NEW PERSPECTIVES ON ANCIENT MARS.

Sean C. Solomon[1], O. Aharonson[2], J.M. Aurnou[3], W.B. Banerdt[4], M.H. Carr[5], A.J. Dombard[6], H.V. Frey[7], M.P. Golombek[4], S.A. Hauck, II[8], J.W. Head, III[9], B.M. Jakosky[10], C.L. Johnson[11], P.J. McGovern[12], G.A. Neumann[13], R.J. Phillips[6], D.E. Smith[7], and M.T. Zuber[13], [1]Dept. of Terrestrial Magnetism, Carnegie Inst. of Washington, Washington, DC 20015, [2]Div. of Geological and Planetary Sciences, Caltech, Pasadena, CA 91125, [3]Dept. of Earth and Space Sciences, U.C.L.A., Los Angeles, CA 90095, [4]Jet Propulsion Laboratory, Pasadena, CA 91109, [5]U. S. Geological Survey, Menlo Park, CA 94025, [6]Dept. of Earth and Planetary Sciences, Washington Univ., St. Louis, MO 63130, [7]Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, [8]Dept. of Geological Sciences, Case Western Reserve University, Cleveland, OH 44106, [9]Dept. of Geological Sciences, Brown Univ., Providence, RI 02912, [10]Lab. for Atmospheric and Space Physics, Univ. of Colorado, Boulder, CO 80309 [11]Scripps Inst. of Oceanography, University of California at San Diego, La Jolla, CA 92093, [12]Lunar and Planetary Institute, Houston, TX 77058, [13]Dept. of Earth, Atmospheric, and Planetary Sciences, M.I.T., Cambridge, MA 02139.

Introduction: Global data sets returned by the Mars Global Surveyor (MGS), Mars Odyssey, and Mars Express spacecraft and recent analyses of Martian meteorites suggest that most of the major geological events of Martian history occurred within the first billion years of solar system formation. This period was a time of heavy impact bombardment of the inner solar system, a process that strongly overprinted much of the Martian geological record from that time. Geophysical signatures nonetheless remain from that period in the Martian crust, and several geochemical tracers of early events are found in Martian meteorites. Collectively, these observations provide insight into the earliest era in Martian history when the conditions favoring life were best satisfied.

Planetary formation and differentiation. The presence of ^{182}W in Martian meteorites indicates that the Martian core formed within the first 10-15 My of the formation time of the oldest solar system objects [1]. Core-mantle differentiation would have warmed the average interior temperature by up to 300°C [2], with superheating of the core and widespread melt production in the mantle as possible outcomes. The correlation of excess ^{142}Nd [3] with excess ^{182}W [1] and the combined ^{142}Nd-^{92}Zr [4] systematics support the formation of distinct crust and mantle reservoirs within 50-100 My of solar system condensation and little or no remixing subsequently. This earliest crustal material remains part of the present crust in the absence of significant subsequent crustal recycling [e.g., 5].

The Early Crust. The topographic identification of numerous partially buried impact basins suggests that much of the present Martian crust had formed by the early Noachian [6]. In particular, there cannot have been subsequent large-scale crustal recycling [5], and thermal history models [e.g., 7] are strongly constrained by limits to additions to at least the upper crust after the early Noachian. Large impacts were important during the Noachian in redistributing crustal material [8]. Gravity/topography admittance values for the southern highlands indicate that the elastic lithosphere of the early to middle Noachian included at most only the upper crust [9]. There is a crustal thickness dichotomy on Mars [10]. In the southern crustal province, crustal thickness tends to thin progressively northward, a consequence of a south-to-north topographic slope. In the northern crustal province, crustal thickness is approximately uniform. The boundary between provinces can be smoothly varying to step-like in character. Generally thicker crust in the southern province may have arisen from heterogeneous magma ocean evolution [11], early mantle dynamics and melt generation [12], or impact excavation and transport [13]. Distinguishing among these ideas is possible, if challenging, in that some mechanisms predict north-south differences in crustal chemistry or early heat flux. On the basis of gravity/topography admittances, the lower crust in the early to middle Noachian was likely ductile [9]. The earliest crustal thickness heterogeneities would therefore drive channel flow of the lower crust, a process that would favor retention of longest-wavelength crustal thickness variations [14]. In particular, such flow, if arrested by subsequent crustal cooling, could leave the pronounced pole-to-pole variations in crustal thickness and topography presently observed [10].

