Mineralisation on Mars: Mechanisms & Terrestrial Analogues

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Abstract The future exploration of Mars will utilise 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. Mineral sand deposited formed via eolian processes are discussed along with hematite and sulphate deposits. 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 have also been acknowledged.

Introduction

The nature of 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 mineralisation 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 mineralisation. Plans for future exploration and the eventual colonisation of Mars by humans calls for a ‘living off the land’ philosophy that makes use of all the in-situ resources available. Mineral resources on Mars will play an important role in such an endeavour and so an understanding of mineralisation mechanisms on Mars and their terrestrial analogues is essential.

The Geology of Mars

The fourth planet from our Sun, Mars, is a rocky, terrestrial-type planet approximately half the size of Earth and, in the absence of oceans, has a surface area equivalent to Earth's continents combined. Mars' thin atmosphere is composed almost entirely of CO_2 and the planet has a mean density of 3.94 g/cm^3. At present significant geological activity and tectonism appears absent on Mars, yet the presence of volcanoes, rift valleys, impact craters and sedimentary successions suggest geological activity has occurred in the past.

The surface of Mars is composed of ancient heavily cratered highlands in the southern 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 (Figure 1) produced using data from the Mars Orbiter Laser Altimeter (MOLA).

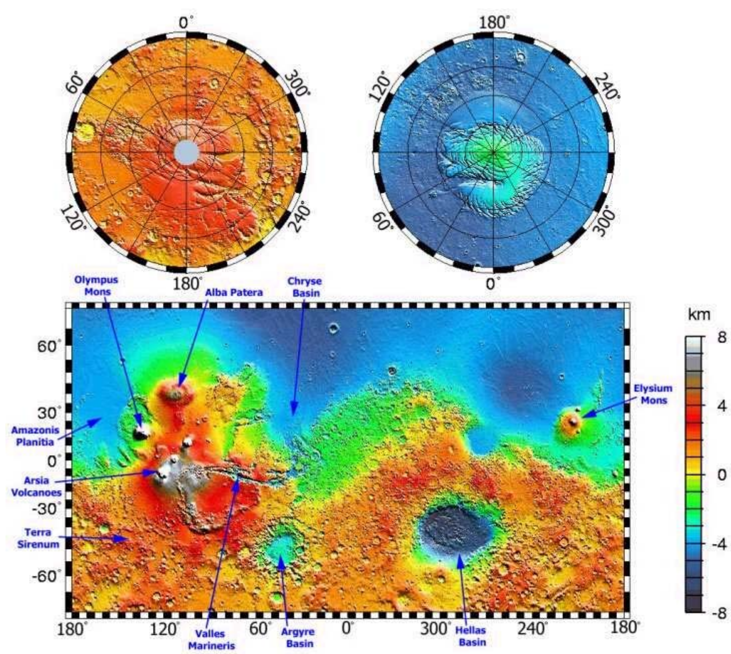

Figure 1 – The topography of Mars as obtained by MOLA

The magnitude of the morphological structures on Mars is staggering. The Tharsis Rise, shown in Figure 2, 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 x 10^6 km^2 (Pirajno, 2005b). 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. 550 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, 1996; Pirajno, 2000; Ernst, 2005; Pirajno, 2005b). The African plate, which has been stationary on Earth for at least 65 million years, is the closest analogue on Earth to a stationary one-plate lithosphere.

