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# A PRELIMINARY ASSESSMENT OF MARTIAN NATURAL RESOURCE POTENTIAL

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The discovery of significant ore deposits on Mars would be important to the development of self-sufficiency for manned bases on Mars and might provide an economic stimulus (i.e., a "metals" rush) to explore and establish numerous manned settlements on the Red Planet.

Most terrestrial mineralization is associated with plate tectonics which has not occurred on Mars. However, the existence of crustal swells, rifting, and volcanism on Mars and Earth, plus abundant Martian volatiles, suggest that some mineralization processes may have occurred earlier in Martian history. Several non-orogenic ore formation mechanisms are evaluated for Mars. The similarities between resource-rich Africa and Mars are stressed.

## INTRODUCTION

Mars offers humanity important new knowledge, spectacular adventure, biological and cultural security, and potentially great material wealth. To claim our Martian heritage we must merely show up on the Red Planet determined to avail ourselves of these extraordinary riches.

Initially, any successful Martian enterprise by humans will demand frugality and efficiency, thus the discovery of economically significant ore bodies on Mars would be an extremely important event in the history of Mars/human interactions. Useful, concentrated metal deposits on Mars would : 1) ease the difficulties in locating and utilizing raw materials for construction, etc., 2) improve the ability of early Martian settlers to actually become self-sufficient (i.e. independent of Earth), 3) spur new opportunities for the new Martians to develop industrial capabilities and an extraterrestrial economy, 4) add to our data base concerning the genesis of terrestrial ore deposits, and 5) provide an economic incentive to go to Mars (Ref. 1); e.g. start a "metals rush" to the Red Planet.

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It has been strongly suspected for a long time that Mars is literally a treasure chest as far as natural resources are concerned. For example, the Viking Landers and Orbiters have confirmed relatively early indications (Refs. 2,3 and others) that the planetary reservoirs of Martian volatiles (e.g. water) are appreciable and - properly utilized - could easily support human settlements on Mars.

In this paper an attempt is made to assess the probability of significant ore bodies and mineral concentrations on Mars. Whether concentrated deposits of substances like copper, uranium, iron, and other useful materials have formed during Martian geological history depends on the prior existence of certain geological and geochemical conditions normally associated with plate tectonic processes on Earth. Typically, a terrestrial exploration geologist or geophysicist envisions volcanism and groundwater interacting to produce a hydrothermal solution which dissolves, transports, and deposits the precious minerals into concentrated formations.

Although no recent detailed study of Martian ore bodies exists, relatively recent papers mentioning this important issue have expressed opposite opinions (Refs. 4 & 5). Smith (Ref. 4) is impressed with the apparent importance of oceans and plate tectonics to terrestrial mineralization processes, and is distressed by Mars' relatively primitive tectonic style. However, Clark (Ref. 5) recognizes that water plus magma intrusions and meteorite impacts might be capable of non-negligible metal concentrations in certain areas.

In this paper a fairly impressive array of theoretical, field, and observational evidence is assembled which argues in favor of the possibility of ore bodies on Mars presently. Most importantly, it is shown that nothing that is known about metallogeny (Ref. 6) or Martian geologic history (Ref. 7) clearly precludes the existence of ore bodies on Mars. However, caution must be exercised in any current study of Martian natural resources. If state-of-the-art exploration theories and techniques could reliably and routinely locate mineral wealth, these principles - as yet unknown - would revolutionize the minerals industry on Earth!

Unfortunately, gaps in our understanding of the theory of ore genesis and practical difficulties in applying these ideas to the real Earth with available geophysical exploration techniques, do not permit extreme confidence in conclusions about Martian mineralization. Indeed, this paper should be viewed as a somewhat speculative extrapolation of terrestrial ore experience to the promising environment of Mars.

