Mineralogy of the Planets: A Voyage in Space and Time

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Mineralogy of the planets: a voyage in space and time

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The centenary of the Mineralogical Society provides an appropriate occasion for integrating information on the terrestrial planets gathered over the last century, and speculating on possibilities for the next century.

The following bulk parameters of the terrestrial planets are important:

	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*
Mercury	0.33	2.44	5.4	5.3	2.5	4	100–600	0.58
Venus	4.86	6.08	5.2	3.9	30	10	700–800	1.08
Earth	5.97	6.37	5.5	4.0	37	11	230–320	1.50
(Moon)	0.07	1.74	3.3	3.4	0.47	2	100–400	1.50
Mars	0.65	3.39	4.0	3.6	3	5	100–300	2.28

a, mass (10^{24} kg); *b*, radius (10^3 km); *c*, real density (g cm^{-3}); *d*, estimated density at 1 GPa (g cm^{-3}); *e*, estimated pressure at centre (10^{10} Pa); *f*, escape velocity (km s^{-1}); *g*, temperature of solid surface (K); *h*, distance to Sun (10^8 km).

Relevant features of the atmospheres are:

Mercury: trace He and H_2; no other gases detected.

Venus: 10^7 Pa at surface; 250 K, 1 Pa above clouds, mostly CO_2, trace CO, H_2O, HCl; refractive index of clouds, 1.45, consistent with H_2SO_4; N_2 and Ar likely but hard to detect.

Mars: 500–1000 Pa at surface, mostly CO_2 but N_2 and Ar likely, trace CO, O_2, O_3, H_2O; variable icecaps, fogs and dust clouds.

Because H_2O- and C-bearing gases are important in the evolution of planetary surfaces and atmospheres, the following phase equilibria were displayed in *PT* space on lantern slides. For H_2O: melting of water ice; stability of zeolites, serpentine and talc; stability of Al-rich amphibole and Fe-bearing phlogopite in peridotites from the Earth; melting of wet basalt. For C; melting of CO_2; condensation of $Fe(CO)_5$; breakdown of coexisting silicate and carbonate to CO_2 and a silicate poorer in Si; breakdown of spurrite and rankinite to larnite and CO_2; tability of the meionite variety of scapolite; breakdown of Mg, Ca-carbonate + Mg-bearing silicate to other silicates + CO_2 or to liquid.

Pressure–temperature curves for the Earth (oceanic and shield geotherms) and the Moon (estimated from electrical conductivity) were used as guides for estimating the 'prete' of other planets. Probably each planetoprete is near-asymptotic to the solidus for a silicate-rich material (perhaps peridotite), but various speculations can be made depending on one's view of the differentiation of the solar nebula. Because of the huge volcanoes, the Martian prete should be asymptotic to a silicate solidus perhaps reaching 1500 K at 2 GPa. If volcanic emissions maintain the Venusian atmosphere, the Venusian prete might rise from *ca.* 750 K to reach

1500 K at 4 GPa. If Mercury melted completely, its present prete should be near a silicate solidus for pressures above 2 GPa. Earlier pretes might have reached temperatures near a basaltic solidus just below the surface.

The mineralogy of the planets must be considered in the context of chemical and physical differentiation of the solar nebula. Astronomical observations reveal warm dust clouds around young stars and evidence for violent processes in stellar nebulae including rapid expansion, strong rotation, high magnetic field, very powerful solar wind and big mass loss. Theoretical analyses are extremely difficult and the results depend greatly on the initial assumptions. An orthodox interpretation using a hot, massive nebula involves: local instability of several solar masses in galactic cloud; contraction to give Sun; temperature rising to over 2000 K at centre to a few degrees at 100 AU†; progressive condensation to give dust; aggregation by several mechanisms including magnetic attraction; clearing and rapid cooling by radiation loss; acceleration to mid-plane of nebula and gravitational instability; multiple collisions producing streamline rotation; growth of planetesimals and ultimately planets; early melting; stunting of Mercury and Mars because of increased velocity of planetesimals near the Sun and Jupiter; inhibition of planet in asteroid region; formation and destruction of moons; intense early bombardment of proto-crust by decaying population of planetesimals; lucky preservation of residual debris as asteroids; 'clean-up' of inner region and removal of atmospheres of terrestrial planets by intense solar wind. Many features should be applicable to models based on a cooler, less massive nebula.

Simple progressive condensation of the solar nebula at ~ 10 Pa yields the following theoretical sequence for a generalized cosmic composition with C/O $\approx$ 0.6: 1800 K refractory metals, 1600–1400 Ca,Al,Ti-oxides, 1400–1300 Fe,Ni,Co-alloy and Mg,Si-oxides, 700 conversion of some metallic Fe to FeS, 500 conversion of some metallic Fe to oxide; 400 OH-silicates; 150 water ice; 100–50 NH_3 and CH_4 clathrates; 20 CH_4 and Ar ices. This sequence seems capable of explaining the general properties of the terrestrial planets and most meteorites, though melting, retrogressive effects, and departure from equilibrium are needed to explain details. Certain meteorites, including enstatite chondrites, can be explained only by derivation from a nebula with C/O near to or greater than unity. Progressive condensation for a near-cosmic composition with C/O $\approx$ 1 gives the following theoretical sequence: 1500 K SiC, CaS, TiN and Fe_3C; 1400 Fe,Ni,Co-alloy, 1200–1100 Ca,Al,Ti-oxides, 1100–1000 Mg,Si-oxides. Perhaps massive loss of H_2O in certain places changes the C/O ratio.

