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Potential martian mineral resources: Mechanisms and terrestrial analogues

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ABSTRACT

The future exploration of Mars is likely to utilize resources that can be extracted in situ. An overview of the geology of Mars has been presented and several mechanisms that could result in the formation of ore deposits have been identified. These include deposits caused by hydrothermal fluids resulting from volcanic activity, large igneous province formation and impact craters. Surface enrichment of mineral sand deposits is also discussed. Where appropriate, terrestrial analogues of these mechanisms have been discussed and supporting evidence from observations of Mars undertaken to date presented. Types of deposits that are unlikely to be found on Mars are also listed.

1. Introduction

The economic mineralization of ores on Earth is a well established science born from many years of scientific research and mineral exploration. Little is known, however, about mineralization on Mars, our nearest neighbour in space and very similar to Earth in many ways. Exploration by robotic spacecraft on the surface and from Mars orbit has revealed much about Mars geology but little of this knowledge has been applied to ore mineralization. Plans for future exploration and the eventual settlement of Mars by humans call for a 'living off the land' philosophy that makes use of all the in situ resources available. Common approaches include the production of rocket propellant, first proposed by Ash et al. (1978), and the use of regolith materials for construction purposes. Potential and postulated mineral resources on Mars will play an important role in future exploration and settlement and so an understanding of mineralization mechanisms on Mars and their terrestrial analogues is essential.

The terrestrial definition of ore is economic. On Earth, ores can be divided into *inferred*, *indicated* and *measured* categories with increasing levels of geological confidence (JORC, 2004).

An *inferred mineral resource* is that part of a mineral resource for which tonnage, grade and mineral content can be estimated with a low level of confidence. It is inferred from geological evidence and has assumed but not verified geological and/or grade continuity. It is based on information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes which may be limited or of uncertain quality and reliability.

An *indicated mineral resource* is that part of a mineral resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a reasonable level of confidence. It is based on exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes. The locations are too widely or inappropriately spaced to confirm geological and/or grade continuity but are spaced closely enough for continuity to be assumed.

A *measured mineral resource* is that part of a mineral resource for which tonnage, densities, shape, physical characteristics, grade and mineral content can be estimated with a high level of confidence. It is based on detailed and reliable exploration, sampling and testing information gathered through appropriate techniques from locations such as outcrops, trenches, pits, workings and drill holes. The locations are spaced closely enough to confirm geological and grade continuity.

Clearly our knowledge of Mars is nowhere sufficient to establish even the lowest confidence level of mineral resources.

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In many cases the technology needed to extract them has not yet been invented. This paper will therefore use the terms potential to describe all such occurrences, if known, and postulated, if inferred from general geological principles.

This paper will summarize the range of primary mineralization styles associated with potential and postulated resources that can be expected on Mars and possible forms of secondary enrichment. The paper will not examine water resources (Baker et al., 1993) or the use of regolith materials for construction purposes as these have been covered elsewhere (Boyd et al., 1989). The focus of this paper will therefore be on potential and postulated metallic (Fe, Cu, Pb, Zn, Ti, Au, Ag, Mg, Al and Platinum Group Elements (PGEs)) and semi-metallic (As, Ga, Si, Se) resources.

Martian mining is a common theme in speculative fiction. One example is in *The Sands of Mars* (Clarke, 1951) which describes a visit to a facility that extracts most of the resources needed for the settlement:

> 'All the oxygen we need is in those ores', said Whittaker, kicking at the caked powder. 'And just about every metal you can think of...' He bent down and picked up a lump more solid that the rest. 'I'm not much of a geologist,' he said, but look at this. Pretty, isn't it? Mostly iron oxide they tell me. Iron isn't much use, of course, but the other metals are. About the only one we can't get easily direct from the sand is magnesium. The best source of that's the old sea bed: there are salt flats a hundred meters thick out in Xanthe and we just go and collect it when we need it.'

Some assessment of resources has featured in most Mars settlement plans, for example Stoker et al. (1993). However, export of martian metallic and semi-metallic resources seems far fetched with near to medium term technology. Realistic markets may be to supply the requirements of martian settlement and, in comparison with terrestrial mining, will be on a small scale. The utilization of potential and postulated martian mineral resources is not likely to occur during initial human exploration but rather when the requirement for resources exceeds the economic practicality of transporting them from Earth and the construction costs of the necessary metallurgical plant. The processing of possible martian resources is also beyond the scope of this paper; however, it is important to note that the technologies employed on Mars for such tasks may be very different to those used on Earth at present.

2. The geology of Mars

The surface of Mars is composed of ancient, heavily cratered highlands in the southern hemisphere and some regions of the northern hemisphere and smooth lowland plains in the remaining areas of the northern hemisphere. The highlands rise between 1 and 4 km above the lowlands which may have been covered by a shallow ocean in its early history. Mars' surface is shaped by rises and volcanoes associated with narrow grabens and fracture systems, channels and valley networks, and impact craters (Carr, 1990). The large variations in the terrain are evident in the global topography map produced using data from the Mars Orbiter Laser Altimeter (MOLA) (Smith et al., 2001).

