Geology of possible Martian methane source regions

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ABSTRACT

Recent observations of methane on Mars suggest that spatially localized source regions are present. Here we discuss the surface morphology and mineralogy of these regions, focusing on features that may provide insights into mechanisms of methane production and/or release. Preliminary trends among methane source regions include old age, deep fractures, past or present subsurface water, and the presence of hydrated minerals, sometimes including serpentine. As the spatial and temporal coverage of Martian methane is expanded, geological observations of proposed source regions will be a powerful tool for understanding the methane cycle on modern Mars.

1. Introduction

One of the most intriguing aspects of recent measurements of methane in the Martian atmosphere is the observed spatial variation in methane concentration, which may indicate localized source regions (Formisano et al., 2004; Geminale et al., 2008; Mumma et al., 2009a). This would imply that the mechanism(s) of production and/or release of methane on Mars are in some way related to the local or regional-scale geology, either at the planet’s surface or in the subsurface. The mode(s) of methane formation and/or release might therefore be constrained by determining what distinguishes the methane source regions geologically, and numerous existing remote sensing datasets can be brought to bear on this question. Information about the subsurface can be inferred from radar, magnetic, and gravitational measurements; here we focus on the surface geology as revealed by orbital imaging and spectroscopy.

The ground-based observations of Mumma et al. (2009a,b) and Villanueva et al. (2009) yield methane distributions simultaneously resolved in latitude, longitude, and season; hence we concentrate on the regions of elevated methane concentration they have reported. Possible source regions identified to date include Nili Fossae, Syrtis Major, and Terra Sabaea during northern summer (Mumma et al., 2009a) and the Terra Sirenum and Thaumasia highlands southwest of Tharsis during southern spring/summer (Villanueva et al., 2009). Mumma et al. (2009a) noted that each of these regions had either morphologic, mineralogic, or chemical data consistent with past or present volatiles. Aside from elevated subsurface hydrogen in Terra Sabaea, none of these regions appears distinctive in its elemental chemistry according to orbital gamma-ray spectroscopy (Karunatillake et al., 2009). We therefore focus instead on insights derived from visible/infrared spectroscopy and high-resolution imaging.

2. Mineralogy and regional stratigraphy

Three of the four regions of elevated methane concentration considered here are in the Noachian highlands (Fig. 1a). Terra Sirenum and the area west of the Isidis basin (including the Nili Fossae) are well-exposed, whereas much of Terra Sabaea is dust-covered (Ruff and Christensen, 2002). The fourth region, Syrtis Major, is a large volcanic complex constructed by lavas emplaced during the Early Hesperian (Hiesinger and Head, 2004). We focus our attention on the stratigraphy and mineralogy at Nili Fossae, which may also be relevant to the shallow subsurface geology of adjacent Terra Sabaea and the shallow crust beneath the Syrtis Major lavas. We also briefly discuss new mineralogic data from the Syrtis Major lavas and volcanic caldera that suggest evidence for post-Noachian aqueous alteration.

2.1. West of Isidis, the Nili Fossae

The Nili Fossae region exhibits the largest exposure of olivine on the Martian surface (e.g., Hamilton and Christensen, 2005) and a stunning diversity of hydrated silicates and other secondary minerals (Ehlmann et al., 2009). There is a distinct three-unit regional stratigraphy west and south of the Isidis basin with, from bottom to top, (1) a brecciated, Fe/Mg-smectite-bearing unit, (2) a regional olivine-rich unit exhibiting evidence for partial aqueous alteration, and (3) unaltered mafic capping materials (Fig. 2; Mustard et al., 2009a). The brecciated unit contains both altered...
and unaltered meter- to kilometer-scale blocks in a smectite-bearing matrix. It is inferred to represent the ancient crust of Mars, churned in repeated basin-forming impacts—most recently the Isidis impact (Mustard et al., 2009a; Ehlmann et al., 2009). The overlying olivine-rich unit has been variably interpreted as Isidis impact melt (Mustard et al., 2007) or early stage lava erupted from Syrtis Major (Tornabene et al., 2008). In some locations, olivine has been altered to form Mg-carbonate and Mg-rich serpentine (Ehlmann et al., 2008b, 2009, 2010). The date of alteration is unknown, but stratigraphic relations constrain the ages of the rocks containing carbonate and serpentine to ~3.9 Ga (Mustard et al., 2009a).