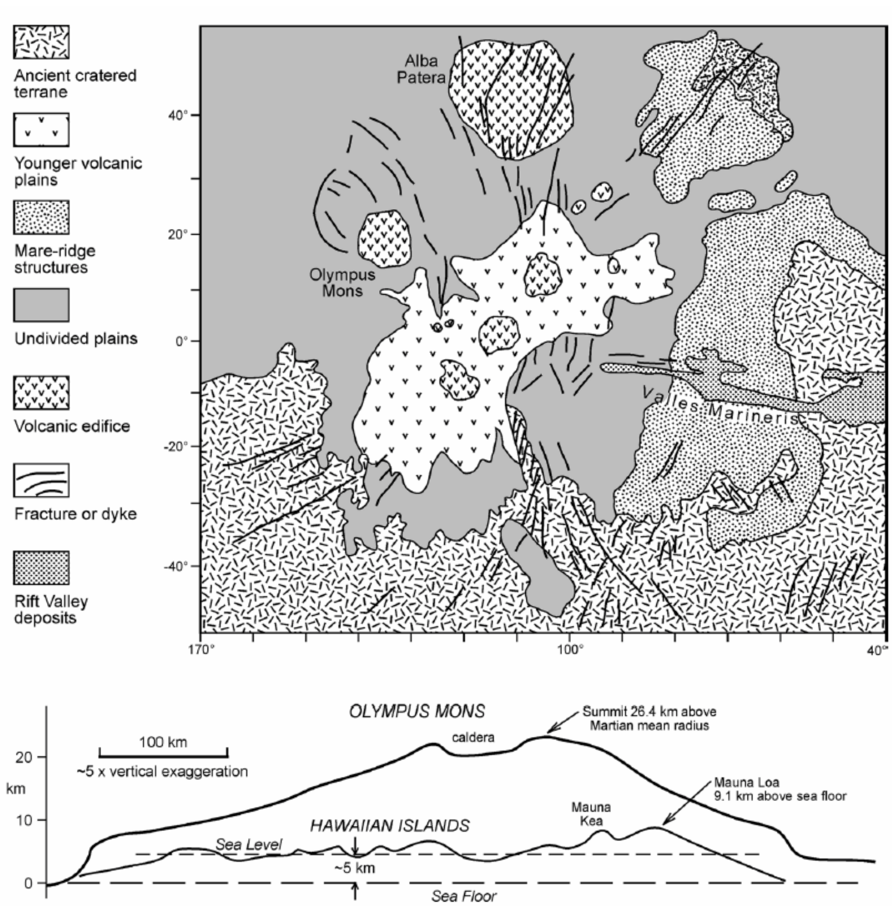

Figure 2 – Schematic geological map of the Tharsis region and profiles of Olympus Mons and the Hawaiian volcanic system (after Carr, 1990)

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, 2005b).

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 nine kilometres deep and 2,100 km across, the basin is surrounded by a ring of material that rises about two kilometers above the surroundings and stretches out to 4,000 km from the basin's center. 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 continental United States, 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 localised 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 mineralized zones.

Martian Volcanism & 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, 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 dyke systems and in the nearby Valles Marineris rift system (Pirajno, 2005 b).

Several examples of volcanic activity on Mars which could result in hydrothermal fluid circulation are worth considering. Wilson et al (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 (Figure 3). Of the possible geomorphic process which could have formed the ridges; eolian, periglacial, landslide, or shallow marine deposition, only dyke 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.

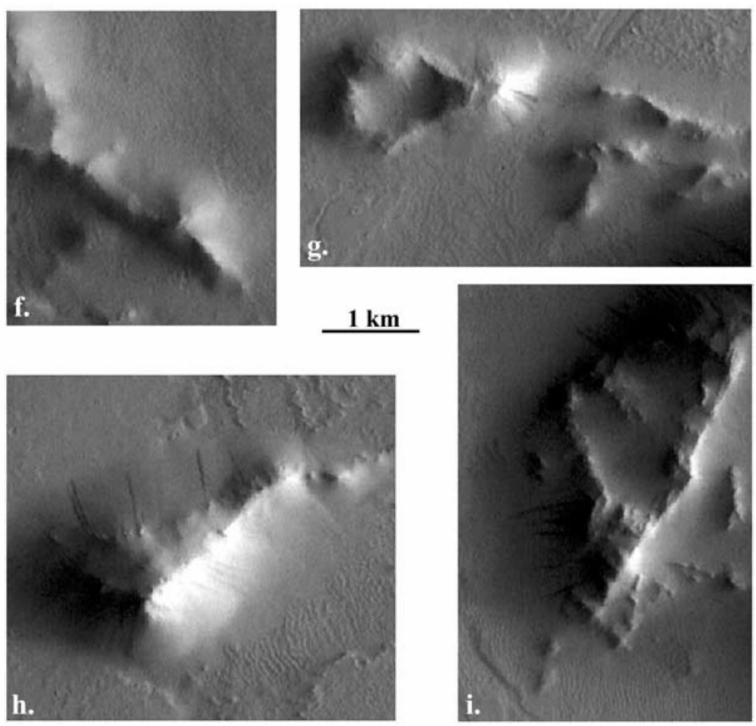

Figure 3 – Several of the ridges located on the northern flanks of Olympus Mons (after Wilson, 2003)

Wilson et al (2003) also observe that each explosive eruption, which results from the heating and consequent expansion of ground ice from the dyke intrusions, is of a very short duration – on the order of 2-3 minutes. Figure 4 shows the manner in which a dyke intrusion and subsequent explosive phreato-magmatic eruption forms the features observed on the northern flanks of Olympus Mons.

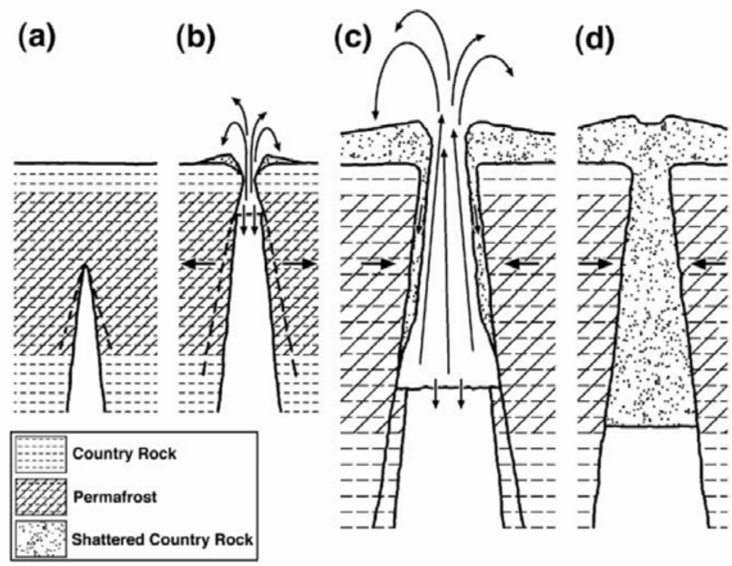

Figure 4 – Sketch of dike in relation to country rock (a) before surface break through; (b) shortly after surface breakthrough; (c) part way through the eruption; (d) after activity has ceased (after Wilson, 2003)

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 mobilised hydrothermal fluids heated by convective heat flux and dyke 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.