## THE INTERIOR OF MARS

The general similarity of their sizes and positions in the solar system suggest that Earth and Mars may have comparable gross compositions and may have undergone some of the same geological processes. While a wealth of scientific evidence exists concerning the interior of Earth (e.g. Refs. 8 & 9), only a few parameters are known for Mars; i.e. the mean density and the moment of inertia. Thus even if we assume Mars consists of merely a chemically homogeneous core and mantle, we can only calculate any two of the three fundamental model parameters (i.e. core radius, core density, and mantle density); the third must be given. In more detailed density models for Mars (Ref. 10) a variety of uncertain physical, chemical, thermal, compositional, and initial parameters must be assumed.

Interestingly, a most striking difference between Earth and Mars is the Red Planet's relatively low density. One interpretation of this fact is that Mars might be depleted relative to Earth in heavy elements, of the type that might compose ore bodies. However, more sophisticated attempts (Refs. 11 & 12) to specify the detailed chemical composition of the interior of Mars indicate that the mantle of Mars has a density which exceeds that of Earth's mantle regardless of which reasonable chemical or physical assumptions are made about Mars' interior. Thus Mars' low mean density does not preclude near-surface metallic ore bodies because models of Mars' mantle are consistent with significant heavy element abundances.

For example, Johnston & Toksoz (Ref. 10) compute zero pressure mantle densities ranging from 3.58 to 3.47 (Earth's is 3.31), while Okal and Anderson (Ref. 11) assume a chondritic bulk composition for Mars and derive mantle densities almost 0.2 lower than Reference 10. Morgan & Anders' (Ref. 13) Mars mantle model features intermediate densities (3.54 to 3.52) and is based on a cosmochemical model which assumes planets and chondrites experienced the same four fractionation processes in the solar nebula. This allows the composition of Mars to be estimated from knowledge of the abundances of only four elements: U, K, Fe, and Tl. While chemical models of the Martian mantle suggest it is enriched in heavy elements relative to Earth's mantle, current data are unable to provide information about whether metal concentrations exist in the upper mantle or crust. (Relevant chemical data is considered later.)

Relatively light, rare, incompatible elements (e.g. Li, Be, B) which can also be geochemically segregated into useful concentrations are probably present in Mars' crust in approximately solar abundances.

## ORIGIN OF MINERAL DEPOSITS ON EARTH

While the major theoretical aspects of ore formation are known with some confidence, many important details remain obscure (Refs. 14, 15, 16). Although many mineral deposits owe their existence to precipitation from hydrothermal solutions, it is not always obvious which mechanisms for dissolving, transporting, and precipitating the metals occurred.

An important source for hydrothermal fluids is metamorphism. Metamorphism of sedimentary rocks liberates water which typically becomes enriched with geochemically scarce metals as metamorphism proceeds. Hydrothermal solutions consisting of scarce metals, sulfur, and water are also produced during cooling of a magma body since these substances are usually excluded from the structures of the first minerals which solidify from the melt. Regional or contact metamorphism associated with Martian volcanism would seem to be capable of producing similar metal deposits assuming the near-surface Martian chemistry is roughly Earth-like.

Although data on the duration of ore-forming events is sparse, it appears that 1000 to 10,000 years are not unreasonable. Hydrothermal circulations were probably occurring during all of terrestrial geologic history, thus ore-forming time scales are no problem for Earth. Likewise, estimates of the duration of Martian volcanic episodes (Ref. 7) are orders of magnitude larger than ore formation time scales.

It is remarkable that the solubilities of primary ore minerals can vary over orders of magnitude, in response to changes in environmental conditions. Thus they can first be mobilized and then reprecipitated, which greatly aids in their transportation and concentration.

Most minerals will precipitate from a solution when cooling occurs. Mixing of hydrothermal fluids with meteoric groundwaters, boiling, or heat loss by conduction to country rocks often produces lowering of temperature and precipitation. Individual cases usually involve numerous effects, often obscuring the details of important physical processes. Large changes in pressure can also trigger precipitation of ore minerals, although the effects are not large and usually are related to other processes (e.g. pressure-induced boiling).

