, and assembly while avoiding repeated descent into and ascent from Mars' gravity well. Useful volatiles or feedstock would enhance this value, but mineral richness is not required for strategic importance.

The unit of analysis should therefore be the Mars-moons system. Surface ISRU can support orbital operations, while orbital infrastructure can lower the cost of accessing small bodies. This feedback loop is one reason Martian mineral economics should not be reduced to shipping Au back to Earth.

8. Asteroids and comets in a Mars-centered architecture

Asteroids extend the analysis because of their compositional diversity and low gravity. (16) Psyche is instructive: pre-arrival assessments no longer support the simplistic image of a pure-metal body, instead indicating a mixed metal-silicate world with substantial uncertainty [30]. Remote characterization must therefore precede any economic valuation.

Cannon et al. [31] reviewed precious and structural metals on asteroids and showed why popular PGE abundance claims can be overstated. Economic studies by Hein et al. [32], Sonter [33], and Elvis [34] emphasize that accessibility, throughput, reuse, product price, and market response can dominate resource concentration. The technology review by Zhang et al. [35] shows that sampling, anchoring, excavation, separation, and transport remain critical bottlenecks.

Comets should be valued differently. Their primary role in a Martian resource network is likely volatile supply rather than gold. Returned cometary materials contain diverse refractory and primitive components [40], while water ice and volatile species can support propellant, life support, and industrial chemistry. In a mature architecture, a volatile-rich body may be economically more important as a refueling resource than as a source of precious metals.

The more robust hypothesis is therefore a differentiated resource network: Mars contributes surface area, atmosphere, ice, and industrial feedstock; its moons provide logistical positions; metallic asteroids provide Fe-Ni and potentially PGEs; carbonaceous bodies and comets provide volatiles. Gold becomes one component of a resource portfolio rather than the sole economic driver.

9. Technologies for prospecting, extraction, and processing

Metal prospecting requires instruments beyond those of a general planetary-geology mission. Orbital sensors can identify mineralogy, alteration, and structures but cannot reliably map low-concentration Au directly. Surface systems combining LIBS, XRF, Raman spectroscopy, mass spectrometry, and magnetometry can discriminate lithologies and ore-related phases. Subsurface radar and seismic methods can define geometry, but grade validation ultimately requires drilling and representative sampling.

Excavation on Mars must cope with low gravity, abrasive dust, thermal cycling, and communication delay. Autonomy will need to include navigation, fault detection, load control, energy management, and predictive maintenance. RedWater pneumatic drilling [22] illustrates how terrestrial methods must be redesigned for low pressure and the absence of heavy drilling muds. Hard-rock deposits may require combined rotary-percussive drilling, localized heating, and thermal fracture.

Beneficiation should precede energy-intensive metallurgy. Magnetic, electrostatic, density, and optical separation can reduce mass and concentrate useful phases. For sulfide systems, future flowsheets may include comminution, concentration, thermal treatment, and selective separation. For oxide/silicate feedstocks, high-temperature electrochemical reduction is attractive because electricity substitutes for large imported reagent inventories [23].

Energy availability will govern the scale of every process. Solar energy is useful in many regions but is constrained by dust, seasonality, and heliocentric distance. Nuclear power offers higher capacity factors for drilling, furnaces, and electrolysis. Industrial optimization should therefore focus on kilograms of useful product per unit of delivered energy, not metallurgical recovery alone.

10. Space Gold Prospectivity Index (SGPI)

The SGPI is proposed as an early-stage decision framework: $SGPI = \Sigma(wi \cdot Si) - \lambda R$, where Si are normalized favorability scores, wi are explicit weights, and R represents uncertainty and risk. Sensitivity analysis is mandatory; otherwise an index can simply hide analyst preference.

Minimum dimensions include Au/HSE geochemical evidence, magmatic/sulfide favorability, hydrothermal evidence, impact or sedimentary concentration potential, accessibility, water availability, energy availability, technology maturity, operational complexity, and data quality. Uncertainty must be penalized. A geologically attractive but poorly characterized target should not automatically outrank a more modest target with strong evidence.

The SGPI is not a mineral-resource code. Its role is to determine where new instruments, drilling, and laboratory work are most valuable. Future validation could use terrestrial analog deposits, thermodynamic simulations, and eventually Martian field data.

11. Techno-economic pathways

Popular space-resource valuations often reduce to $V = M \times P$, multiplying theoretical mass by current terrestrial price. A serious analysis must include discovery probability, recovery, throughput, capital investment, energy, maintenance, transport, mission life, discounting, and market response [32–36].

For products returned to Earth, price sensitivity is especially important. Hein et al. [32] showed that the economics of platinum return depend strongly on market reaction. Elvis [34] likewise emphasized that only a small fraction of resource-rich asteroids would become ore-bearing in an economic sense because accessibility and size matter as much as concentration.

Mars changes the economic frame because many products would be consumed locally. The shadow value of a kilogram of water, oxygen, steel, or glass on Mars is not its Earth commodity price; it includes the avoided cost and risk of launching that kilogram from Earth. Under this logic, an iron-and-glass operation for local infrastructure may generate more system value than an Au mine designed for Earth export.

Three markets should therefore be modeled separately: Earth-return markets, cislunar/interplanetary markets, and the local Martian market. Au and PGEs may become important early in high-reliability electronics, contacts, sensors, coatings, and catalysts manufactured off Earth. Large-scale Earth return would be a later option contingent on transport cost and market scale.