Pirajno and van Kranendonk (2005) propose a model, shown in Figure 5, 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 dykes, to produce sulfate rich hydrothermal solutions, which then discharge at the surface forming sinter-like deposits.

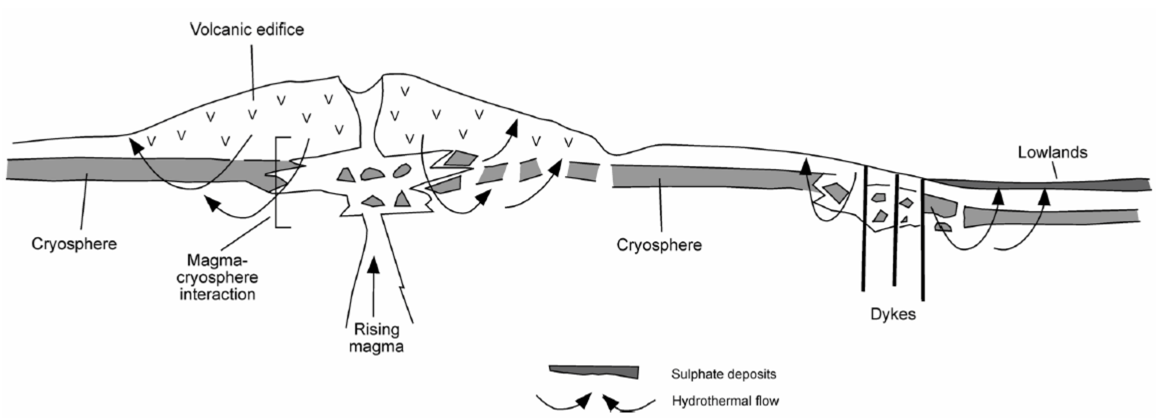

Figure 5 – Schematic model showing patterns of hydrothermal circulation in the subsurface of Mars (after Pirajno, 2005 b)

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 et al (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 dykes such as those discussed above. The Aram Chaos is shown in Figure 6 with the area of hematite detected by the TES highlighted. The hydrothermal formation of this hematite deposit on Mars is supported by analogs on Earth. For example the formation of massive specularite by hydrothermal activity and metasomatism in ancient rocks in Yukon, Canada was brecciated by forceful release of hydrothermal fluids.

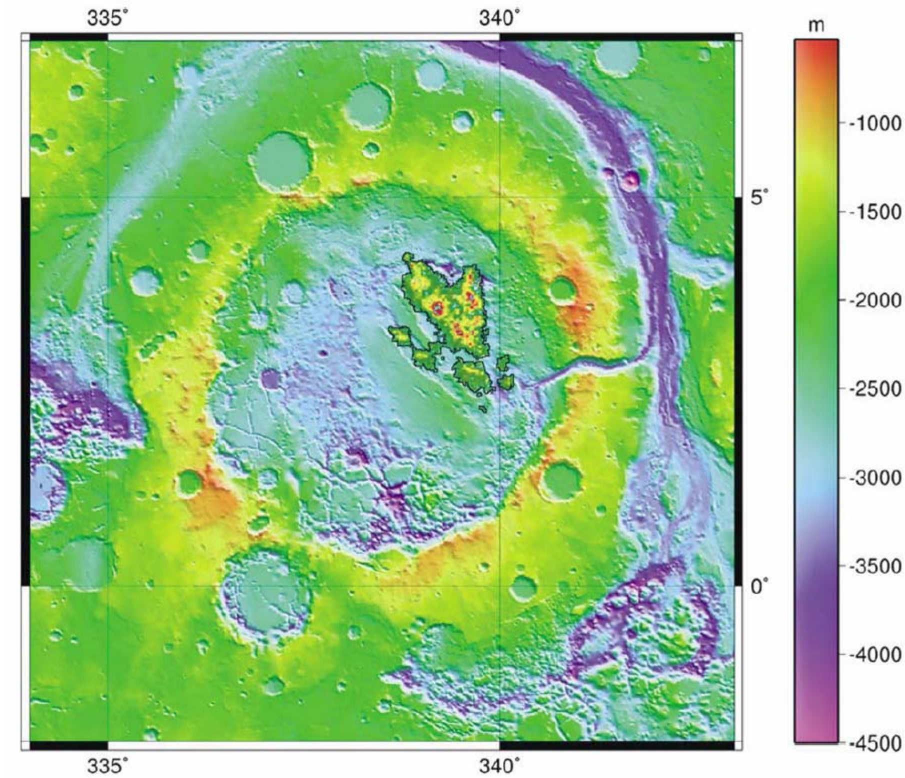

Figure 6 – Aram Chaos topography with the area enriched in coarse-grained crystalline hematite overlaid. The overlay is based on the spectral signatures from TES (after Catling, 2003)

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 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 sea-floor sediments at temperatures of 100-150°C which presupposes large and long standing oceans on the surface of Mars at some point in its history – a claim not out of the question but at this stage unproven.