The ballistics are very difficult to model theoretically because perturbations diverge for most multiple orbits. Approach of a planetesimal to a planet could result in either a direct hit, a glancing collision, or a near-miss. The near-miss could lead to disintegration inside the Roche limit or to orbital deflexion. From the chemical viewpoint, the interaction could lead to accretion of any fraction from zero to unity. Some material might end up in orbit around the planet. Considerable chemical differentiation might occur from differential ballistics, momentum transfer, and selective melting and volatilization. Simple considerations suggest that near-misses are common and that debris clouds should form around each planet. A debris cloud might accrete into one or more moons if its density is high enough to overcome the tendency towards dispersal by later collisions. For several reasons involving the higher escape velocity, larger planetesimals should grow faster than smaller ones leading to a 'tadpole' effect. Tidal interaction causes a prograde satellite to recede away from and a retrograde satel-

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† 1 AU $\approx 150 \times 10^9$ m.

lite to fall into a fast-rotating planet, whereas for a slow-rotating planet all satellites can fall inwards. Tidal effects lead to synchrony.

Bearing all these factors in mind, the following general considerations pertain to the terrestrial planets. Do the bulk compositions correlate with distance from the Sun, and can they be related to a simple model in which the chemistry depends on equilibrium condensation to a certain temperature at which the remaining nebula was blown away? Such a model requires near-streamline rotation, and could be contrasted with a model in which deflexion of planetesimals causes non-streamline rotation and similar composition of adjacent terrestrial planets. Was accretion of a planet chemically homogeneous or heterogeneous, and did formation of a proto mantle block equilibrium between the final core and mantle? The evidence from the Moon demonstrates intense bombardment of the crust until − 4Ga, and the surfaces of Mars and Mercury suggest a similar bombardment; hence can one expect deep 'stirring' of some hundreds of kilometres of the outer part of all the terrestrial planets? Any primary atmosphere on the Earth must have gone because of the data on noble gases. Was the secondary atmosphere already oxidizing (with implications for the crust and mantle), or did massive escape of H_2 oxidize a primeval reducing atmosphere, or did biological activity produce the oxidation? This is an extremely difficult question involving the escape velocity, the extent of ionization, the temperature profile of the atmosphere (e.g. possible cold trap for H_2O in troposphere), relative rate of volcanic emission and reaction of atmosphere with solid and liquid surface, origin and timing of biological activity, etc.

This coordination of ideas, largely from the existing literature, allows me to select a few deas about the terrestrial planets for further exploration. I tend to favour catastrophic processes, and emphasize that simple processes are insufficient though the natural first target of theorists.

Earth and Moon: Did this pair result from disintegrative capture of an unusually large planetesimal by the proto-Earth involving formation and accretion of a debris ring from which volatiles were expelled and Fe preferentially lost to Earth? Did the Moon undergo total crystal–liquid differentiation (probably by prolonged partial melting) producing a plagioclase–pyroxene-rich crust, an olivine–pyroxene-rich mantle and an Fe,Ni,S core about −4.5 Ga? If no rocks on Earth survive from before −3.8 Ga, was the early crust of the Earth very transient because of a high geothermal gradient combined with bombardment from the same populations which hit the Moon? How was fusible material stored in the Earth's mantle, and what is the ultimate origin of magmas rich in CO_2 and H_2O? Are the oxidized crust and apparently reduced core of the Earth really out of equilibrium, or can this be explained by disproportion of Fe at high pressure? Is inhomogeneous accretion necessary? Some prime areas for study are: mineralogy and chemistry at high pressure using tools such as the diamond pressure cell; petrology, mineralogy and chemistry of nodules in kimberlites and alkali basalts; petrology, mineralogy and chemistry of early Archaean rocks; kinetics of solid–liquid–gas reactions; volatiles in magmas and in the inclusions in minerals, especially diamonds.

Mercury: This innermost planet must have much metallic Fe to explain the high density, but the spatial distribution of silicate and metal is debatable. The simplest assumption is that Mercury differentiated completely by melting because of high accretion energy and perhaps high U content from accretion of only a high-temperature condensate. Non-streamline motion of planetesimals with differential accretion of Fe-rich metal over Mg-rich silicate is an alternative to a popular model for accretion of a streamline high-temperature condensate. The latter should have given Si-poor volcanic rocks in contrast to Si-rich rocks from the former. Discovery of sulphide in veins and vugs (as on the Moon) would tend to discredit the latter model.