Chemical reactions with adjacent rocks may influence ore body formation by changing the oxidation state of the solution. Serpentinization, which lowers the activity of oxygen, may transform the fluid environment into one more conducive to metal precipitation (e.g. gold). Alternatively, wallrock/hydrothermal reactions may supply components which ultimately trigger solidification of ore minerals.

It appears that the physical and chemical environment of Mars - within present uncertainities - would present no difficulties to the formation of hydrothermal ore bodies during its geological history, assuming the proper volcanic and tectonic conditions occurred on the planet.

Gillett (Ref. 17) has emphasized the importance of sedimentary processes in the formation of mineral deposits. One example is Colorado Plateau-type uranium ("roll-front") deposits (Ref. 18), in which uranium precipitation is localized by redox variations in groundwater. Evaporites (water soluble salts) are another strong sedimentary possibility for Mars. If Martian evaporite deposits do not form in conventional salt pans, they might occur interstitially in pore spaces. In addition to Cl, such sedimentary processes might concentrate elements like Li and K.

Currently, aqueous concentration processes may be precluded by Mars' frigid surface conditions. However, earlier in Mars' history - during its warmer, wetter climate regime (e.g. Refs. 19 & 20) - various sedimentary processes could have formed significant mineral deposits. Survival probabilities of these concentrations to the present would be enhanced by Mars' relatively low level of tectonic and volcanic activity.

Mineral deposits may also form as phases which separate from the magma because of their immiscibility (Refs. 14, 15, 16). Gillett (Ref. 21) and Haskin (Ref. 22) have suggested that the Moon may have significant concentrations of important substances. Since the super-dry lunar environment apparently precludes hydrothermal deposits, Gillett suggests ore bodies consisting of nearly pure anorthosite (an Al source), layered igneous intrusions similar to those which produce most of Earth's chromium, chalcophile element concentrations due to immiscible sulfide phases, and others. These mechanisms also appear to be ore-forming candidates for Mars in certain areas, as are the poorly understood oxide-rich immiscible melts which form magnetite or ilmenite-dominated ore bodies.

## VOLCANISM & TECTONISM ON MARS & EARTH

Tectonism and volcanism are important controls on styles of mineral deposits. Plate tectonics is apparently the most important - but not the sole - producer of ore bodies on Earth (Ref. 6). While Mars' tectonic style is certainly more complex and evolved than the Moon's, Mars does not possess the global (ocean) ridge system, volcanic (island) arc/trench associations, and large fold mountain complexes associated with a mobile lithosphere on Earth (e.g. Refs. 7 & 12). Nevertheless, Mars does display crustal swells, large rifts, and certain types of volcanoes (Ref. 23) often linked with mineral deposits on Earth.

Many volcanic and structural features on Mars have been favorably compared with important terrestrial landforms. Reimers and Komar (Ref. 24) have identified several volcanoes in the Tharsis, Elysium, and Hellas regions which do not resemble large shield volcanoes but share numerous characteristics with terrestrial volcanic cones and composite volcanoes. Typical of these relatively small structures with steep slopes and radial channels is Ceraunius Tholus just northeast of Ascraeus Mons. Ceraunius is about 6 km high with typical slopes of 10 degrees. The morphology of Ceraunius can be explained by explosive volcanism (i.e. nuees ardentes) although strong phreatic eruptions (involving groundwater) with basaltic magmas could mimic this behavior. Ceraunius has been compared to Barcena Volcano in Mexico (Ref. 24).

Elysium Mons is a moderately large (14 km high) Martian volcano with 10-12 degree slopes and large channels which radiate from the summit caldera. On the basis of Elysium's morphology and structure, Malin (Ref. 25) has suggested it is a composite volcano (with alternating lava and ash deposits) and that its Earth analog is Emi Koussi in Tibesti (Sahara).

Southwest of Elysium in the Hesperia Planum/Hellas Planitia region are several volcanoes with interesting characteristics. Tyrrhena Patera, also called the Dandelion, is a depressed central area with several external depressions surrounding it. Tyrrhena may be a highly eroded ash flow (Ref. 7) serving as further evidence of relatively explosive volcanism on Mars. Although other examples exist on Mars, these strongly suggest that Mars has experienced nearly the full range of Earth-type volcanic styles, further enhancing the chances of significant metal concentrations.

