THE MARTIAN CRUSTAL DICHOTOMY: PRODUCT OF ACCRETION AND NOT A SPECIFIC EVENT?

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Attempts to explain the fundamental crustal dichotomy on Mars range from purely endogenic to extreme exogenic processes (1,2) but to date no satisfactory theory has evolved which is generally accepted. What is accepted is (a) the dichotomy is an ancient feature of the martain crust, and (b) the boundary between the cratered highlands and northern plains which marks the dichotomy in parts of Mars has undergone significant and variable modification during the observable parts of martian history. Fundamental uncertainties remain, including: (a) the true present and former extent of the boundary (i.e., is it global?), (b) the nature of the crustal materials underlying the northern part of the dichotomy (is the dichotomy both topographic and compositional?), (c) the nature and duration of the formative process(es?), and (d) the relation between the establishment of the crustal dichotomy and the overall internal and crustal evolution of Mars. These are important questions because crustal dichotomies are a common feature among the terrestrial planets.

Wilhelms and Squyres (2) call on a single mega-impact event, essentially an instantaneous rearrangement of the crustal structure (topography and lithospheric thickness). Wise et al. (1) prefer an internal mechanism: a period of vigorous convection subcrustally erodes the northern one third of Mars, causing foundering and isostatic lowering of that part of Mars. This major tectonic rearrangement of the lithosphere is also considered an "event" in martian history, ending by crater ages 50,000 to 100,000. In this paper we review the evidence for each of these two extreme theories, conclude there is little to recommend or require either, and suggest an alternative: the formation of the crustal dichotomy on Mars was not a specific tectonic "event" but a by-product of the accretionary process and therefore a primordial characteristic of the martian crust, predating the oldest recognizeable landforms.

The Mega-Imapact Hypothesis: Because it is a well-defined process, the formation of the martian crustal dichotomy through a 7700 km diameter impact (2) is more easily examined that the less precisely defined alternative (1). Exceptions to the impact hypothesis are several. The described small circle suggested as the basin rim is incomplete and better described as a semicircular arc covering less than 180° of longitude. Circularity in any case is a necessary but not sufficient condition to demonstrate impact. The basin "rim" is highly variable in expression and character and its location in western Mars is inferred from presumption of circularity and continuity. Even where well displayed, features used to define the rim vary along its length by more than might be expected for a single impact, even allowing for likely variation in the subsequent erosional processes which have clearly modified the boundary (3,4,5,6). Massifs used to define the rim in many cases have been ascribed to other smaller basins (7,8,9). There is a lack of both concentric and in particular radial structures over the entire circumference that might be expected for such a large impact. Detailed mapping of detached plateaus and knobby terrain along and away from the presumed rim (10,11) does not support the statement that all the old cratered terrain lies outside the suggested basin. Outcrops north of Olympus Mons and in particular the highstanding old subsurface characterized by the knobby terrain in Elysium-Amazonis (12,13,14) which lies near the center of the basin are difficult to reconcile with an impact basin structure. Topographically the basin has rim-like gradients only along its southernmost portion in Amenthes-Aeolis; elsewhere the slope from cratered highlands into the northern plains is much more gradual and lacks rim-like character.

Subcrustal Erosion and Underplating: The Wise et al. (1) model lacks quantitative detail which could be tested. Calculations of the amount of surface crustal material that would have to be removed from the north and deposited in the cratered terrain are presented and found inadequate (15), but no similar volumetric calculations are provided for the favored subcrustal erosion and subsequent underplating. It is not explained how lower density crustal blocks are preserved in the higher density and hotter mantle for the time period between the lowering of the northern third of Mars and the later isostatic rise of Tharsis. It is not easy to understand why such surviving blocks would preferentially collect in one or two locations (pre-Tharsis and pre-Elysium?) rather than being uniformly distributed over the remaining two thirds of the martian lithosphere. The duration of the vigorous convection required by this mechanism is not specified and the stability of the simple convective pattern pictured may also be questioned. Vigorous convection may in fact never have been part of martian history: thermal models suggest a more moderate episode of core formation which raises the global temperatures on Mars by only 200°C (16,17). If pieces of old, unfoundered crust exist in the northern third of Mars (11,12) then ad hoc preservation mechanisms must be invoked or pre-existing lithospheric heterogeneity undermined the effectiveness of the subcrustal erosion.

An Alternative to the "Single Event" Approach: The geophysical difficulties associated with the subcrustal erosion theory and the evidence against the single mega-impact model require that alternatives to account for the martian crustal dichotomy be considered. There is no requirement that the modification to the martian lithosphere be due to a single "event" and in fact there is little available evidence to recommend such one-shot scenarios. Perhaps more useful would be considering the cumulative effects of multiple smaller scale events. Impacts are appealing because of their ability to drastically alter (locally) the lithospheric structure. Because the single giant impact hypothesis seems inconsistent with the observational evidence, we raise the question of whether or not the crustal dichotomy on Mars could be due to the combined effects of many more moderately-sized impacts such as might occur at the tail end of the accretionary process.

Recognition of ancient impact basins is hampered by the processes associated with the formation and evolution of basins (7,18). Despite this, new basins continue to be found on Mars (8,9). If the Chryse Basin (7) is taken as the largest currently accepted impact structure on Mars and a D^{-2} scaling is used to estimate the number of smaller impact basins that could exist on the planet, then an estimate of the number of "missing" or undiscovered basins can be made: 7 with diameters larger than 1000 km, 32 larger than 500 km and 155 larger than 250 km. The combined area of these exceeds that of the suggested Borealis Basin. If these structures were all in the northern hemisphere of Mars (which is unlikely), the overlap expected to occur between them would still allow large portions of the ancient cratered terrain to remain as isolated islands between basins. In particular large blocks such as the Elysium-Amazonis knobby terrain unit might survive. The patchy distribution of possible old crust in the northern plains (11,12) as well as the topographic irregularities found there are more easily understood in terms of multiple overlapping impacts than with a single giant impact.

Multiple impacts could be expected to produce drastic and long-lived effects in the martian lithosphere which in sum might be far more effective at establishing and maintaining a crustal (lithospheric) dichotomy than either of the two single event theories. Large impacts will thin the lithosphere both mechanically and thermally (19,20,21). The depth-diameter relation for very large impacts is not known, but it is likely to be a shallow function. Therefore overlapping large impacts could produce a greater total mechanical thinning (locally) than might be accomplished by a single giant impact, especially away from the presumed center of such a mega-impact. Detailed thermal histories for large scale impacts are still few, but most show enhancement of the thermal gradients below the basin for several hundred million years after impact (19,22). During late stage accretion overlapping impacts could occur within this period. Volcanism in such areas might be accelerated and the establishment of a deep-seated thermal anomaly is not unreasonable. It has been suggested that impact basins play a role in the development of both Elysium and Tharsis (8): we suggest that multiple overlapping impacts may offer the best opportunity for development of a longlived volcanic complex through maximum thinning of the lithosphere and localization of thermal effects.

Given the efficiency of major impacts (especially overlapping impacts) for thinning the lithosphere and localizing volcanism and the expected high rate of such impacts during the final accretionary sweep-up, it seems likely that a crustal dichotomy may will have been primordial, a primary characteristic of the martian crust.

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