12. Governance and space-resource law

Technical feasibility does not eliminate legal uncertainty. Space-resource activities take place under an international regime that prohibits national appropriation of celestial bodies but continues to evolve regarding extraction and ownership of recovered materials. De Zwart, Henderson, and Neumann [37] note that current international law offers insufficient clarity for large commercial resource operations and that domestic legislation and multilateral arrangements are influencing emerging state practice.

Large-scale Martian operations would raise questions about safety zones, interference with scientific sites, planetary protection, waste, contamination, and priority of access. Sustainable governance should distinguish resource extraction from territorial appropriation, require minimum operational transparency to prevent conflict, and establish environmental obligations proportionate to risk.

Regulatory risk can be treated as an external SGPI variable. Two geologically similar targets may have different practical value if one lies near a site of exceptional scientific significance or creates a much higher contamination burden. Interplanetary economic geology therefore has to integrate law and ethics at the exploration stage rather than after discovery.

13. Roadmap toward precious-metal mining on Mars

The first phase is mapping: existing orbital datasets should be integrated into a prospectivity atlas combining volcanism, alteration mineralogy, sulfur, structures, impact features, magnetic signatures, ice, and accessibility. The second phase is targeted robotic prospecting using rovers explicitly designed for economic geology and systematic sampling rather than broad geological characterization alone.

The third phase is drilling and pilot processing. Recent Mars ice-drilling work shows that mining engineering can begin with essential resources [22]. A multipurpose platform could drill ice at one site and competent rock at another, recover core, conduct physical separation, and run kilogram-to-tonne metallurgical tests. The fourth phase would be a multiproduct industrial plant supplying water, oxygen, construction feedstock, and base metals. Only after this foundation exists does large-scale Au/PGE processing become plausible.

The fifth phase is integration with Phobos, Deimos, and small bodies. Reusable vehicles, propellant depots, and off-Earth maintenance would make resource comparisons operational rather than speculative. The decision between a Martian anomaly and a metallic asteroid could then be expressed as levelized cost per kilogram of useful product delivered to a specified node.

14. Discussion

The first major conclusion is that there is a scientific basis for Martian gold prospectivity, but not for known Martian gold reserves. Au/HSE measurements and late-accretion models establish a noble-metal inventory [6–9]. Magmatic and hydrothermal models provide plausible concentration mechanisms [10–16]. Mineral mapping and aqueous history identify terrains in which element mobilization could have operated [17,18]. What is missing is mineralization-focused exploration with representative sampling.

Second, gold is unlikely to be the first resource that makes a Martian economy viable. Water, oxygen, propellant, aggregate, glass, iron, and construction materials provide immediate value by displacing imports [1–5, 19–28]. Au becomes more valuable once an off-Earth economy needs local electronics, catalysts, coatings, and high-reliability components.

Third, Mars has potential value as a node. Its atmosphere, ice, surface, moons, and relative position with respect to the main belt make supply chains conceivable that do not terminate on Earth. This changes the definition of profitability: resources are valued by the functions they perform within space infrastructure.

Finally, the SGPI converts uncertainty into an explicit research program. An index does not discover gold, but it forces analysts to identify variables, weights, and data gaps. This transparency is essential for transforming a futuristic narrative into falsifiable planetary-resource science.

15. Limitations

The most important limitation is sampling bias. Martian meteorites represent a tiny, non-random fraction of the planet. Orbital observations have finite resolution and elemental sensitivity. Current rovers explore only a few sites selected for objectives other than mining. Planet-wide extrapolation must therefore remain cautious.

A second limitation is model transfer from Earth. Mars lacks modern plate tectonics comparable to Earth and has different thermal, hydrological, and redox histories. Some terrestrial ore-deposit classes may have no direct Martian analog [11,12]. The present framework therefore emphasizes general physical and chemical mechanisms but still requires Mars-specific validation.

Economic uncertainty is a third limitation because launch, energy, and autonomy costs may change radically. For that reason this study avoids assigning absolute dollar values to hypothetical deposits. A fourth limitation is regulatory uncertainty: space-resource law is evolving and can substantially alter investment incentives.

16. Conclusions

Available evidence confirms Au and other HSEs in Martian materials but does not demonstrate economically mineable gold deposits. The missing scientific step is to identify anomalous concentrations and prove localized mineralizing processes. Magmatic provinces, hydrothermal systems, large impact structures, and selected sedimentary environments are the most defensible targets for a first generation of Martian economic geology.

Precious-metal mining must be embedded in a broader industrial sequence. Water, oxygen, propellants, construction feedstock, and base metals are likely to be the earliest products with operational value. MOXIE, regolith processing, construction studies, and ice-drilling technology already provide partial demonstrations of that sequence [1–5, 22–28].

Phobos, Deimos, asteroids, and comets enlarge the economic frontier without displacing Mars from the center of the analysis. The strongest long-term hypothesis is a network of complementary inner-Solar-System resources with Mars as a potential industrial and logistical node. Gold may be part of that economy, but its future value will depend more on where it is used than on today's terrestrial commodity price.

The SGPI offers a conceptual tool for turning this question into an exploration program. Any future Martian gold rush would begin not with a mine, but with a prospectivity map, a drill hole, and a reproducible chain of evidence.

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Financiamiento de la investigación

Con recursos propios.

Declaración de intereses

Declaro no tener ningún conflicto de intereses, que puedan haber influido en los resultados obtenidos o las interpretaciones propuestas.

Declaración de consentimiento informado

El estudio se realizó respetando el Código de ética y buenas prácticas editoriales de publicación.