Frey (Ref. 27) has studied the rifts of Valles Marineris and compared them to rift systems in East Africa. When normalized to planetary radius, the rift systems of both planets have length distributions that are nearly indistinguishable, suggesting a similar origin. Martian canyons tend to be significantly wider than their terrestrial counterparts probably due to Mars' thicker crust.

Individual rift trends are more variable on Earth probably reflecting more complex and active tectonic processes.

In addition, Schultz (Ref. 28) has examined Martian and lunar craters which have been modified by volcanism. Craters on Mars exhibit very non-lunar characteristics (e.g. wide, elevated hummocky wall areas), probably the result of interactions of rising magma bodies with ground ice or water. These are the conditions which might produce hydrothermal circulations and ore bodies (Ref.28). If meteor impacts can trigger interactions between local fluids and magma bodies (e.g. by furnishing a zone of weakness), as inferred for the Sudbury structure (Ref. 29) on Earth and possibly endogenically modified craters on Mars, metal concentrations could be relatively frequent on Mars. This suggestion is supported by Viking soil composition analysis, which indicated present inferred constituents (iron-rich smectites, carbonates, iron oxides, and sulfates) would be likely products of magma/ground water interactions on Mars (Ref. 30). High sulfur content of the soil suggests the possibility of sulfide-rich ore bodies on Mars (Ref. 28).

In summary, while Mars probably never experienced large-scale horizontal lithospheric plate motions (i.e. plate tectonics), both Mars and Earth appear to have crustal swells, rift systems, large shield volcanoes, stratocones and ash eruptions, and abundant water. This suggests that non-orogenic ore formation mechanisms - particularly those associated with continental hot spots, rifts, impacts, and water - are the best hopes for Martian metallogeny.

## HOT SPOTS, RIFTS, & THE AFRICA-MARS ANALOGY

The fact that many terrestrial examples of mineralization are not related to plate tectonic processes should be of great interest to the future settlers of Mars. Numerous cases and processes are discussed in Mitchell and Garson (Ref. 6) and elsewhere, and no attempt will be made to adequately summarize this enormous topic here. Our purpose is merely to indicate by example the sorts of mineral deposits which might be encountered on Mars.

Continental hot spots (Ref. 31) and rifts - probably good Martian analogs - are associated with some significant mineral deposits on Earth. Interestingly, it appears mineralization is most likely for stationary plates since an excellent example of a moving Cenozoic hot spot, which produced the Snake River Plains basalts and presently resides below Yellowstone, is unmineralized (Ref. 6). Since most ore formation due to differentiation of a parent magma is expected to occur during the last magmatic activity in a region (and moving plates are soon carried away from their magma source), stationary plates might exhibit more concentrated metal deposits (Ref. 32). (We should recall that Mars' lithosphere has been quite stationary for billions of years.)

Tin, uranium, apatite, magnetite, and several other important substances of potentially economic significance are associated with continental hot spots and do not appear to be related to the collisional aspects of active plate tectonics. For example, tin is found in economic deposits in granites emplaced above mantle plumes in the Jos Plateau, Nigeria (Ref. 33) and is present in the St. Francois Mountains, Missouri (Ref. 34) and elsewhere.
Bokan Mountain in southeastern Alaska is a type area for granite-related uranium mineralization (Ref. 35) associated with hot spot settings. Apparently both magmatic and hydrothermal processes have produced the uranium concentrations.

Convection in the country rock powered by a nearby magma body may be as important as anything in determining the nature of the resultant mineralization (Ref. 17). This is because the mineralization may result more from the material leached from the country rock than anything intrinsic to the magma. The degree of leaching depends both on the scale of the convective circulation and the presence of concentratable substances. Recent work indicates convective circulations around cooling plutons can be very large (Ref. 36).

