

tions during the Amazonian. Even when Mars has primarily been an icy world rather than a wet one, localized flow of water has occurred at its surface.

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References

- Arfstrom, J., Hartmann, W.K., 2005. Martian flow features, moraine-like ridges, and gullies: Terrestrial analogs and interrelationships. *Icarus* 174, 321–335.
- Atkins, C., Dickinson, W.W., 2007. Landscape modification by meltwater channels at the margins of cold-based glaciers, Dry Valleys, Antarctica. *Boreas* 36, 47–55.
- Banks, M.E., Lang, N.P., Kargel, J.S., McEwen, A.S., Baker, V.R., Grant, J.A., Pelletier, J.D., Strom, R.G., 2009. An analysis of sinuous ridges in the southern Argyre Planitia, Mars using HiRISE and CTX images and MOLA data. *J. Geophys. Res.*, in press.
- Bao, H., Campbell, D.A., Bockheim, J.G., Theimans, M.H., 2000. Origins of sulphate in Antarctic dry-valley soils as deduced from anomalous ^{17}O compositions. *Nature* 407, 499–502.
- Berman, D.C., Crown, D.A., Bleamaster, L.F., 2009. Degradation of mid-latitude craters on Mars. *Icarus* 200, 77–95.
- Brackenridge, G.R., 1993. Ancient martian valley genesis and paleoclimatic inference: The present as a key to the past. Workshop on Early Mars: How warm and how wet? LPI Technical Report, 93-03, pt. 1, pp. 2–3.
- Burr, D.M., Enga, M.-T., Williams, R.M.E., Zimbleman, J.R., Howard, A.D., Brennard, T.A., 2009. Pervasive aqueous paleoflow features in the Aeolis/Zephyria Plana region, Mars. *Icarus*, 200.
- Carr, M.H., 1996. *Water on Mars*. Oxford University Press, New York, 229 pp.
- Carr, M.H., Clow, G.D., 1981. Martian channels and valleys; their characteristics distribution, and age. *Icarus* 48, 91–117.
- Carr, M.H., Head, J.W., 2003. Basal melting of snow on early Mars: A possible origin of some valley networks. *Geophys. Res. Lett.* 30, 2245. doi:10.1029/2003GL018575.
- Carrivick, J.L., Russell, A.J., 2006. Glacial landforms, sediments: Glacifluvial landforms of deposition. In: Elias, S.A. (Ed.), *Encyclopedia of Quaternary Science*, pp. 909–920.
- Chapman, M.G., Tanaka, K.L., 2002. Related magma–ice interactions: Possible origins of chasmata, chaos, and surface materials in Xanthe, Margaritifer, and Meridiani Terrae, Mars. *Icarus* 155, 324–339.
- Christensen, P.R., 2003. Formation of recent martian gullies through melting of extensive water-rich snow deposits. *Nature* 422, 45–48. doi:10.1038/nature01436.
- Christensen, P.R. and 10 colleagues, 2003. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci. Rev.* 110, 85–130.
- Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Sci. Rev.* 19, 1763–1783. doi:10.1016/S0277-3791(00)00090-1.
- Clark, B.C., Van Hart, D.C., 1981. The salts of Mars. *Icarus* 45, 370–378.
- Clark, B.C. and 22 colleagues, 2005. Chemistry and mineralogy of outcrops at Meridiani Planum. *Earth Planet. Sci. Lett.* 240, 73–94.
- Costard, F., Forget, F., Mangold, N., Peulvast, J.P., 2002. Formation of recent martian debris flows by melting of near-surface ground ice at high obliquity. *Science* 295, 110–113. doi:10.1126/science.1066698.
- Craddock, R.A., Howard, A.D., 2002. The case for rainfall on a warm, wet early Mars. *J. Geophys. Res.* 107, 5111. doi:10.1029/2001JE001505.
- Denton, G.H., Sugden, D.E., Marchant, D.R., Hall, B.L., Wilch, T.I., 1993. East Antarctic ice sheet sensitivity to Pliocene climatic change from a Dry Valleys perspective. *Geogr. Ann.* 75, 155–204.
- Dickson, J.L., Head, J.W., Kreslavsky, M.A., Marchant, D.R., 2006a. Linear lobate debris aprons, piedmont-like lobes, and crater fill in the Acheron graben region, Mars: Evidence for debris-covered glacier formation and flow. *Lunar Planet. Sci.* 37, Abstract 1321.
- Dickson, J.L., Head, J.W., Marchant, D.R., 2006b. Modification of graben along the dichotomy boundary in eastern Arabia Terra (Coloe Fossae; 53–59°E, 37–41°N): Nature and evolution of lobate debris aprons and their relationships to lineated valley fill and glacial systems. *Lunar Planet. Sci.* 37, Abstract 1317.
- Dickson, J.L., Head, J.W., Kreslavsky, M.A., 2007. Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography. *Icarus* 188, 315–323.
- Dickson, J.L., Head, J.W., Marchant, D.R., 2008. Late Amazonian glaciation at the dichotomy boundary on Mars: Evidence for glacial thickness maxima and multiple glacial phases. *Geology* 36, 411–414.
- Dickson, J.L., Fassett, C.I., Head, J.W., 2009. Amazonian-aged fluvial valley systems in a climatic microenvironment on Mars: Melting of ice deposits on the interior of Lyot Crater. *Geophys. Res. Lett.* 36, L08021. doi:10.1029/2009GL037472.
- Dyke, A.S., 1993. Landscapes of cold-centred Late Wisconsinan ice caps, Arctic Canada. *Prog. Phys. Geogr.* 17, 223–247.