Diverse alteration conditions, varying in space and time, were present in this region during the Noachian and perhaps into the early Hesperian. Both near-surface weathering and hydrothermal activity are indicated by observations of kaolinite, chlorite, prehnite, mica, opal, zeolites, and sulfates in addition to serpentine, carbonate and widespread Fe/Mg smectite clays (Ehlmann et al., 2009; Mustard and Ehlmann, 2010). Prehnite in particular indicates low temperature (200–350°C) hydrothermal conditions and is found in craters near the border of the Noachian terrains with overlying Syrtis Major lavas. Several different hypotheses have been proposed to account for the hydrothermal assemblages including impact-induced hydrothermalism (Marzo et al., in press), low-grade metamorphism resulting from burial (Ehlmann et al., 2009), or contact metamorphism resulting from emplacement of Syrtis lavas on the volatile-rich Noachian surfaces (Harvey and Griswold, 2010). Future work to distinguish between these hypotheses would provide a clearer picture of when and where conditions needed for hydrothermal alteration and/or serpentinization may have been present in this region.

2.2. Terra Sabaea

Terra Sabaea is dust-covered and lacks distinctive mineralogic signatures, except as exposed in and around impact craters. However, Mustard et al. (2009a) have argued that the minerals exposed near the Nili Fossae and southeast of Syrtis may be representative of the Noachian crust on a broader scale. In eastern Terra Sabaea, for example, Leighton crater (3° N, 58° E) near Schroeter crater excavates through Syrtis lavas and exposes hydrated minerals similar to those found in craters near the Nili Fossae, including Fe/Mg-smectite, chlorite/prehnite, and kaolinite (Mustard et al., 2009b).

2.3. Syrtis Major

Syrtis Major is a classic Martian dark region. The Hesperian lavas are relatively dust-free and their composition has been modeled to include olivine, low- and high-calcium pyroxenes, and plagioclase using both thermal emission and reflectance spectroscopy (e.g., Rogers and Christensen, 2007; Poulet et al., 2009). Based on comparisons of the spectral properties of fresh crater ejecta vs. surrounding bedrock, it has been proposed that the surface of the flows was subtly altered through interaction with volatiles sometime before ~2 Ga (Baratoux et al., 2007; Skok et al., 2010). Recent data indeed indicate aqueous alteration, and potential hydrothermal activity, post-dating emplacement of the Syrtis Major lavas; evidence includes amorphous silica deposits within the Nili Patera caldera (Skok et al., 2009 and manuscript in preparation) and jarosite as well as polyhydrated sulfate associated with flows on the northeast Syrtis flank (Mustard and Ehlmann, 2010).

2.4. Terra Sirenum

Methane source regions identified in the southern hemisphere (Villanueva et al., 2009) span much of Terra Sirenum and eastward...
into the Claritas Fossae/Thaumasia highlands region discussed by Anderson et al. (2001). These terrains are largely Noachian in age (Scott and Tanaka, 1986). The Claritas Fossae are one of the few locations other than Nili Fossae where serpentinite has been identified to date, accompanied by other alteration minerals including kaolinite and chlorite (Ehlmann et al., 2010). Farther west, Terra Sirenum hosts widespread deposits of Fe/Mg-phyllosilicates and chlorides on the intercrater plains (Osterloo et al., 2008; Murchie et al., 2009; Wray et al., 2009b). In addition, a group of large craters in northwest Sirenum contains diverse sulfates and Al-phyllosilicates in finely bedded deposits; these minerals may have precipitated from Late Noachian crater lakes fed by upwelling groundwater (Swayze et al., 2008; Wray et al., 2009a).

3. Morphology

3.1. Nili Fossae

The deepest bedrock exposures around the Nili Fossae exhibit megabreccia (Fig. 3), i.e. diverse, randomly oriented blocks up to 100 s of meters wide cemented in a finer-grained matrix (McEwen et al., 2008). Some breccia blocks contain unaltered mafic minerals whereas others are phyllosilicate-bearing, and some blocks are internally layered (Mustard et al., 2009a). The diverse colors of these blocks (Fig. 3a and b) likely reflect diverse compositions, and possible non-conformable layers (Fig. 3b and c) and faults (Fig. 3d) within blocks attest to a complex history of sedimentation, erosion, and tectonics predating the disruptive event(s) – probably impact – that formed the megabreccia. Global cataloguing of megabreccia exposures is still in progress (Tornabene et al., 2010), and it is not yet clear whether these ancient materials exist at depth everywhere on Mars or are only regional in extent. Regardless, regional-scale exposures such as that found around the Nili Fossae are uncommon, and it is possible that some component of the megabreccia in this region formed during the Isidis impact (Mustard et al., 2009a).