The magnitude of the morphological structures on Mars is staggering. The Tharsis Rise is a 4000 km wide bulge that rises to about 10 km at its centre and covers 25% of the planet's surface. It was formed by an igneous province of some 6.5×10^6 km^2. On its northwest flank, aligned along a northeast-trending line, are three large shield volcanoes and further to the northwest is the largest known volcano in the Solar System, Olympus Mons. Five hundred and fifty km in diameter and 24 km high, this shield volcano is three times higher and four times wider than the largest volcano on Earth, Mauna Loa. Most researchers consider the Tharsis region the surface expression of a mantle plume on a stationary one-plate lithosphere (Gregg and Williams, 1996; Pirajno, 2000; Ernst et al., 2008; Pirajno and van Kranendonk, 2005). The African plate, which has been stationary on Earth for at least 65 million years (Burke, 1996), is the closest analogue on Earth to a stationary one-plate lithosphere.

Mars, like the African plate on Earth, contains intraplate volcanoes as well as a large rift system. Valles Marineris is the largest canyon in the Solar System and extends for more than 4000 km across nearly half of the planet. In places it is 600 km wide and as much as 10 km deep (Carr, 1990). The walls of Valles Marineris reveal a layered succession, about 8 km thick, which includes basaltic lava flows (Pirajno and van Kranendonk, 2005).

As mentioned above, the southern highlands are littered with impact craters. Unlike on Earth, plate tectonics and recycling of the crust have removed the impact record. One of the most notable impact craters is the Hellas Planitia (or Basin). Nearly 9 km deep and 2100 km across, the basin is surrounded by a ring of material that rises about 2 km above the surroundings and stretches out to 4000 km from the basin's centre. This ring of material, thrown out of the basin during the impact of an asteroid, has a volume equivalent to a 3.5 km thick layer spread over the Australian continent, and it contributes significantly to the high topography in the southern hemisphere.

It is important to note that despite the large variations in topography, much localized martian geology is flat lying; therefore the probability of finding an ore deposit that intersects the surface will be low. Crater walls, central uplifts and the edges of canyons are therefore the prime sites for mineral exploration because they expose the stratigraphy and potential mineralized zones.

3. Large igneous provinces on Mars

The martian crust is poorly differentiated compared to Earth and has a bulk mafic composition (Singer and McSween, 1993). Abundant ultramafic rocks are not indicated by the available data, and there is no evidence for extensive differentiated crust of intermediate to felsic composition, such as that which makes up the terrestrial continents.

The massive volcanic edifices of the Tharsis Montes region, and particularly Olympus Mons, are the most striking example of a large igneous province (LIP) on Mars. Fuller and Head (2003) report that individual martian volcanic flows can be as long as 1800 km. In addition, widespread annular structures (diameter 50–2600 km), termed coronae, are distributed along rift zones on Mars and are believed to result from mantle diapirs of igneous origin (Ernst et al., 2008).

Strong links exist on Earth between LIPs and the formation of large deposits of chalcophile and siderophile elements such as Ni–Cu–PGE, Ti, Fe and Cr. The ore minerals are separated by fractional crystallization and related processes during magmatic differentiation. Most of the world's platinum and chrome comes from the largest known mafic-ultramafic intrusion, the 2060 Ma Bushveld intrusion in South Africa. Another renowned terrestrial example is the Noril'sk deposits, which resulted from the 250 Ma Siberian Trap event, and produce 70% of the world's palladium. According to Ernst et al. (2008), Archean greenstone belts that contain komatiites are also an important source of Ni–Cu–PGE ores. Mafic dike swarms are also associated with LIPs and over 140 exist on Earth greater than 300 km long (Pirajno, 2000). These intrusions host economically important concentrations of platinoids, and Ni and Cu sulfides.

Recent gravity modelling of Mars has demonstrated the existence of extinct magma chambers beneath volcanoes at several locations including Tyrrhena Patera, Hadriaca Patera and Amphitrites Patera. Observations of the gravity anomaly over Syrtis Major, an ancient martian basaltic shield volcano, have been obtained by the Mars Global Surveyor spacecraft (Kiefer, 2004) and also indicate the existence of an extinct magma chamber beneath the volcano. Kiefer (2004) states that pyroxene is the most likely cumulate material in the solidified system below Syrtis Major, although he concludes that olivine may also be present. The best terrestrial analogue of the structure beneath Syrtis Major is the mafic Bushveld intrusion mentioned above. The presence of intrusions and other structures indicative of LIPs on Mars suggest that Ni–Cu and PGE ores are also very likely to be found in these regions.

4. Martian volcanism and hydrothermal deposits

Impact cratering rates calculated from Mars Orbiter Camera (MOC) images of lava flows suggest recent to contemporary volcanism on Mars. This volcanism is dominated by mafic and ultramafic products (Gregg and Williams, 1996). The possibility of finding incidences of hydrothermal activity is very high. Such activity is likely to be located in and around volcanoes, caldera floors, fractures and rift valleys. The Tharsis region is a prime candidate since hydrothermal convective cells are known to have been active in the past around and within the several volcanoes, along the major fracture and dike systems and in the nearby Valles Marineris rift system (Pirajno, 2005).

Several examples of volcanic activity on Mars which could result in hydrothermal fluid circulation are worth considering. Wilson and Mouginis-Mark (2003) have studied MOC images of the Olympus Mons aureole and have discovered ridges on the northern flanks of the volcano that appear to have formed via explosive volcanism (Fig. 1). Of the possible geomorphic processes which could have formed the ridges—eolian, periglacial, landslide, or shallow marine deposition—only dike intrusion into a shallow layer of ice-rich regolith is plausible. The ridges formed on top of the young lava flows of Olympus Mons and appear to be made of fresh, unconsolidated material. Wilson and Mouginis-Mark (2003) also observe that each explosive eruption, which results from the heating and consequent expansion of ground ice from the dike intrusions, is of a very short duration on the order of 2–3 min. Fig. 2 shows the manner in which a dike intrusion and subsequent explosive phreato-magmatic eruption form the features observed on the northern flanks of Olympus Mons.