Large Igneous Provinces on Mars

The massive volcanic edifices of the Tharsis Montes region, discussed earlier, and particularly Olympus Mons are the most striking example of a large igneous province (LIP) on Mars. Fuller et al, (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, 2005).

Strong links exist on Earth between LIPs and the formation of Ni-Cu-PGE (platinum group element) ore deposits. Ore minerals are separated by fractional crystallization and related processes during magmatic differentiation forming mafic-ultramafic magmatic deposits of Cu, Ni, Fe, Ti, Cr and PGEs. 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 (2005) archean greenstone belts which contain komatiites are also an important source of Ni-Cu-PGE ores. Mafic dyke swarms are also associated with LIPs and over 140 exist on Earth greater than 300 km long (Piranjno, 2000). These intrusions host economically important concentrations of platinoids, and Ni and Cu sulphides.

Recent gravity modeling 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 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.

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. Unlike Earth, Mars has an enormous impact record because of the absence of plate tectonics and other mechanisms to recycle the planet's crust. Interestingly, the ejecta blankets of impact craters on Mars are distinctly different to those found on the Moon or Mercury. Craters less than 5 km 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 and Piranjo, 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, 2005). This has 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 Masaitas (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 Masaitas (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 downdropped 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 sulphide mineralization of the Sudbury Igneous Complex in Canada is the best example of a syngenetic deposit on Earth. The multi ringed structure is on the order of 200-250 km in diameter and was formed about 1850 Ma. Its centre features the mineralisation 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 (Trotter, 1991 and Stoffler 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 (Stoffler et al, 1994). Hence mineralisation must have resulted from the impact. The present day form of the Sudbury Igneous Complex, as shown in Figure 7, is the result of erosion and tectonic activity.

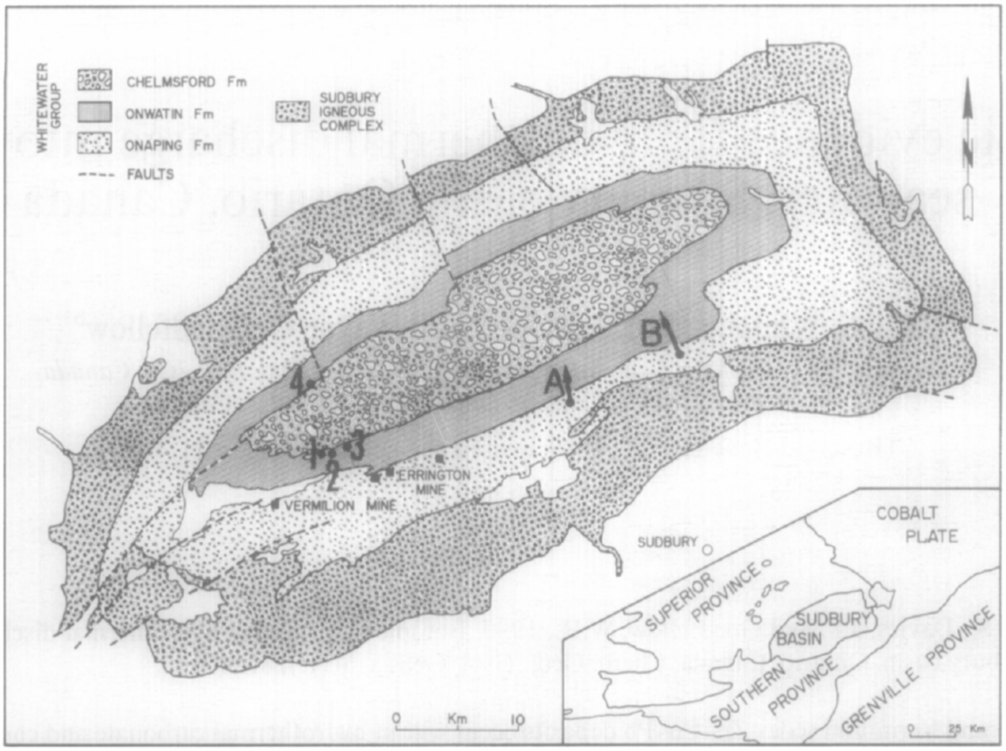

Figure 7 – Geology of the Sudbury Basin (after Whitehead et al, 1990)

The very high pressures produced by impacts (> 35 GPa) have formed diamonds in several localities. Impact diamonds are generated from pre-exisiting carbon, for example graphite, in the target rocks. They are often polycrystalline, yet harder than mantle derived diamonds (Hough et al, 1995 and 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.

