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Advances in the Earth paradigm applicable to the geophysics of the other terrestrial planets

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Our attempts to understand the internal evolution and current geophysical behaviour of the other three terrestrial planets (TPs) are, of course, strongly coloured by what we think we know about our own and what is going on inside it. So this contribution outlines the big changes in this that are already well in train. We then suggest how these changes in paradigm can affect our geophysical expectation and interpretation on the constitution and dynamical behaviour in the other TPs.

Our starting point, for all four TPs, is their planetary construction and the formation of their iron cores. To achieve their individually very high orbital specific angular momenta, relative to solar material, the nebula must be present and do it for their feedstock throughout their growth. This short timescale (<5 Ma?) completely rules out the >30 Ma timescales inferred for cores-by-percolation models, necessitating reversion to the Ringwood model, with the further great benefit of forming the solar planetary system's water by chemical reaction of nebular H with erupted FeO [1]. The resulting Fe is then 'subducted' in non-reacting lumps, to build the core. This mechanism also has potential to carry lithophiles (U,Th) into the core.

It turns out that the inevitable incorporation of a lot of this water in the mineral structure of the mantle has dominated the magmagenetic and (via its rheological effect) the dynamical evolution of the Earth [1,2]. Prior to 2.5 Ga this permitted convective extraction of early heating and genesis of komatiite, the predominant high-melting magmatic effusive, all without the need for mantle plumes.

After that, its non-linear effect upon rheology [3] as the ocean emerged resulted in a complete hiatus in plate tectonics ~2.45-2.2 Ga [2,4,5], during which oxygenic life was able to win its battle against acidic (mainly CO_2) volcanic exhalations at MORs, marking the initiation of our oxygen-bearing atmosphere, to which we owe our very existence. Concomitantly, it also oxidized the previously low-pH ocean water, bringing deposition from it of most of the world's iron ore reserves (BIF). MOR collapse greatly lowered (>3km) sea-level and the resultant erosion of cratons lowered atmospheric CO_2 by weathering to the point that Earth's first global glaciations (Huronian) occurred during the hiatus.

Since that time, and (as I will show) is globally explicit in the dynamics of plate motions for the past 150 Ma, this rheologically 'stiffened' mantle has (despite seismological interpretation to the contrary, on account of its persisting late-Archaean content of interstitial fluid) remained attached to the undersides of cratons as 'deep keels' reaching to or near the base of the Upper Mantle [2,5]. That fluid is apparently the source of the metasomatism in kimberlite xenoliths erupted through cratons.

Another group of mantle-constitution factors - phase changes - needs attention by geophysical modellers, on account of the very large volume changes, per joule in or out, exhibited by most of them, relative to pure thermal expansivity. As thermally induced volume changes these can have big effects upon topography, a feature readily observed on other TPs. In particular [2], that of spinel peridotite to garnet peridotite, whose volume change/joule is around 50-fold, is typically present at somewhere between 50-90km below our ocean floor. The volume change is a density change and affects gravity, so the result is readily confused, using pure expansivity, with the convective injection of very large volume of hot magma to that sort of depth, whereas the heat from quite a narrow volcanic duct - in much thicker plate - may readily do the job. An important consequence of this solid-state volume increase is that its horizontal expression may split the plate further. Moreover, if you have a planet, as was the Earth during the hiatus, on which the global lithosphere is cooling and shrinking horizontally, this will produce limited-extension rifts, such as are widely evident on cratons in this interval. The feature emphasizes the importance of within-plate changes in thick plates. Another feature of thick plates is that narrowly splitting them is a fertile mechanism for mantle magmagenesis and its segregation [6].

Moving now to the other TPs, the preservation of closely circular orbits for Venus, Earth and Mars, the consequence of construction in the presence of gas-drag (as required by core construction), means that none experienced a post-nebular late giant impact. So the Moon has a different origin, attributable to the Earth capturing only ~2.7% of the ejecta from such an impact on Mercury [7]. The lunar bombardment at 3.9 Ga and the lunar maria may be attributable to encountering a final tranche of that debris. The mascons of that, and the small core in the Moon tell us that some of Mercury's core was also ejected. Consequently the interpretation of Mercury is fraught with special complications.

Venus, near-twin of Earth, probably had its spin slightly reversed by retrograde tidal capture of much more of the Mercurian debris, also removing any satellite that it had. Venus had started life like Earth, with a water-weakened mantle, and rapid convective overturn, but solar proximity resulted in evaporation of the water evolved at 'MORs', preventing formation of an ocean. But its CO_2 atmosphere tells us that, like the Earth, such vigorous 'MOR' activity was not short-lived so must have involved subduction. We conclude that its upper mantle reached the same lock-up state [3] as caused our own tectonic hiatus. But in Venus the failure to restart shows that this was too widespread for the ensuing build-up of heat to do that. Studies of the resulting magmatic resurfacing and epeirogenic development of surface relief will need to consider phase-change effects and, in this case, the powerful epeirogenic action of the thermal release of water at depths that inhibit its escape [8].

Skipping briefly to Mars, its distance from Mercury means that little of that impact debris would have reached that far, so cratering-based inferences as to its surficial age(s) should be adjusted for that. The 4.5 Ga age of ALH84001, which was dug out of Mars only ~15 Ma ago, tells us that at least one patch is very old. Ringwood-mode core formation would have gone slower in the smaller planet but, halted by nebular departure, more FeO will have been left in its mantle, giving higher density. This will affect calculations of the depth of its CMB until seismological observation can be done. As with the other TPs, the final removal of the huge water-excesses from core formation was probably very early, at the time of final nebular clear-out, and contributed to the envelopes of the Giant Planets [9]. In that case, present near-surface Martian water is, after allowance for loss by hydrodynamic escape, all that has evolved from its mantle, consistent with the apparently limited magmatic resurfacing.

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