Another example, the Shalbatana Vallis channel, approximately 3000 km from the Tharsis bulge, shows evidence of water outflow from confined subsurface aquifers initiated by magmatic activity associated with the volcanoes of the Tharsis bulge. Cabrol et al. (1997) have shown that the intersection of two fault systems in this region have caused weak points where magmatic material from Mars' lithosphere have entered the upper crust and interacted with the ice-saturated cryosphere. The result is mobilized hydrothermal fluids heated by convective heat flux and dike intrusions which are capable of producing zones of mineralized hydrothermal alteration. Such intrusions could form mafic-related hydrothermal volcanic hosted massive sulphide (VHMS) deposits similar to Cyprus type deposits found on Earth which yield Cu, Zn, Pb, As, Ag and Au ores. Mafic-related hydrothermal vein deposits of Ag, Au and Te may also form in cracks, fissures and faults that the hydrothermal fluid travels through. Several Australian examples of ore-grade mineralization by hydrothermal fluid alteration have also been investigated as Mars analogues (West et al., 2010).

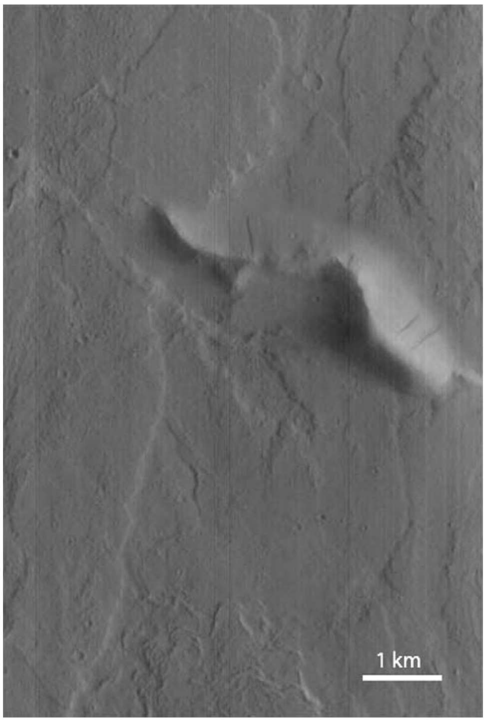

Fig. 1. A ridge on the northern flank of Olympus Mons that Wilson and Mouginis-Mark (2003) suggests has been formed via explosive volcanism. The ridge has formed on top of the older lava flows from Olympus Mons, which trend from the top to the bottom of the image. None of the flows appear to have been diverted by the ridge. MOC image SP2-46605, courtesy of NASA/JPL/MSSS.

Pirajno and van Kranendonk (2005) propose a model, shown in Fig. 3, of hydrothermal circulation in the subsurface of Mars which could lead to the formation of sulfate deposits in lowlands. Such deposits would arise as a result of the reaction of volcanic H_2S with water derived from the melting of cryosphere ice, via rising magma or dikes, to produce sulfate rich hydrothermal solutions, which then discharge at the surface forming sinter-like deposits.

A possible expression of the model outlined above has already been inferred by the detection of coarse-grained crystalline hematite by the Thermal Emission Spectrometer (TES), which is aboard the Mars Global Surveyor spacecraft. Catling and Moore (2003) conclude that the hematite deposits of Aram Chaos were deposited by hydrothermal fluids initiated by the melting of ground ice or the expulsion of groundwater into the basin. This could have occurred as a result of a magmatic intrusion or dikes, such as those discussed above. The hydrothermal formation of this hematite deposit is supported by analogues on Earth, for example, the formation of massive specularite by hydrothermal activity and metasomatism in ancient rocks in Yukon, Canada that were brecciated by forceful release of hydrothermal fluids (Thorkelson et al., 2001).

Further evidence of hydrothermal circulation in the martian past is shown by the development of fault ridge traces (Treiman, 2008) by the selective erosion of indurated fault systems. These fault systems indicate the presence of large scale hydrothermal systems extending along strike for at least 70 km in the largest know cases, and have vertical extents of at least 7 km. The evidence of such large scale former hydrothermal systems is highly encouraging with respect to the possibility of mineralization on Mars (Clarke, 2008).

Although Walter (1999) speculates that sediment hosted Pb, Zn, Ag and Au deposits like those found at MacArthur River in northern Australia may be found on Mars, given our current