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, 2005 a).

Numerous examples of terrestrial ores produced by impact induce hydrothermal circulation exist. Examples include the Cu, Zn, Pb and Au vein-type mineralization at Vermillion in the Sudbury structure, Canada (Molnar, 2001) and the Pb, Zn, Ag and Ba deposits at Silijian, Sweden and Serpent Mound, USA (Pirajno, 2000).

Impact Induced Hydrothermal Deposits

Mars' surface has been shaped by significant quantities of water in the recent past. Images from the Viking orbiter testified to river-like beds, canyons and dendritic channel networks. More recent missions have produced startling images of gullies and debris aprons in impact craters that bear testament to water flows from subsurface aquifers. The western rim of E-Gorgonum crater, as imaged by the Mars Orbiter Camera, is a prime example and is shown in Figure 8 (Cabrol et al, 2001). A 7 km diameter crater in the Newton basin (Figure 9) exhibits a streamlined, layered, and smooth platform at its northern end. This is indicative, along with the debris aprons present, of the presence of a body of water in this crater or just below its surface at some time in the past.

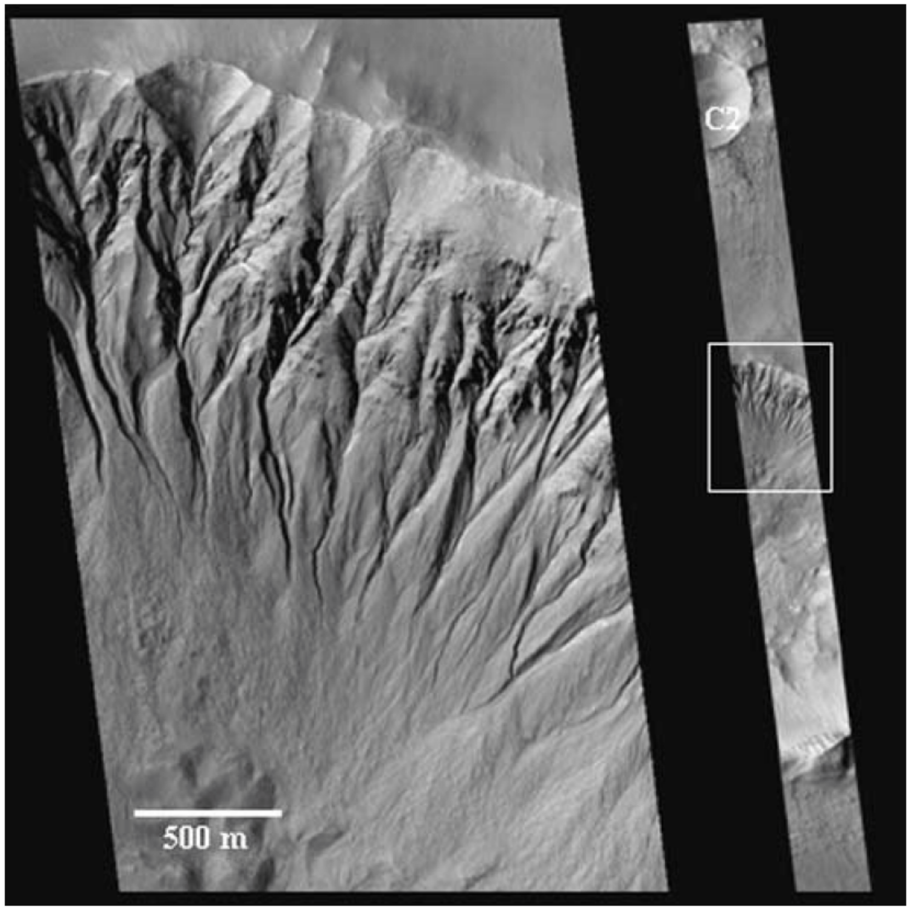

Figure 8 – Gullies and debris aprons in the E-Gorgonum crater (MOC image MO7-1873, 2.79 m/pixel resolution)