Venus: Accretion models range from ones involving only condensates more refractory that FeS to ones with an Earth-like composition. The former requires streamline motion and a special relation between progressive condensation and turn-on of the T Tauri solar wind. The latter is more tolerant of erratic events and is preferred. Complete melting should have occurred, especially as capture of a moon (to explain slow retrograde rotation) would provide extra energy. Ionization of H_2 from all water and hydrocarbon could give extra oxidation of crust (perhaps extra few kilometres of magnetite) and extra CO_2. An alternative is diffusion barriers in crust and atmosphere, with retention of H_2O in mica and amphibole in the outer few tens of kilometres. The concept of a runaway greenhouse is questioned because the crust and atmosphere should have started hot from catastrophic processes. Is the thick, hot atmosphere maintained by intense volcanic emissions which overpower the extraction of gases by mineralogical reactions at the surface? Scapolite, sodalite, cancrinite and anhydrite provide potential sinks for Cl, CO_3 and SO_4, while carbonate–silicate reactions may provide a buffer for CO_2. Certainly the metamorphism cannot be lower than the amphibolite facies, and the Venusian crust may be dominated by granulite (s.l.). The mineralogy should be simple with absence of all minerals which decompose below *ca.* 750 K. Chemical profiling of the atmosphere together with more thorough examination of the chemistry of the solid surface (a very difficult job!) would go far towards testing the dynamics of chemical cycles. Radar profiling with a resolution < 1 km from a fly-by mission might test whether volcanoes are prominent.

Mars: Various proposals for a core made entirely of either magnetite or Fe, Ni or FeS are perhaps less satisfactory than one for a Fe,Ni (minor S) core. Differential capture might allow a smaller proportion of Fe,Ni,S than on Earth, and a similar silicate composition for the mantle. All models predict a strongly hydrous nature unless massive ionization and loss occurred. Major climatic changes could cause major changes in the surface mineralogy. Perhaps large beds of zeolite result from hydration of volcanic ash; however, clay minerals may dominate if CO_2/H_2O is high. Clathrates are possible in particularly cold regions.

Minor planets (*asteroids*): Mineralogical speculation must bear in mind the diversity of orbital parameters and surface reflectivity. Some asteroids (e.g. the Apollos) probably provided meteorites, but others (e.g. the Trojans) almost certainly did not. About half of some hundreds of asteroids give spectral reflectivities which match those of meteorites, especially carbonaceous ones, but the others have not been matched. Asteroids may derive from primary condensation, catapulting of disrupted planetesimals by planets, and burn-out of comets. Because the terrestrial planets have undergone prolonged differentiation, chemical and mineralogical study of asteroids should be pursued vigorously to look for clues to the early solar system.

Meteorites: A vigorous debate continues whether meteorites derive from asteroids, comets or elsewhere. Some important problems pertinent to the origin of the planets follow. Do the variations in isotopes (especially of oxygen) result from solar or extra-solar causes? How many mechanisms are needed to form irons and stony-irons? Are eucrites, howardites and diogenites fragments of a disrupted moon originally in orbit round a planet, or are they from unsampled regions of the Moon? What mechanisms are responsible for the wide variation of oxidation state? Do some chondrules result from a liquid spray formed during disintegrative near-collisions? Probably fly-by and landing missions to selected asteroids, including Vesta with a basalt-like reflectivity, will help greatly in clarifying the origin of meteorites. Present mineralogical and petrological data suggest that most meteorites underwent complex processes, and that simple, progressive condensation in the solar nebula was applicable to only a few meteorites of which the C-3 Allende is a particularly good example.

Techniques for remote study: It is hard to believe that much material will be returned to Earth in the next century, even if political, social and religious tensions ease. From the viewpoint of mineralogy in the broadest sense, the following techniques are needed. Orbiting telescopes fitted with detectors for a wide spectral range are needed to make general surveys. Close fly-by missions are desirable to give maps of the surface of suitable bodies, especially asteroids and comets, to as high resolution as possible. In addition to morphology, the bulk chemistry of the extreme outer surface should be determined from γ and X-ray techniques. Landing missions should exploit bulk analysis of both major and trace elements provided by the combination of proton, α and X-ray fluorescence methods. Lunar studies have shown that bulk analyses of regolith need to be supplemented by detailed mineralogical studies. Microscopic study of a regolith with a stereomicroscope capable of up to a hundredfold resolution should enable simple sorting of various components including basalt fragments, glass spheres, agglutinates and distinctive mineral grains. Chemical techniques for single crystals or rock fragments would be very useful: perhaps a direct-reading arc spectrograph might be developed. X-ray diffraction might also be exploited, of which the powder techniques (and Gandolfi?) should be easiest. Finally for the study of planetary interiors, the development of the diamond cell to allow pressures over 10^{11} Pa is particularly promising.

After a demonstration of how much information was provided by the chemistry and polymorphism of even such a simple mineral group as the Fe-rich metals, the lecture concluded with an opinion that the mineralogical sciences are currently among the most dynamic of the physical sciences and promise further great advances in knowledge of the solar system over the next century.

Detailed acknowledgements for help from many scientists will be given in the full paper.