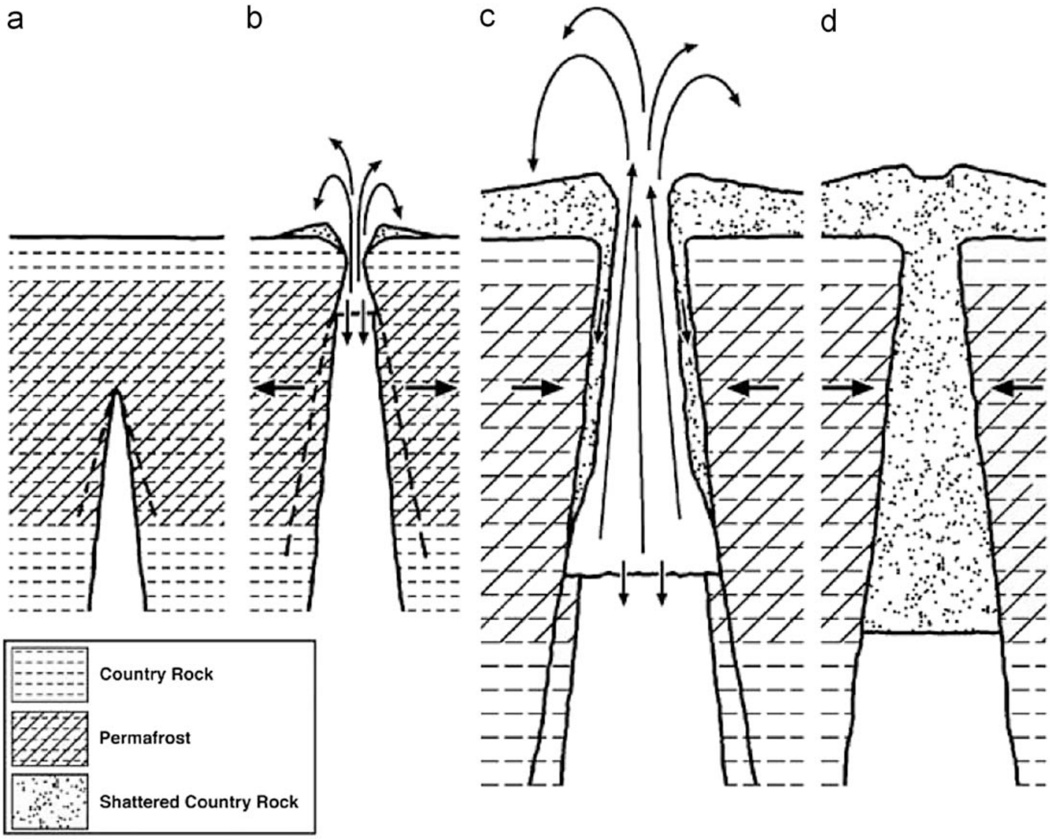

Fig. 2. Sketch of dike in relation to country rock (a) before surface breakthrough; (b) shortly after surface breakthrough; (c) part way through the eruption; (d) after activity has ceased (after Wilson and Mouginis-Mark, 2003).

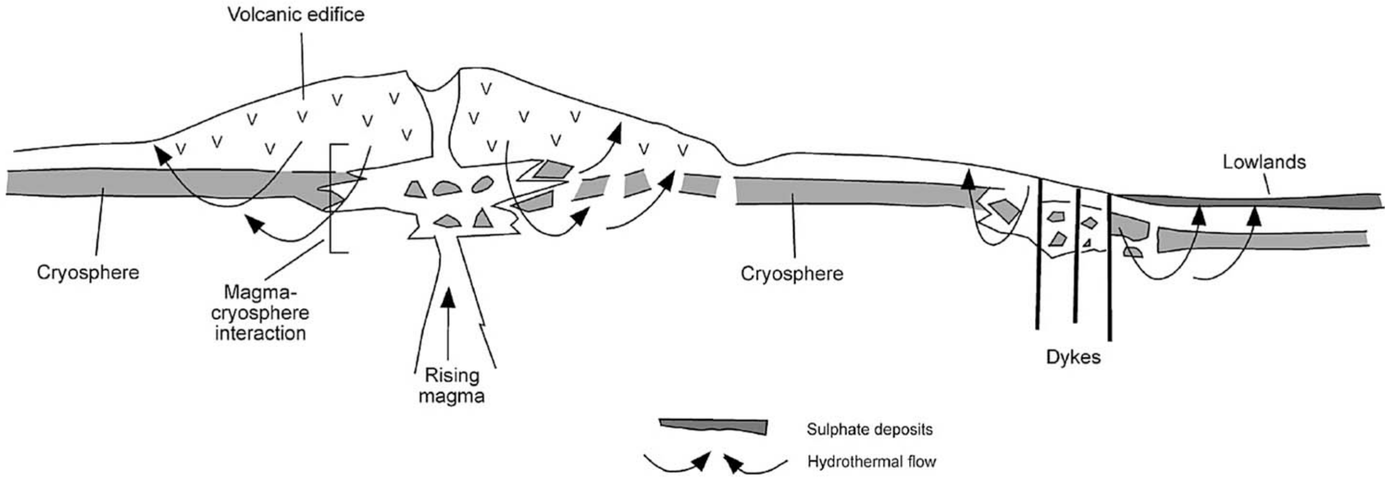

Fig. 3. Schematic model showing patterns of hydrothermal circulation in the subsurface of Mars (after Pirajno and van Kranendonk, 2005). Published with the permission of the Geological Society of Australia.

understanding of Mars it is very unlikely. The conventional interpretation of these deposits is that the sulfide that precipitated the metals was produced by a chemical reaction of sulphate when it reacted with organic matter in sea-floor sediments. The presence of such deposits on Mars would be an extraordinary discovery because the process requires organic matter in the sediments. Organic matter requires biological activity and at this stage such activity, either past or present, has not be detected on Mars. Furthermore, these deposits are formed in thick sedimentary sequences from sea-floor sediments, which presupposes large and longstanding oceans on the surface of Mars at some point in its history—a claim not out of the question but at this stage unproven.

