Marine and Petroleum Geology 26 (2009) 1866–1878

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Martian mud volcanism: Terrestrial analogs and implications for formational scenarios

James A. Skinner, Jr.[a]*, Adriano Mazzini[b]

[a] U.S. Geological Survey, Astrogeology Team, 2255 North Gemini Drive, Flagstaff, AZ 86001, USA
[b] Physics of Geological Processes, University of Oslo, Box 1048, 0316 Oslo, Norway

A R T I C L E I N F O

Article history:
Received 26 June 2008
Received in revised form
23 January 2009
Accepted 14 February 2009
Available online 28 February 2009

Keywords:
Mars
Mud volcano
Analogs
Surface processes
Astrobiology

A B S T R A C T

The geology of Mars and the stratigraphic characteristics of its uppermost crust (mega-regolith) suggest that some of the pervasively-occurring pitted cones, mounds, and flows may have formed through processes akin to terrestrial mud volcanism. A comparison of terrestrial mud volcanism suggests that equivalent Martian processes likely required discrete sedimentary depocenters, volatile-enriched strata, buried rheological instabilities, and a mechanism of destabilization to initiate subsurface flow. We outline five formational scenarios whereby Martian mud volcanism might have occurred: (A) rapid deposition of sediments, (B) volcano-induced destabilization, (C) tectonic shortening, (D) long-term, load-induced subsidence, and (E) seismic shaking. We describe locations within and around the Martian northern plains that broadly fit the geological context of these scenarios and which contain mud volcano-like landforms. We compare terrestrial and Martian satellite images and examine the geological settings of mud volcano provinces on Earth in order to describe potential target areas for piercement structures on Mars. Our comparisons help to evaluate not only the role of water as a functional component of geological processes on Mars but also how Martian mud volcanoes could provide samples of otherwise inaccessible strata, some of which could contain astrobiological evidence.

Published by Elsevier Ltd.

1. Introduction

Pitted cones, mounds, and lobate flows are common landforms on the Martian surface and are most generally interpreted as having formed through an array of overlapping volcanic, glacial, periglacial, and/or impact processes (e.g., Frey et al., 1979; Lucchitta, 1981; Garvin et al., 2000; Dickson et al., 2008; Burr et al., 2008). Other researchers have used terrestrial mud volcanism as an analog for the formation of many of these features, primarily as an alternative to magmatic volcanism (Komar, 1990; Davis and Tanaka, 1995; Tanaka, 1997; Tanaka et al., 2003a,b, 2005; Farrand et al., 2005; Kite et al., 2007; Skinner and Tanaka, 2007; Skinner et al., 2007). However, dissimilar geologic processes commonly result in landforms of broadly-similar shape (the geomorphological concept of "equifinality"). Inferring geologic processes based strictly on geomorphology can implicate, both directly and indirectly, very specific and often unintentional formational characteristics and conditions.

It is unclear whether the current understanding of Mars' geologic evolution reasonably supports the geologic conditions implied by a mud volcano analogy. Terrestrial studies reveal that mud volcanoes are geomorphologically variable and are subtly affected by many overlapping processes and conditions. For extraterrestrial studies, we are forced to rely heavily on remote-based geomorphological observations to interpret geologic processes and history. Though mud volcanism may be a plausible Martian geologic process based on gross morphologic similarities of terrestrial and Martian landforms, the geologic implications of the analogy have not yet been fully assessed.

Herein, we summarize the components of terrestrial mud volcanoes and use these as a framework to examine the physical characteristics whereby mud volcanoes may form on Mars. Because a comprehensive summary of Mars' exploration, datasets, and geologic setting is not tractable in the following text, further information is included as an Appendix.

2. Framework for terrestrial mud volcanism

The terminology that is used to describe the surface and subsurface movements of large masses of sediments and fluids is broad and sometimes misleading. For terrestrial studies, these terms include

---

* Corresponding author. Tel.: +1 928 556 7043; fax: +1 928 556 7019.
E-mail addresses: jskinner@usgs.gov (J.A. Skinner Jr.), adriano.mazzini@fys.uio.no (A. Mazzini).

0264-8172/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.marpetgeo.2009.02.006

diapirs, diatremes, domes, mud intrusions, chimneys, pockmarks, piercement structures, and mud volcanoes. Though such terms are descriptive, they are often confusingly applied, resulting in an unintended divergence of consistent scientific discussion. Herein, we apply a simplified definition of mud volcanoes as “geological phenomena made manifest through the sudden eruption or quiescent extrusion of sediment, rock, and fluid from deeper strata”.

On Earth, the occurrence of a mud volcano implies not only a suite of geologic conditions but also a sequence of events that result from these conditions. Processes and conditions that can lead to the growth of a mud volcano include (1) high rates of basin sedimentation and/or subsidence, (2) illitization of clay minerals, (3) expansion of pore fluids, (4) generation of hydrocarbon-rich fluids at depth, (5) presence of impermeable (or low permeability) strata as capping rock for pressurized units, (6) vertical or lateral compression of basin sediments, and (7) seismicity. When these conditions are achieved, mud volcanism may occur through a sequence of events that includes the build-up of pressure at depth (generally driven by gas (methane) production), the brecciation of sedimentary strata along a vertical conduit, and the eruption or extrusion of mud (mud breccia) with water, oil, and/or gas. The geomorphic result is generally a crater-shaped vent, perhaps located on a topographic cone, mound, or ridge of various size and shape, that is composed and surrounded by mud (mud breccia) flows (e.g., Khalilov and Kerimov, 1981; Kholodov, 2002; Kopf, 2002).