Fractures at a range of scales are common throughout the Nili Fossae region and may facilitate the release of gases from the subsurface. The fossae themselves are graben up to 10 s of km wide and 100 s of km long oriented concentrically to the Isidis basin, and likely formed in response to basin loading during the Late Noachian (Wichman and Schultz, 1989). Smaller-scale fractures are also widespread here, and in some cases these smaller fractures appear modified by unknown processes. For example, a crater west of the Nili Fossae (Fig. 4) shows fractures that are variably bounded by broader troughs and transition into chains of pits or even isolated depressions. These features are enigmatic despite the fact that morphologically similar troughs have been visited by the Mars Exploration Rover Opportunity in Meridiani Planum (Fig. 4e), where they were interpreted as impact-related fractures possibly modified by incipient sulfate karst processes (McLennan et al., 2005). The fractures shown in Fig. 4b and d may also be impact-related given their geographic setting (Fig. 4a). Polygonal fracture patterns are also observed on some outcrops in the region (Ehlmann et al., 2008a, 2009; Mustard et al., 2009a).

Linear ridges are another type of modified fracture found near Nili Fossae. These ridges have been identified in the region's clay-bearing basement rocks (Mangold et al., 2007), where they may be magmatic or clastic dikes but could alternatively be former fractures that were cemented via mineralization from Fig. 3. Megabreccia near Nili Fossae. (a, d) are from PSP_006923_1995 (19.38° N, 76.42° E); (b, c) from PSP_007464_1985 (18.51° N, 65.11° E; context shown in Fig. 4a). Arrows in (b, c) indicate possible unconformities or cross-bedding within layered blocks.

Fig. 4. (a) Impact crater (~30 km diameter) west of Nili Fossae at 18.5° N, 65.1° E (Viking MDIM), with approximate locations of other images labeled; (b–d) fractures and pit chains on crater ejecta (b, c; HiRISE PSP_008110_1990) and floor (d; PSP_007108_1985); (e) similar fractures (including the Anatolia depression) and pit chains near the Mars Exploration Rover Opportunity landing site in Meridiani Planum (1.94° S, 354.48° E; PSP_001414_1780).
fluids circulating in the subsurface (Fig. 2; Mustard et al., 2009a). On the floor of Jezero crater in eastern Nili Fossae, we identify paired ridges that transition into linear fractures (Fig. 5). These features are reminiscent of the double-ridged structures observed in the Arabia Terra region by Okubo et al. (2009), who attributed them to induration of fracture walls by cements precipitated from circulating fluids. In Jezero crater, these occur in the “coherent capping unit iv” that overlies smectite-bearing deposits on the crater floor (Ehlmann et al., 2008a), suggesting that subsurface fluid circulation may have occurred here after the period of fluvial activity that transported smectites into Jezero. This fluvial period itself dates to the Late Noachian or Early Hesperian (Fassett and Head, 2005; Mangold et al., 2007; Ehlmann et al., 2008a), later than much of the mineralogic alteration that formed Fe/Mg-smectites throughout the region (Mustard et al., 2009a).

Constraining the timing of the most recent fracture activity in Nili Fossae is difficult, but it is noteworthy that at least some fractures appear to cut (i.e., postdate) eolian bedform migration in the region (Fig. 6). The age of bedform migration in Nili Fossae is unknown, but for comparison, the most recent ripple migration in Meridiani Planum probably occurred ~100–300 ka (Golombek et al., 2010). If the bedforms in Nili Fossae have a comparable age, then the fractures in Fig. 6 must have formed or expanded relatively recently.