5. Impact cratering

The impact of meteorites and comets has played a significant role in Mars' geological history and the nature of the present day surface. The highlands in the southern hemisphere of Mars, for example, are one of the most heavily cratered areas in our Solar System. Interestingly, the ejecta blankets of impact craters on

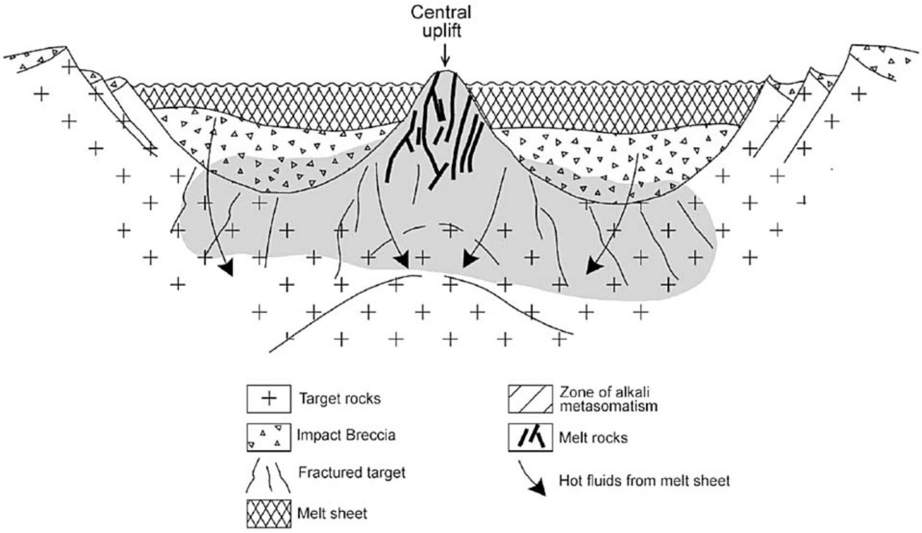

Fig. 4. Stage 1 of the model for hydrothermal fluid circulation in an impact structure proposed by Pirajno (2005). Published with the permission of the Geological Society of Australia.

Mars are distinctly different to those found on the Moon or Mercury. Craters less than 5 km in diameter on Mars resemble those found on the Moon, with their radial ejecta blankets. Many larger craters, however, have distinctive patterns of lobate ejecta blankets that suggest that the impacting object hit target rocks saturated with water (Melosh, 1989; Pirajno, 2000).

The energy imparted to the martian surface by an impact has the potential to melt large quantities of rock and locally elevate the temperature of such rock for long periods of time (hundreds of thousands of years: Pirajno and van Kranendonk, 2005). This has astrobiological implications (Cockell and Lee, 2002; Cabrol et al., 2001) as well as important consequences for the formation of mineral deposits on Mars. An examination of terrestrial mineral deposits formed as a result of an impact provides a useful insight into the process that could be expected on Mars.

Grieve and Masaitis (1994), when detailing the economic potential of terrestrial impact structures, classified such mineral deposits as either progenetic, syngenetic or epigenetic. This classification scheme is also useful for describing possible martian mineral deposits. Ore deposits that exist prior to an impacting event but are modified during or after the impact are known as progenetic deposits. Examples of such deposits on Earth include the Canadian Carswell structure, which is 39 km in diameter, aged 155 Ma and has yielded economic U ores; and the Fe and U ores of the Ternovka structure in the Ukraine, which is 15–18 km in diameter and aged 375 Ma. Grieve and Masaitis (1994) also propose that the Au and U Witwatersrand ores associated with the 300 km diameter Vredefort multi-ring structure should be considered as a progenetic deposit. They assert that the deposits owe their present day exposure and preservation to the down dropped annular ring located away from the central uplift core produced during an impact approximately 2025 ± 4 Ma. In a similar way, on Mars large impacts are likely to provide the mechanism for exposing deeply buried ore deposits caused by other martian geological processes. The amazing results from the second of the Mars Exploration Rovers, *Opportunity*, which landed inside Eagle Crater (20 m diameter), highlights the important role that impacts play in exposing interesting geological structures and stratigraphy on Mars.

Deposits that formed as a direct result of a meteorite or comet impact are known as syngenetic deposits and in the terrestrial context are known to produce Cu–Ni, PGE and diamond deposits (Pirajno, 2000; Koeberl et al., 1997). The magmatic Ni–Cu sulfide mineralization of the Sudbury Igneous Complex in Canada is the best example of a syngenetic deposit on Earth. The structure, which consists of a series of rings, is on the order of 200–250 km in diameter and was formed about 1850 Ma. The mineralization zone, which formed as a result of impact melting of the upper and lower crust from the impact of a massive meteorite some 14 km in diameter, features in the centre of the complex along with several sedimentary units (Trotter, 1991; Stöffler et al., 1994). Researchers have found clear textural, chemical and isotopic evidence for the absence of any significant magmatic or volcanic processes involved in the melt complex and the melt-bearing breccias (Stöffler et al., 1994). Hence mineralization must have resulted from the impact. The present day form of the Sudbury Igneous Complex is the result of subsequent erosion and tectonic activity.

The very high pressures produced by impacts (>35 GPa) have formed diamonds in several localities. Impact diamonds are generated from pre-existing carbon, for example, graphite, in the target rocks. They are often polycrystalline, yet harder than mantle derived diamonds (Hough et al., 1995; El Goresy et al., 2003). Impact diamonds have been found in the Kara and Popigai structures in Russia and the Reis crater in southern Germany along with several other locations. The formation of diamonds from impacts on Mars is not out of the question yet pre-existing and concentrated carbon sources would be required.