Apatite, magnetite, vermiculite, and pyrochlore deposits are found associated with carbonatites and alkaline and ultrabasic rocks believed to be due to hot spot melting. Many areas in Tanzania, Egypt, Libya, and elsewhere may be related to hot spots which triggered the formation of the East and South Africa rift systems (Ref. 6). (For reference, recall that apatite is a source of phosphate used in fertilizers, magnetite is a source of iron, vermiculite is used as a insulator and in plaster and concrete, and pyrochlore is a source of niobium and other elements.) Gemstones like sapphire, zircon, and ruby originate in alkalai basalts in Kampuchea and Thailand, and are thought to be triggered by mantle plumes (Ref. 6).

Rift systems like that in East Africa are associated with a variety of mineral deposits including apatite, vermiculite, chromium, nickel, copper, silver, uranium, evaporites and salts, and even diamonds. The gigantic Bushveld Complex in south Africa is apparently a Precambrian layered igneous intrusion. Dry magma processes - which formed Bushveld and other complexes - seem more common in Precambrian times; probably due to more elevated geothermal gradients.

Prior to the loss of much of its thermal energy, Mars may have produced many "Bushvelds" which easily survived to the present. Apparently the potential for material wealth on Mars is enormous, however the resources which constitute riches on Mars will be those that are most useful and least abundant.

It is easy to be impressed with the mineral riches of Africa and the geologic similarities between Africa and Mars. Most of the important features of Mars - crustal swells, rifts, volcanism, water, stationary plates - are also displayed in Africa, and are associated with important mineral deposits (Refs. 37 & 38). It is suggested here that Africa may be a preview of future mineral attractions, which patiently await the first Mars colonists and entrepreneurs.

Liu (Ref. 37) uses gravity data to compute the subcrustal stress system in Africa attributed to mantle convection. The mantle flow pattern is correlated with topography; i.e. upwelling with hot spots or high spots and sinking with basins. Most significant is the fact that the major ore deposits of Africa are correlated with rifts and upwelling of the mantle. (African ores consist of everything from copper and magnetite to gold, diamonds, platinum, and uranium.)

Apparently, hot rising mantle material provides a heat source to power the hydrothermal circulations which have produced these resource bonanzas in Africa. Given Africa's obvious volcanic and tectonic similarities to portions of Mars, it is very tempting to expect to encounter similar mineral delights just beneath the surface of Mars.

If present indications concerning the absence of a considerable ancient Martian biota are accurate, the prospects for vast deposits of hydrocarbons are dim. However, Gold (Refs. 39 & 40) has suggested that substantial stores of abiotic primordial methane exist deep in the Earth. This natural gas apparently occasionally escapes during earthquakes and from crustal rifts. Whether this speculative mechanism is relevant to Mars is, at present, difficult to assess.

## SUMMARY AND CONCLUSIONS

Nothing we know about the physics and chemistry of mineralization, ore body tectonics, or the geology of Mars precludes the existence of significant ore bodies on Mars. In fact, interplanetary analogs strongly suggest the possibility of economically significant Martian mineral caches. Terrestrial hydrothermal, dry-magma, and sedimentary mineral concentration processes have been identified which may have operated on Mars. In particular, mineral-rich Africa seems to share many volcanic and tectonic characteristics with portions of Mars and may be suggestive of the potential mineral wealth of Mars.

The conclusions of this paper remain somewhat speculative because we do not yet understand the details of ore formation on Earth and are ignorant of the details of the geologic history of Mars. Perhaps the largest gap in our knowledge is the global geochemistry of Mars. The Mars Geoscience/Climatology Orbiter will help assuage this problem.

Standard geophysical, geological, and remote sensing techniques can be utilized by humans in the vicinity of Mars to determine the existence and locations of important (hypothesized) Martian ore bodies.

Assuming that ground ice is, and has been, widespread, and that magma bodies have produced hydrothermal solutions often during the history of Mars, the Martian mining economy should be booming by the middle of the 21st century.

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