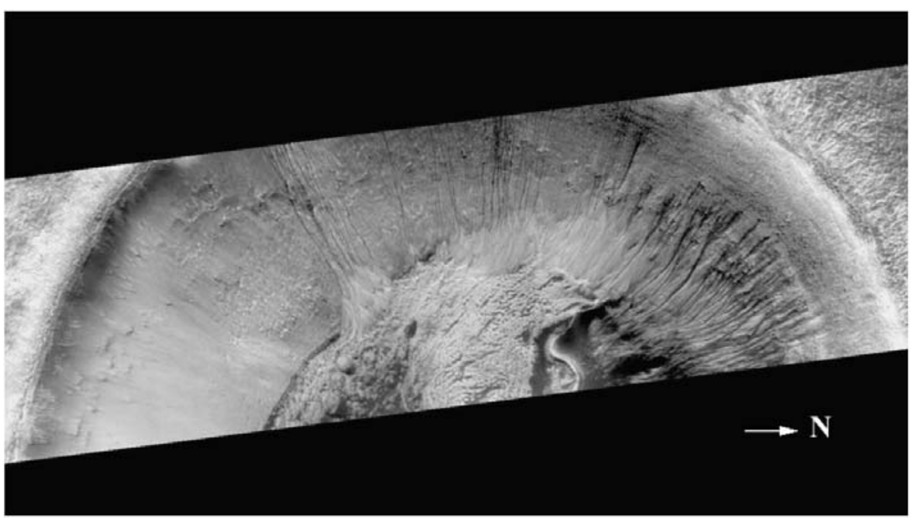

Figure 9 – Detail of the systems of gullies and aprons in the 7-km crater in Newton basin (MOC image M11-00944, 2.78 m/pixel resolution)

Since liquid water is unstable on the present martian surface general consensus is that martian water is now present as ground ice and permafrost, also known as the cryosphere. The origin of water flows on the surface of Mars is still unclear yet they may have been derived from deep frozen aquifers; having been melted and mobilized as a result of tectonic activity and/or magmatic heat, as discussed above. Impacts are another means by which water could be released, triggering hydrothermal ore formation, particularly if the impact area contains water trapped as permafrost. Wang et al (2005) even go so far as to suggest that impacts producing craters with diameters of 100 km or greater may cause global liquefaction and stream flow of the martian cryosphere.

The High Resolution Stereoscopic Camera (HSRC) aboard Mars Express has very recently (July 2005) discovered a patch of water ice on the floor of an unnamed crater near the martian north pole. The crater, shown in Figure 10, is 35 km wide and has a maximum depth of approximately 2 km beneath the crater rim. The impact crater is located on Vastitas Borealis, a broad plain that covers much of Mars' far northern latitudes, at approximately 70.5° North and 103° East.

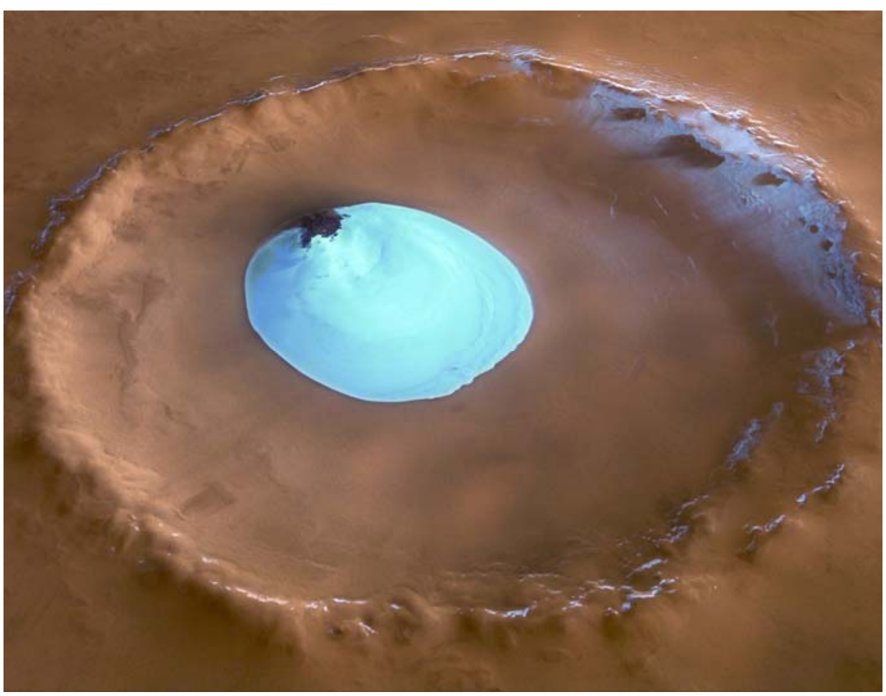

Figure 10 – Water ice in an impact crater near the martian north pole

The circular patch of bright material located at the centre of the crater is residual water ice. The white patch of water ice shown in Figure 10 is present all year round, as the temperature and pressure conditions at this location on Mars do not favour the sublimation of water ice. Faint traces of water ice are also visible along the rim of the crater and on the crater walls. The absence of ice along the north-west rim and walls may occur because this area receives more sunlight due to the Sun's orientation. The patch observed at the base of the crater cannot be frozen carbon dioxide since carbon dioxide ice had already disappeared from the north polar cap at the time the image was taken (late summer in the Martian northern hemisphere).

The origin of the water ice is still unknown but one possible explanation is that it welled up from the martian cryosphere as hydrothermal fluid driven by the heat of the impact that formed the crater. The hydrothermal fluid then promptly froze on the surface. If such a scenario occurred hydrothermal alteration zones, and hence ore mineralization, could be found in the rocks through which the heated fluids moved on their way to the surface.