6. Impact induced hydrothermal deposits

The final deposit type associated with impact structures are known as epigenetic deposits and are the most likely to occur on Mars. Epigenetic deposits form as a result of hydrothermal circulation caused by the cooling of impact melts or related impact induced magmatic activity. The circulation of heated fluids occurs within the impact structure and in the immediate vicinity (crater walls, etc.). Extensive fracturing also results from impact events which enhances the permeability of the target rocks, allowing the flow of fluids heated by the impact. It is therefore possible that large impacts could result in hydrothermal circulation at considerable distances from the impact structure, since the depth extent of hydrothermal flow is directly related to the size of the impact (Pirajno and van Kranendonk, 2005). These fluids would leach metals from crustal rocks and deposit them in lower temperature and pressure regimes as vein and replacement

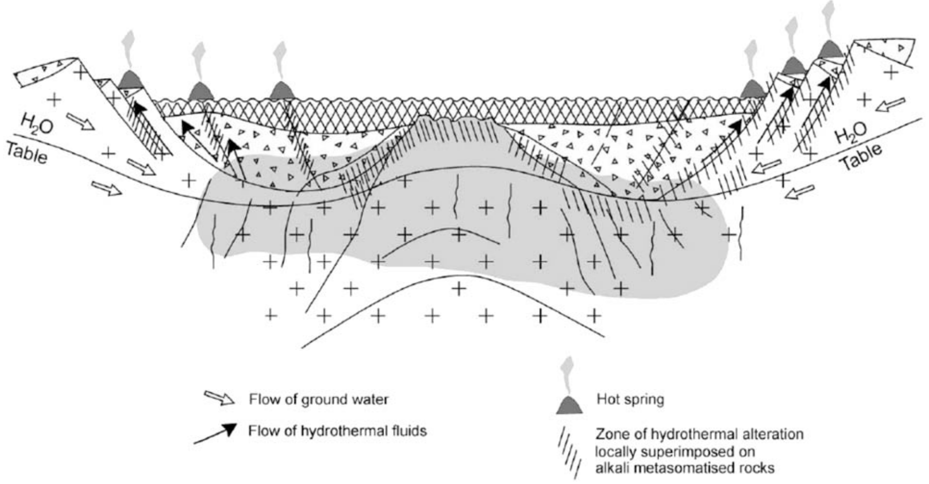

Fig. 5. Stage 2 of the model for hydrothermal fluid circulation in an impact structure proposed by Pirajno (2005). Published with the permission of the Geological Society of Australia.

deposits associated with the impact-generated fracture systems or by exploiting pre-existing stratal and fracture porosity.

Based upon impact structures on Earth, Pirajno and van Kranendonk (2005) have proposed a two stage working model describing the activity of a hydrothermal system caused by a meteorite impact. Not all aspects of the model are applicable to Mars but the model provides some useful insights nonetheless. In the first stage (Fig. 4) magmatic heat supplied by the melt sheet and melt injected into the surrounding target rocks drives the hydrothermal fluid circulation. On Earth, the average temperature experienced for extended periods during this stage is on the order of 500–600 °C and therefore significant metasomatism results. This type of alteration affects the shattered target rocks well below the melt sheet and is best manifested at the lower levels of the impact structure.

Numerous examples of terrestrial ores produced by impact induced hydrothermal circulation exist. Examples include the Cu, Zn, Pb and Au vein-type mineralization at Vermillion in the Sudbury structure, Canada (Molnar et al., 2001) and the Pb, Zn, Ag and Ba deposits at Silijian, Sweden and Serpent Mound, USA (Pirajno, 2000). The impact induced hydrothermal activity at the Haughton Crater in the high Canadian Arctic is also of interest in this context because of the value of the structure and surrounding terrain as a terrestrial Mars analogue (Osinski et al., 2001; Lee and Osinski, 2005).

While all aspects of the first stage of Pirajno's model are applicable to martian impact craters, the second stage has some significantly different manifestations on Mars compared to Earth. Stage two, shown schematically in Fig. 5, results from the progressive cooling of the melt sheet and the decrease in temperature of the magmatic fluid system ($<500\,^{\circ}$C in the terrestrial context). This is coupled with the inflow of meteoritic waters from the water table. On Earth this could come from a variety of sources, including precipitation and the local water table. When considering the martian context, meteoritic waters could only be supplied from the cryosphere, i.e. the water stored as ground ice and permafrost.

The flow of the hydrothermal fluid in this stage is controlled by fractures and cracks and most of the thermal energy is provided by the hot rocks of the central uplift. On Earth, hot springs may discharge at the surface in the vicinity of the crater producing hydrothermal mineral assemblages that form alteration types like those of volcanic epithermal systems. Cabrol et al. (2001) also propose that hot springs are likely to form for short periods on Mars following an impact. Hydrothermal fluids may also discharge to the surface to form crater lakes or ice sheets on Mars like those photographed by Mars Express from orbit. The water is unlikely to remain in liquid form and will either boil off rapidly as a result of Mars' low atmospheric pressure or freeze rapidly because of Mars' low surface temperatures. Such an ice sheet has been photographed by Mars Express (Fig. 6), but may have formed inside the crater as a result of a process other than hydrothermal activity. Irrespective of the fate of the hydrothermal fluids induced from an impact, if such hydrothermal circulation does occur on Mars ore mineralization may result.