Magnetic field. Two scenarios have been put forward for the timing of the core dynamo implied by magnetization of the Martian crust [15]. In the first, the dynamo was active in the early to middle Noachian and ceased prior to or near the end of heavy bombardment [15]. In the second, dynamo onset postdated the youngest impact basins [16]. Arguments favoring an early Noachian dynamo include the pronounced concentration of regions of high magnetization in the ancient southern uplands [15], a lack of correlation of magnetic anomalies with late Noachian or younger volcanic units or impact structures, and the observed magnetization of carbonates at least 3.9 Gy old in Martian meteorite ALH84001 [17]. A postulated link between the end of crustal recycling [5] and the cessation of the dynamo [18] is tenable only if both events occurred in the early Noachian. While neither the strength nor spatial scale of magnetic anomalies correlate strongly with other geophysical observations, the maximum anomaly magnitude increases with crustal thickness. One interpretation is that magnetization was acquired very early, during cooling of an early crust, and subsequently was heterogeneously removed by thermal or chemical processes. Alternatively, if the dynamo postdated the formation of large-scale crustal structure, regions of thicker crust may have been cooler than regions of thinner crust, contributing to their preservation and permitting a greater vertical extent of later magnetization of intrusive bodies or chemical remanence. The sparse magnetic anomalies of modest amplitude in the northern plains might be the result of the northern crustal province postdating the dynamo, a predominance of anomalies having wavelengths < 200 km, reheating by volcanism and intrusion, burial by sediments and postdynamo lavas, or hydrothermal alteration. The fourth explanation is only a partial contributor, the third can be discounted if volcanism occurred primarily in thin flows, and the second is testable with future lowaltitude or surface magnetic observations.

Tharsis. The Tharsis province was the site of voluminous magmatism and concentrated deformation by the middle Noachian [19, 20]. It is likely that Tharsis originated after the establishment of the crustal thickness dichotomy and S-to-N slope, on the basis of observed patterns of crustal thickness and magnetization and the location of the center of Tharsis near the dichotomy boundary. Geological observations at Syria Planum and Thaumasia [e.g., 21] and evidence from admittances for widespread crustal underplating [9] are consistent with the interaction of an early Noachian plume with the Martian lithosphere. Stress modeling supports the inference that the lithospheric load of Noachian Tharsis was of a size and scale similar to those at present [22]. Late Noachian valley networks formed after the S-to-N slope was established and after much of Tharsis magmatism had occurred [20].

Water. Abundant evidence for pervasive water-surface interactions on Mars during the Noachian includes large areas displaying extensive erosion [e.g., 23] and widespread Noachian resurfacing of the northern hemisphere inferred from the superposition of younger impact basins on Utopia basin fill [6]. The atmospheric D/H ratio indicates that Mars has lost perhaps two thirds of its water inventory over solar system history [24]. Early climate was strongly influenced by early atmospheric loss via impact ejection, solar wind sputtering, and formation of carbonates, but the relative importance and timing of these mechanisms and even the differences in climate between the Noachian and later periods are not known [25]. Recent upward revisions in the probable water content of Martian magmas [26] suggest that early to middle Noachian construction of Tharsis released substantial quantities of magmatic volatiles to the atmosphere, with possible influences on climate [20]. Deep hydrothermal circulation of water in the Martian crust likely accelerated crustal cooling and the preservation of crustal thickness variations. Such circulation would also have chemically altered the carriers of crustal magnetization, likely rendering any residual crustal magnetization beneath the lowest areas of major drainage basins undetectable from orbit, which if this occurred, could be consistent with the persistence of a dynamo for as long as one billion years. [27].

References. [1] T. Kleine et al*.,* Nature, 418, 952, 2002; [2] S. C. Solomon, *PEPI, 19,* 168, 1979; [3] C. L. Harper et al. *Science, 267,* 213, 1995; [4] C. Münker et al., *MAPS, 36*, A143, 2001; [5] N. H. Sleep, *JGR, 99,* 5639,1994; [6] H. V. Frey et al., *GRL, 29,* doi: 10.1029/2001GL013832, 2002; [7] S. A. Hauck, II, & R. J. Phillips, *JGR, 107,* doi: 10.1029/2001JE001801 2002; [8] D. E. Smith et al., *Science, 284,* 1421, 1999; [9] P. J. McGovern et al., *JGR, 107,* doi: 10.1029/2002JE001854, 2002; [10] M. T. Zuber et al., *Science, 287,* 1788, 2000; [11] P. C. Hess & E. M. Parmentier, *LPSC, 32,* 1319, 2001; [12] S. Zhong & M. T. Zuber, *EPSL, 189,* 75, 2001; [13] H. V. Frey & R. A. Schultz, *GRL, 15,* 229, 1988; [14] F. Nimmo & D. J. Stevenson, *JGR, 106,* 5085, 2001; [15] M. H. Acuña et al., *Science, 284,* 790, 1999; [16] G. Schubert et al., *Nature, 408,* 666, 2000; [17] B. P. Weiss et al., *LPSC, 32,* 1244, 2001; [18] F. Nimmo & D. J. Stevenson, *JGR, 105,* 11969, 2000; [19] R. C. Anderson et al., *JGR, 106,* 20563, 2001; [20] R. J. Phillips et al., *Science, 291,* 2587, 2001; [21] B. M. Webb & J. W. Head, *GSA Abstracts, 33,* A309, 2001; [22] W. B. Banerdt & M. P. Golombek, *LPSC, 31,* 2038, 2000; [23] B. M. Hynek & R. J. Phillips, *Geology, 29,* 407, 2001; [24] B. M. Jakosky & L. Leshin, *Eos Trans. AGU, 82,* S246, 2001; [25] B. M. Jakosky & R. J. Phillips, *Nature, 412,* 237, 2001; [26] H. Y. McSween, Jr., et al., *Nature, 409,* 487, 2001; [27] S.C. Solomon et al., *Science,* submitted, 2004.