- Fassett, C.I., Head, J.W., 2006. Valleys on Hecates Tholus, Mars: Origin by basal melting of summit snowpack. *Planet. Space Sci.* 54, 370–378.
- Fassett, C.I., Head, J.W., 2007a. Layered mantling deposits in northeast Arabia Terra, Mars: Noachian–Hesperian sedimentation, erosion, and terrain inversion. *J. Geophys. Res.* 112, E08002. doi:10.1029/2006JE002875.
- Fassett, C.I., Head, J.W., 2007b. Valley formation on martian volcanoes in the Hesperian: Evidence for melting of summit snowpack, caldera lake formation, drainage and erosion on Ceramius Tholus. *Icarus* 189, 118–135.
- Fassett, C.I., Head, J.W., 2008a. The timing of martian valley network activity: Constraints from buffered crater counting. *Icarus* 195, 61–89.
- Fassett, C.I., Head, J.W., 2008b. Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrology. *Icarus* 198, 37–56.
- Fastook, J.L., Head, J.W., Madeline, J.-B., Forget, F., Marchant, D.R., 2009. Modeling northern mid-latitude glaciation with GCM-driven climate: Focus on Deuteronilus–Protonilus Mensae valleys. *Lunar Planet. Sci.* 40, Abstract 1144.
- Forget, F., Haberle, R.M., Montmessin, F., Levrard, B., Head, J.W., 2006. Formation of glaciers on Mars by atmospheric precipitation at high obliquity. *Science* 311, 368–371.
- Fountain, A.G., Dana, G.L., Lewis, K.J., Vaughn, B.H., McKnight, D., 1998. Glaciers of the McMurdo Dry Valleys, Southern Victoria Land, Antarctica. In: Priscu, J.C. (Ed.), *Ecosystem Dynamics in a Polar Desert: The McMurdo Dry Valleys, Antarctica*, pp. 65–76. In: *American Geophysical Union Antarctic Research Series*, vol. 72. Washington, DC, 369 pp.
- Fountain, A.G., Nysten, T.H., MacClune, K.L., Dana, G.L., 2006. Glacier mass balances (1993–2001), Taylor Valley, McMurdo Dry Valleys, Antarctica. *J. Glaciology* 52, 451–462.
- Ghatan, G.J., Head, J.W., 2004. Regional drainage of meltwater beneath a Hesperian-aged south circumpolar ice sheet on Mars. *J. Geophys. Res.* 109, E07006. doi:10.1029/2003JE002196.
- Gulick, V.C., Baker, V.R., 1990. Origin and evolution of valleys on martian volcanoes. *J. Geophys. Res.* 95, 14325–14344.
- Haberle, R.M., McKay, C.P., Cabrol, N.A., Grin, E.A., Schaeffer, J., Zent, A.P., Quinn, R., 2001. On the possibility of liquid water on present day Mars. *J. Geophys. Res.* 106, 23317–23326.
- Hartmann, W.K., 2005. Martian cratering 8: Isochron refinement and the chronology of Mars. *Icarus* 174, 294–320.
- Hauber, E., van Gasselt, S., Ivanov, B., Werner, S., Head, J.W., Neukum, G., Jaumann, R., Greeley, R., Mitchell, K.L., Muller, P., the HRSC Co-Investigator Team, 2005. Discovery of a flank caldera and very young glacial activity at Hecates Tholus, Mars. *Nature* 434, 356–361. doi:10.1038/nature03423.
- Hauber, E., van Gasselt, S., Chapman, M.G., Neukum, G., 2008. Geomorphic evidence for former lobate debris aprons at low latitudes on Mars: Indicators of the martian paleoclimate. *J. Geophys. Res.* 113, E02007. doi:10.1029/2007JE002897.
- Head, J.W., Marchant, D.R., 2003. Cold-based mountain glaciers on Mars: Western Arsia Mons. *Geology* 31, 641–644.
- Head, J.W., Marchant, D.R., 2006. Evidence for global-scale northern mid-latitude glaciation in the Amazonian period of Mars: Debris-covered glacier and valley glacier deposits in the 30°–50°N latitude band. *Lunar Planet. Sci.* 37, Abstract 1127.
- Head, J.W., Marchant, D.R., 2009. Inventory of ice-related deposits on Mars: Evidence for burial and long-term sequestration of ice in non-polar regions and implications for the water budget and climate evolution. *Lunar Planet. Sci.* 40, Abstract 1356.
- Head, J.W., Pratt, S., 2001. Extensive Hesperian-aged south polar ice sheet on Mars: Evidence for massive melting and retreat, and lateral flow and ponding of meltwater. *J. Geophys. Res.* 106, 12275–12299. doi:10.1029/2000JE001359.
- Head, J.W., Wilson, L., 2007. Heat transfer in volcano–ice interactions on Mars: Synthesis of environments and implications for processes and landforms. *Ann. Glaciol.* 45, 1–13.
- Head, J.W. and 13 colleagues, 2005. Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars. *Nature* 434, 346–351.
- Head, J.W., Marchant, D.R., Agnew, M.C., Fassett, C.I., Kreslavsky, M.A., 2006. Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change. *Earth Planet. Sci. Lett.* 241, 663–671.
- Head, J.W., Marchant, D.R., Kreslavsky, M.A., 2008. Formation of gullies on Mars: Link to recent climate history and insolation microenvironments implicate surface water flow origin. *Proc. Natl. Acad. Sci.* 105, 13258–13263. doi:10.1073/pnas.0803760105.
- Head, J.W., Marchant, D.R., Dickson, J.L., Kress, A.M., Baker, D.M., 2009. Northern mid-latitude glaciation in the Late Amazonian period of Mars: Criteria for the