As with hydrothermal activity caused by magmatic and volcanic activity, impact induced hydrothermal circulation could produce mafic-related hydrothermal VHMS, stockworks and vein deposits, containing chalcophile elements such as Cu, Zn, Pb, Sb, Se, Cd, As, Ag, Au and Te. A deeply eroded impact crater in the south polar region of Mars gives evidence of the scale and complexity of such impact related hydrothermal systems on Mars (Fig. 7) that could give rise to the postulated mineralization.

7. Sediment-hosted hematite and sulfate deposits

Iron-rich minerals are important on Mars. Measurements made at the Mars Pathfinder site determined that iron comprises about one-fifth of the weight of the soil and approximately 16% average abundance in rocks (Catling and Moore, 2003). The Mars Global Surveyor spacecraft has detected, using its Thermal Emission Spectrometer, deposits of coarse-grained, grey crystalline hematite (Fe_2O_3) in Sinus Meridiani, Vallis Marineris and the previously mentioned Aram Chaos deposits.

The Mars Exploration Rover *Opportunity*, which is still (2009) exploring Meridiani Planum, has made several extraordinary discoveries. One of the most notable is the presence of hematite spherules embedded in the ancient sedimentary rocks at Endurance Crater. Termed 'blueberries' by the mission scientists (although 'peppercorns' would more accurately describe their size and colour) they have been interpreted as concretions deposited by aqueous fluids and are composed almost entirely of hematite (Squyres and Knoll, 2005). The hematite 'blueberries', as shown in Fig. 8, were found to be abundant in the eolian sandstone examined by *Opportunity* and had also been eroded and were therefore widespread in the region surrounding the exposed outcrop. Hematite is the dominant component of many iron ore

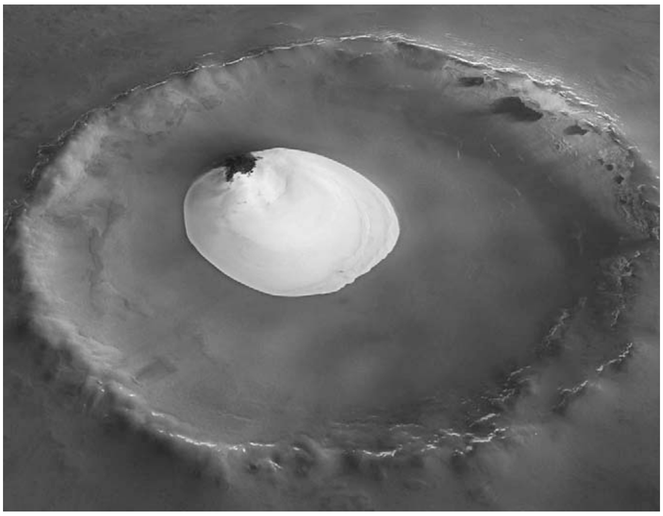

Fig. 6. Water ice in an impact crater near the martian north pole. HSRC image, courtesy of ESA/DLR/FU Berlin.

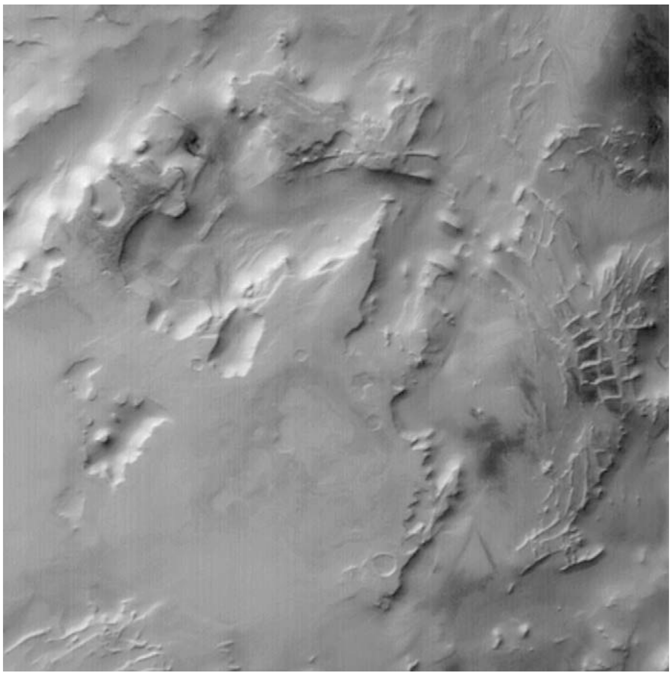

Fig. 7. MOC image E09-00186 showing erosion-resistant curvilinear fracture system formed beneath a deeply eroded impact feature, being exhumed from beneath younger cover. System is located at 82°S, 67°W and is 86 km wide. MOC image E09-00186, courtesy of NASA/JPL/MSSS.

deposits and, pre-concentrated by eolian processes (see below), these deposits could be readily scooped up with minimal equipment.

8. Sediment-hosted sulfate deposits

The sulfate mineral kieserite (Mg-sulfate) has been detected in the lowlands of Mars by the Visible and Infrared Mineralogical Mapping Spectrometer aboard the European Space Agency's Mars Express spacecraft (Gendrin et al., 2005). According to Kerr (2004) these sulfate deposits may be have formed from volcanic degassing of sulfuric acid mixing with water. In light of the possibility that Mars has a significant cryosphere of ground ice and permafrost and that the interaction of magmatic S_2, SO_2 and H_2S with such a cryosphere could result in hydrothermal circulation, Pirajno and van Kranendonk (2005) suggest two alternative explanations for the observations made by the Mars Express instrument.