Based upon impact structures on Earth, Pirajno (2005a) has 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 (Figure 11) 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.

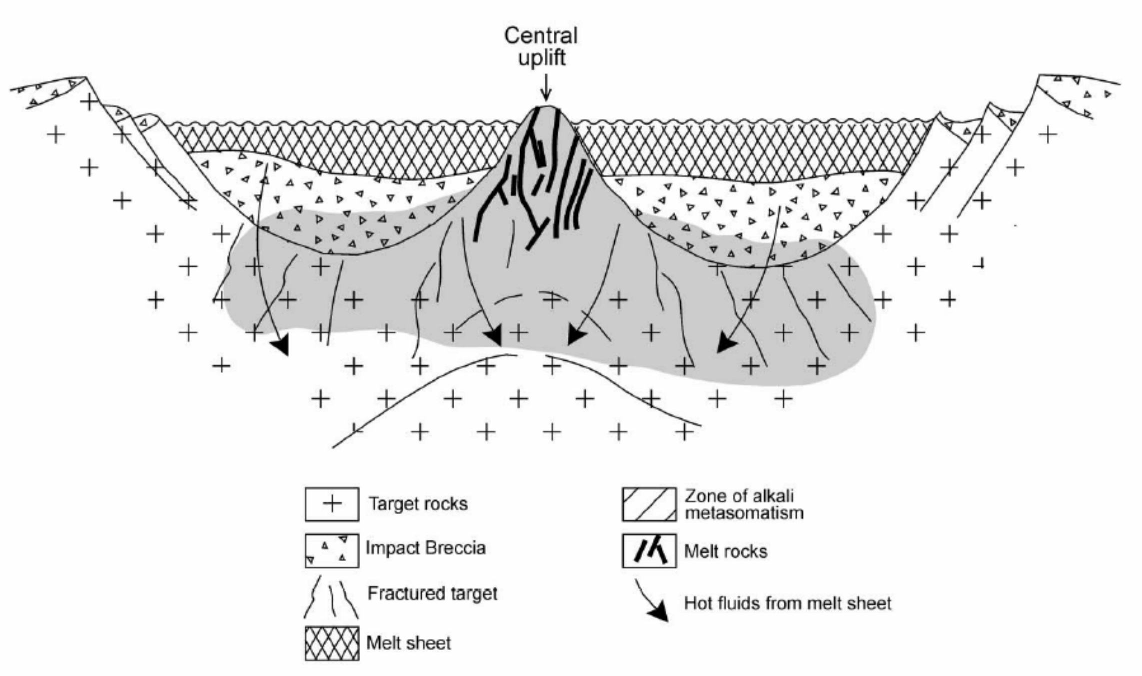

Figure 11 – Stage 1 of the model of hydrothermal fluid circulation in an impact structure proposed by Pirajno (2005 a)

While all aspects of the first stage one 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 Figure 12, results from the progressive cooling of the melt sheet and the decrease in temperature of the magmatic fluid system (< 500°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, 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 mineralisation will result.

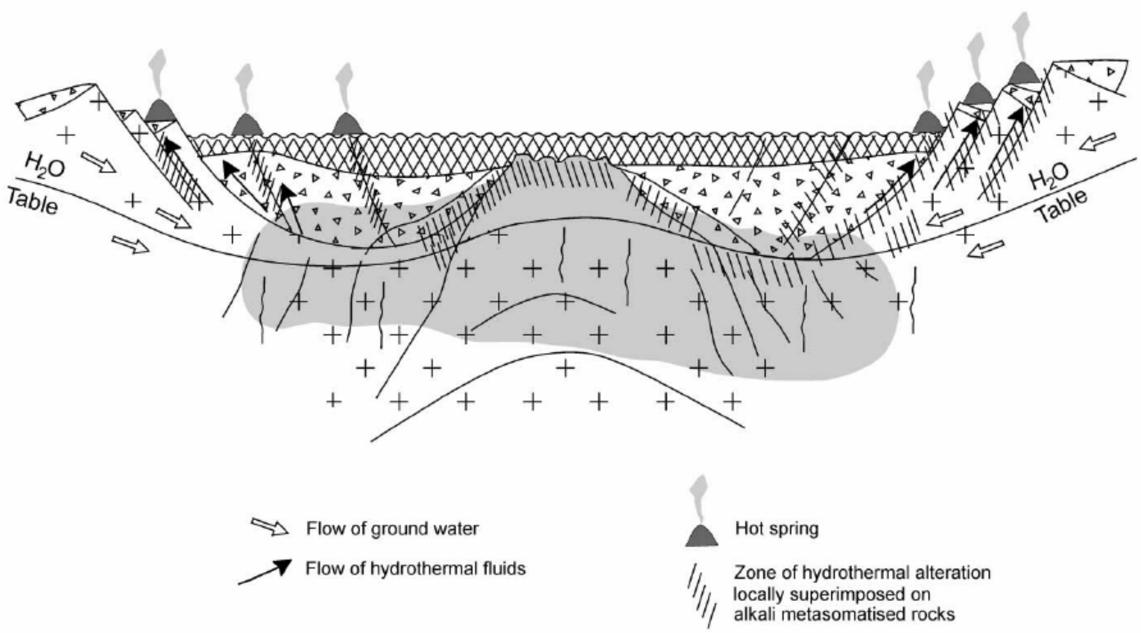

Figure 12 – Stage 2 of the model of hydrothermal fluid circulation in an impact structure proposed by Pirajno (2005 a)