3.2. Syrtis Major

The cratered Syrtis lava flows exhibit typical lava morphologies, including wrinkle ridges (Mueller and Golombek, 2004), and are heavily fractured. However, morphologies indicative of water-related activity are also observed. To the north, near the boundary with the Noachian units around the Nili Fossae, fluvial channels incise the lavas and have been interpreted as evidence for subsurface water mobilization related to Hesperian volcanism (Mangold et al., 2008). The irregular border of the lava flows entering the Isidis basin has been interpreted to indicate interaction of lavas with underlying volatile-bearing sediments (Ivanov and Head, 2003). Finally, in the Nili Patera caldera, the newly discovered silica-bearing deposits are superposed on a cone within the caldera, and are hypothesized to have formed from fumaroles or springs driven by hydrothermal circulation of fluids (Skok et al., 2009 and in preparation).

3.3. Terra Sirenum

The origin of the Thaumasia highlands east of Terra Sirenum is enigmatic, but Montgomery et al. (2009) interpreted their broad-scale structure as the result of a gravity-driven “mega-slide” facilitated by abundant hydrated salts and/or ice in the subsurface. This interpretation is not unique (e.g., Nahm and Schultz, 2010), but would be consistent with a high content of subsurface volatiles in the Thaumasia highlands, similar to the northern hemisphere regions of elevated methane concentration (Mumma et al., 2009a). Also similar to the Nili Fossae region, Terra Sirenum and Thaumasia are highly fractured. Specifically, these regions are cut by vast graben systems (e.g., Fig. 1b) radial to Tharsis (Mennnonia, Sirenum, Icaria, and Claritas Fossae), which are unique to this part of the southern highlands (Anderson et al., 2001). The faults underlying these graben may have channeled subsurface fluids down the slope of the Tharsis rise.

Adjacent to the Sirenum Fossae at 33°S, 206°E is one of the largest exposures of chloride-bearing plains and associated phyllosilicates in the southern highlands (Fig. 7a; Osterloo et al., 2008; Murchie et al., 2009). The chlorides occur in light-toned materials occupying broad topographic depressions fed by valley networks and in inverted channel deposits within the valleys (Fig. 7b). Fan-shaped landforms containing chlorides are found at the mouths of some channels (Fig. 7c). As elsewhere on Mars (Osterloo et al., 2008), the chloride-bearing deposits here are polygonally fractured (Fig. 7d), consistent with desiccation or dehydration of constituent minerals. The age of these chlorides is unknown, though globally they are found in Noachian to Early Hesperian terrains (Osterloo et al., 2008). This age corresponds to that of the highland valley networks (e.g., Fassett and Head, 2008; Hoke and Hynek, 2009), but Terra Sirenum has relatively few such valleys (Carr, 1995). By contrast, global hydrologic models predict enhanced groundwater upwelling in Terra Sirenum relative to the

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Fig. 5. Double-ridge landforms on the floor of Jezero crater (18.5°N, 77.5°E) interpreted as fractures whose walls now stand in positive relief due to mineralization by subsurface fluids (PSP_002743_1985).

Fig. 6. Bedforms cut by fractures (e.g., arrows) near the Nili Fossae (21.27°N, 74.26°E; PSP_003086_2015), after Sullivan et al. (2008).
rest of the southern highlands during the Late Noachian/Early Hesperian (Andrews-Hanna et al., 2007).

Terra Sirenum also hosts a dense concentration of geologically recent gullies, which has been interpreted as evidence for a regional aquifer (Malin and Edgett, 2001). Several of these gully systems have been active within the past ten years (Malin et al., 2006; Dundas et al., 2010). The formation mechanism(s) of gullies remain debatable; recent studies have argued that most gullies form from snowmelt (e.g., Dickson and Head, 2009) or possibly even dry CO2 frost-related activity (Dundas et al., 2010) rather than emerging groundwater. Nevertheless, there is morphologic evidence that at least some gullies in Terra Sirenum may have a groundwater source (Kolb et al., 2007). Combined with the arguments for Noachian/Hesperian groundwater, these youthful gullies are consistent with a long history of subsurface water in this region.

4. Discussion and conclusions

As was also recently noted by Villanueva et al. (2009) and Mumma et al. (2009b), the above observations hint at potential correlations between methane and surface age, deep fissures, past or present subsurface water, and hydrated minerals including serpentine. Of course, it will be more difficult to determine which – if any – of these correlated features is causally related to methane production.