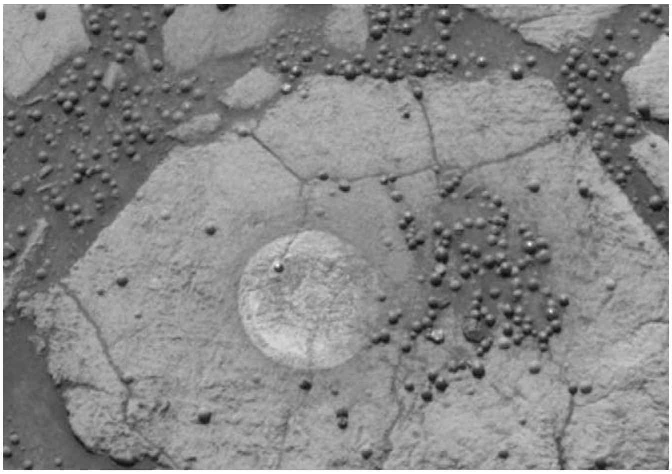

Fig. 8. The hematite 'blueberries' discovered by the Mars Exploration Rover *Opportunity*. Image courtesy of NASA/JPL/Cornell/USGS.

The first explanation proposes that the same oxidative process of volcanic H_2S on Earth applies on Mars and that the martian sulfates are in fact chemical hydrothermal precipitates which have reacted with water to produce sulfate-rich hydrothermal solutions. Such solutions have subsequently discharged at the surface as thermal springs forming sinter-like deposits. The other explanation proposed by Pirajno and van Kranendonk (2005) suggests that the kieserite can be explained by large hydrothermal-evaporative deposits. Such deposits could form in a fashion similar to saline lake evaporitic sediments on Earth. Obviously debate still rages as to the process by which Mars' sulfate deposits have been formed and will only be resolved via more investigations on the surface and from Mars orbit by future spacecraft.

The Mars Exploration Rover *Opportunity* showed that in at least one case the sulfates occur as bedded magnesium sulfate sediments (Squyres et al., 2004). The sulfates were deposited in an extensive ancient salt lake during the early Hesperian period on Mars. Such deposits, all of considerable quantity, are widespread on Mars, as shown by the review of Gendrin et al. (2005).

Magnesium in sulfates is a potential resource as it can be readily electrolysed, even though terrestrial electrolytic processes use magnesium carbonate or magnesium chloride as feedstock because of their greater abundance. Furthermore, on Earth, assimilation of sulfates by basic and ultramafic magmas flowing over them has been linked to the precipitation of massive copper and nickel sulfide deposits, such as the very large Noril'sk province (Barnes and Lightfoot, 2005). The presence of extensive coeval sulfate deposits and mafic magmatism on Mars means that such deposits can be postulated.

9. Mineral sand deposits

Eolian activity is strong on Mars, as shown by extensive dune fields and global dust storms. Many martian sands are dark in colour and derived from basalt. Martian basalts are rich in Cr (Ruzicka et al., 2001) and we can postulate chromite (CrO_2) deposits concentrated by eolian activity, along with magnetite (Fe_3O_8) and ilmenite ($TiFeO_3$), also found in basalt. The hematite found by the Mars Exploration Rover *Opportunity* have been concentrated by the wind to form lag and ripple deposits and are a potential resource. Any location on Mars that is capable of wind-sorting particles is likely to contain such mineral sand deposits, the largest and most obvious place being the floor of Valles Marineris, the largest canyon in the Solar System.

10. Deposits unlikely on Mars

It is important to also note that several common deposit types present on Earth are not likely to be found on Mars. These are deposits associated with highly fractionated (i.e. continental) crust in lithophile elements of economic interest. The intermediate and felsic rocks that make up such crust, and therefore the sediments derived from them, are very rare on Mars. These include porphyry related Cu and Au, sediment-hosted Pb, Zn and Au (as discussed above in reference to the MacArthur River deposit), deposits of rare Earth elements, phosphates, U, Th and V. Also likely to be absent are those deposits that require abundant oxygen and deep weathering, such as bauxite and sedimentary ironstones. The absence of large supplies of meteoritic waters; the absence of large amounts of organic matter; and no substantial evidence to date of past biological activity on Mars, which is needed to initiate the formation of some of the deposits listed above, are additional reasons that some of these deposits are very unlikely to be found on Mars.

Recently, three nickel-iron meteorites have been discovered by the Mars Exploration Rovers; one by *Opportunity* and two by *Spirit* (Schröder et al., 2008). This has led some to suggest that such meteorites are common on Mars' surface and present a potential source of metallic iron useful for steel manufacture (Landis, 2009). This is an interesting proposition, however, given the very high scientific value of such meteorites it is unlikely that they would be melted down for this use. Furthermore, the mass per square meter of iron is much lower in scattered meteorites than in the hematite 'blueberries' and so collecting the 'blueberries' and extracting their iron is a more plausible option.

11. Conclusion

In summary, a wide range of mineralization styles is likely on Mars, including those associated with mafic and ultramafic igneous activity and associated hydrothermal activity. Very large impact craters may generate their own style of deposits and even medium-size impact events may form smaller hydrothermal deposits. Regolith processes, including sedimentary deposition, diagenesis, and erosion are known to have produced several concentrates that may one day prove to be economic resources capable of supporting Mars settlement. Other types of mineral deposits, associated with highly fractionated crust, oxygen-rich environments, and biological activity are unlikely.

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