As with hydrothermal activity caused by magmatic and volcanic activity, impact induced hydrothermal circulation could produce mafic-related hydrothermal VHMS and stockworks (Cu, Zn, Pb, As, Ag and Au) and mafic-related hydrothermal vein deposits (Au/Ag/Te).

Hematite & 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, 2003). The Mars Global Surveyor spacecraft has detected, using its Thermal Emission Spectrometer (TES), deposits of coarse-grained, gray crystalline hematite in Sinus Meridiani, Aram Chaos and Vallis Marineris. The Aram Chaos deposits have been discussed earlier.

The Mars Exploration Rover *Opportunity*, which is still 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 they have been interpreted as concretions deposited by aqueous fluids and are composed almost entirely of hematite, which is a common iron mineral α-Fe_2-O_3 (Squyres, 2005). The hematite 'blueberries, as shown in Figure 13, were found to be abundant in the eolian sandstone examined by *Opportunity* and had also been eroded and so were widespread in the region surrounding the exposed outcrop. Hematite is also known as red iron ore and as such these spherules would be a valuable source of Fe on Mars and could be extracted with only a vacuum cleaner!

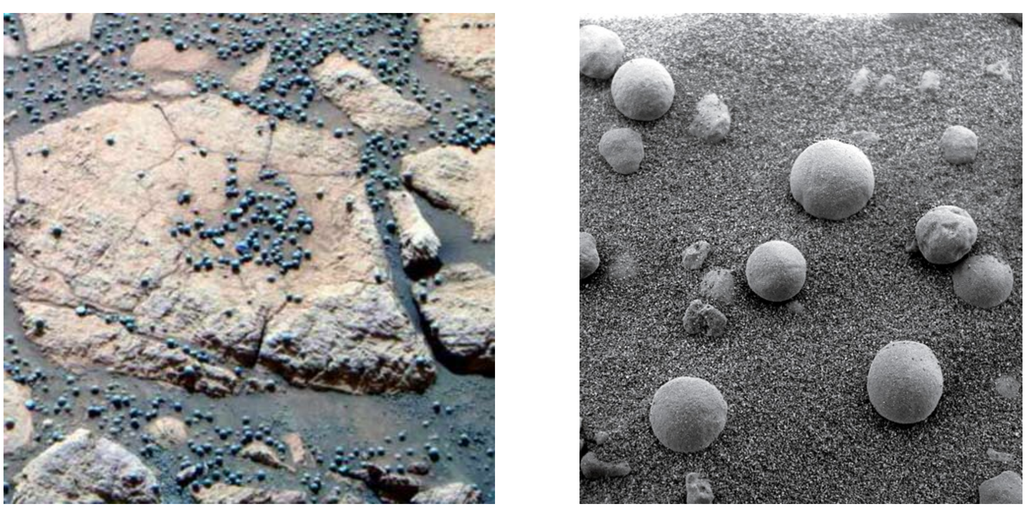

Figure 13 – The hematite 'blueberries' found by Opportunity (left) and a close up taken with Opportunity's microscopic imager (right)

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. 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.

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.

Mineral Sand Deposits

Mars is renowned for its dust storms which can, at times, envelope the planet and loft particles as high as 50 km into the atmosphere. Martian sands are primarily basalt derived TiO and are rich in Ti and other rarer elements. They are also rich in ilmenite and magnetite. The findings of the Mars Exploration Rover *Opportunity* discussed earlier also testify to the presence of hematite in sands near outcrops containing the hematite 'blueberries' (Squyres et al, 2005). Eolian process operating over long periods will concentrate these minerals in low areas in heavy sand layers which are easily extractable. 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.

Deposits Unlikely on Mars

It is important to also note that several common deposits present on Earth are not likely to be found 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 as well as Al in the form of bauxite and finally sedimentary ironstones. Some of the reasons that such deposits are very unlikely include the absence of large supplies of meteoritic waters; the absence of large amounts of organic matter and no substantial evidence to date of biological activity on Mars which is known to initiate formation of some of the deposits listed above.

Conclusion

An overview of the geology on Mars has been provided and possible mechanisms of mineralisation on Mars and their terrestrial analogues have been discussed. The concentration and exposure mechanisms identified include martian volcanism, LIPs and impact cratering which can all induce varying degrees of hydrothermal activity. Eolian processes, which provide mineral sorting, and hematite and sulphate deposits have also been considered. These mechanisms suggest that many different ore deposits are likely to be found on Mars in the future. The deposit types for which past or present conditions on Mars are not favourable have also been stated.

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