Serpentine has been found in two of the four terrains over which methane concentrations are elevated: Nili Fossae and the Claritas Rise in Terra Sirenum (Ehlmann et al., 2010). Serpentinization of olivine-rich rocks produces H2, which can lead to abiotic methane production (Oze and Sharma, 2005) and/or become an energy source for methanogenic organisms (Schulte et al., 2006). In either case a source of inorganic carbon is needed. This could be supplied by preexisting carbonate in rocks or by groundwater in contact with atmospheric CO2. In the case of Nili Fossae, the spatial association of carbonate with serpentine-bearing rocks indicates that carbon was present in that aqueous alteration system. The olivine in the Nili Fossae/Syrtis Major region has a ~ Fo80 composition (Koeppen and Hamilton, 2008), which is within the compositional range for which significant H2 production is thermodynamically favored (Oze and Sharma, 2007). However, as Ehlmann et al. (2010) have noted, if ongoing serpentinization is responsible for the observed methane plumes, then this process – and its mineral products, including serpentine – would be confined to the subsurface and not directly related to the serpentine detected at the surface. Nevertheless, missions to the Martian surface planned for the next decade do not include a deep drilling capability, so in situ study of ancient serpentine at a landing site such as that proposed by Mustard and Ehlmann (2010) may be the best near-term path to improving our understanding of serpentinization processes on Mars.

On Earth, production of H2 via oxidation of ferrous materials generally occurs under hydrothermal conditions (e.g., Sleep et al., 2004). The mineralogy and morphology of the Nili Patera silica deposits and the mineralogy of impact craters surrounding the Syrtis region (including zeolites, hydrated silica, and especially prehnite) suggest that hydrothermal activity must have occurred in the past, possibly extending to the end of the Hesperian. It is unknown whether such processes continue at depth in the present era. Volcanically driven hydrothermal activity would be expected to produce other trace gases in addition to methane (e.g., sulfur-bearing compounds), with the relative proportions of these gases dependent on chemical conditions in the source region (e.g., Giggenbach, 1987). Therefore, determining which (if any) other trace gases accompany the CH4 released seasonally on Mars should help to constrain the conditions of methane formation.

As discussed above, the ground-based methane observations acquired to date indicate that concentrations are elevated over ancient bedrock in highland terrains. By contrast, the limited spatial coverage presented by Mumma et al. (2009a) suggests that the younger plains of Isidis and Utopia east of Nili Fossae are relatively methane-poor. Intermediate methane concentrations of ~ 20 ppb were found over some parts of Utopia (Mumma et al., 2009a), including the highland-lowland boundary region in which mounds and pitted cones have been identified as evidence for mud volcanism (Skinner and Tanaka, 2007). The distribution of these putative mud volcanoes does not closely match the observed methane distribution, but as noted by Komatsu et al. (in this issue), these morphologic features could be related to past methane emission even if they are not currently active. Release of methane from magmatic volcanoes is also observed on Earth (e.g., Etiope et al., 2007), but no concentration of methane is observed over the Elysium volcanic province on Mars during any season observed to date (Mumma et al., 2009a). The volcanoes of Elysium are among the most recently active on Mars (Hartmann and Berman, 2000; Werner, 2009), so a lack of methane there argues against a modern volcanic origin for Martian methane.

The apparent confinement of modern methane plumes to Noachian and Hesperian terrains is noteworthy. Such an age dependence could indicate that methane formed long ago and is slowly being released from the subsurface via deep fractures (Max...
and Clifford, 2000); mechanisms for trapping methane and its subsequent release are discussed further by Komatsu et al. (in this issue). This could occur preferentially in regions with abundant fractures and/or in which the ancient crust is relatively well exposed. Alternatively – and perhaps more likely given the high methane release rate inferred by Mumma et al. (2009a) – perhaps some property of ancient Martian rocks (e.g., mafic compositions or high permeability due to impact damage) facilitates modern methane formation and/or storage.

Observations of Martian methane and orbital reconnaissance of the surface morphology and mineralogy are both ongoing, and it is possible that any or all of the preliminary geologic trends described above may be disproved once more complete global maps of methane are available. For the purpose of tying these maps to the surface geology, we suggest that global coverage is the most critical objective for methane observations in the near future, followed by improving the spatial resolution of observations during the apparent peak of activity (spring/summer) in each hemisphere. Once these observations are in hand, correlating the surface geology to the inferred methane plumes will be a powerful tool for understanding the origin and fate of methane on Mars today.

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References