Most terrestrial mud volcanoes form proximal to paleo-depocenters within structurally-controlled sedimentary basins that are experiencing active tectonic deformation. As a result, mud volcanoes are frequently located along major geologic structures such as faults and fold axes related to deformation of the sedimentary sequence. Terrestrial mud volcanoes can occur both offshore (e.g., Black Sea, Gulf of Cadiz, Caspian Sea, and Mediterranean Sea) and onshore (e.g., Azerbaijan, Indonesia, Trinidad), just to name the best known and characterized fields (e.g., Jakubov et al., 1971; Barber et al., 1986; Cita et al., 1996; Ivanov et al., 1996; Dia et al., 1999; Pinheiro et al., 2003; Isaksen et al., 2007).

The most spectacular terrestrial mud volcanoes have a conical shape with a summit crater, similar to magmatic equivalents. Some mud volcanoes reach up to 5 km in diameter and 500 m in height. The total volume of erupted mud breccia can be $>12\ \text{km}^3$ for single volcanoes and up to $250\ \text{km}^3$ for mud volcano complexes. Mud volcano flows can cover areas as large as $100\ \text{km}^2$ (e.g., Dimitrov, 2002). One of the most spectacular terrestrial eruptions occurs on the Java Island at the Lusi mud volcano, which has erupted continuously for more than two years (at the time of this writing) covering $>7\ \text{km}^2$ (Mazzini et al., 2007).

A critical element of the extraterrestrial analogy for mud volcanoes is what the morphology/morphometry of a potential Martian mud volcano indicates about the underlying formational conditions (e.g., Skinner and Tanaka, 2007). Such conditions include tapping depth, fluid content, stratigraphic architecture, and triggering mechanism. Size and morphology of terrestrial mud volcanoes vary widely depending on factors such as eruption frequency and vigor, lithology and water content of the erupted mud breccia, type of meteoric erosion (e.g., wind, rain, bottom currents), rates of basin subsidence, thickness of the affected sequence, and character of the confining strata or structure. The characteristics of these analogies and their known geologic settings provide the framework for describing formational contexts and scenarios of Martian mud volcanism.

3. Framework for Martian mud volcanism

In the absence of field-based data, terrestrial analogs provide the basis for deciphering the geologic history of extraterrestrial surfaces and inferring the conditions through which they form. For Mars, orbiting spacecrafts have historically provided the most fundamental datasets for investigating global and regional geologic characteristics (Appendix A1). Herein, we summarize geomorphological characteristics of Martian features as they appear in selected topographic and image datasets. For our characterizations, we viewed relevant Martian datasets (Appendix A2) as spatially-registered layers in a geographic information system (GIS). For morphological analogy, we note that many of the imaging instruments orbiting Mars were adapted from Earth-orbiting imaging instrument parameters, including spectral range, band-pass, and resolution. As such, we use terrestrial satellite images of Earth (supplemented by field-based images) as comparative examples to Martian mud volcanoes (see Fig. 6 caption for details on comparative images).

3.1. Global physiography

Global physiography provides the most broad and basic framework for understanding a planet’s evolutionary processes. The form and arrangement of large-scale Martian surface features provide a record of the planet’s geologic history. This record includes impact, volcanic, fluvial, periglacial, and eolian resurfacing processes, all of which variously overlap and intercalate with one another through time (Appendix A3). One of the most dominant Martian physiographic features is the highland–lowland boundary (HLB) scarp, a globe-encircling feature that elevates more ancient, higher-standing and densely-cratered terrains by 1–5 km above younger, lower-lying and sparsely-cratered terrains (Fig. 1). The Martian HLB establishes a globally-occurring topographic basin within which geologic processes can be examined and analyzed.

The cratered highlands dominate the southern two-thirds of the Martian surface and are chiefly composed of very ancient (older than 3.5 Gyr; Tanaka, 1986; Hartmann and Neukum, 2001) impact crater and basin lithologies that are intercalated, onlapped, and buried by volcanic and sedimentary deposits (e.g., Scott and Carr, 1978; Scott and Tanaka, 1986; Greeley and Guest, 1987). By contrast, the Martian lowlands dominate the northern one-third of the Martian surface and are chiefly composed of (relatively) younger (younger than 2.5 Gyr) sedimentary and volcanic deposits (e.g., Tanaka et al., 2005). These units fill and bury ancient topographic and structural basins, which likely formed through both endogenic and exogenic processes very early in Mars’ evolution (e.g., Nimmo and Tanaka, 2005). The lowland basins appear to be temporally equivalent to the oldest exposed highlands (Frey, 2006). However, the ancient lowland surfaces are thoroughly buried by thick sequences (Buczkowski, 2007) of impact ejecta, erosional detritus, and volcanic rocks and sediment (Tanaka et al., 2003a, 2005), forming the low-relief topographic undulations that characterize the lowland plains (Fig. 1).

An important step toward evaluating Mars’ geologic history includes framing the lowlands as a global-scale depocenter that consists of multiple overlapping, albeit unique, topographic and stratigraphic basins. This inherently implies that lowland processes were spatially partitioned, an assertion at least partly supported by recent geological maps (Tanaka et al., 2005). We suggest that these physiographic characteristics helped to establish accommodation space for the accumulation of sediments and development of a stratigraphic framework for the potential growth of mud volcanoes.

3.2. Stratigraphy

The lowlands represent Mars’ largest and longest-lived depocenter for the accumulation of sediments eroded from adjacent