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# Advective Fluxes in the Martian Regolith as a Mechanism Driving Methane and Other Trace Gas Emissions to the Atmosphere

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**Key Points:**

- Wind-induced pressure gradients in regolith, a well-known mechanism that influences soil emission on Earth, may be relevant under Martian conditions and drive the methane abundance detected by Mars Science Laboratory
- Methane and other trace gas species should be emitted or produced between the surface and the first few meters of depth
- Fractured media are the best candidate to emit methane and other trace gases driven by pressure pumping in the Martian regolith

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**Abstract** Advective fluxes influence methane and $CO_2$ soil emissions into the atmosphere on Earth and may drive trace gas emissions in the Mars atmosphere. However, their relevance in the Martian regolith has not been evaluated to date. Our regolith transport simulations show that advective fluxes can be relevant under Martian conditions and may drive the methane abundance detected by Mars Science Laboratory. Trace gas emissions would be highest in regions where winds interact with topography. Emissions in these regions may be further enhanced by time-varying pressure fields produced by diurnal thermal tides and atmospheric turbulence. Trace gases such as methane should be emitted or produced from the first layers of regolith, or quickly transported to this region from a deeper reservoir through fractured media.

**Plain Language Summary** Regolith emissions are driven by diffusion and/or advection, depending on the scenario. Advective fluxes influence methane and $CO_2$ soil emissions into the atmosphere on Earth and may drive trace gas emissions in the Mars atmosphere. However, their relevance in the Martian regolith has not been evaluated to date. Our regolith transport simulations show that advective fluxes produced by winds and atmospheric pressure fluctuations can be relevant under Martian conditions and may drive the methane abundance detected by Mars Science Laboratory. Trace gases such as methane should be emitted or produced from the first layers of regolith, or quickly transported to this region from a deeper reservoir through fractured media.

## 1. Introduction

Numerous mechanisms for Martian methane production and emission have been proposed to date (Hu et al., 2016; Yung et al., 2018, and references therein). Some of them imply methane sources on the surface, such as wind erosion and abrasion of methane inclusions trapped in basalts (McMahon et al., 2013; Safi et al., 2019), or degradation by ultraviolet (UV) radiation of organics brought by meteorites and comets (Fries et al., 2016; Keppler et al., 2012; Schuerger et al., 2012). The weak correlation between the seasonal variations of methane and surface UV observed by Mars Science Laboratory (MSL) (Webster et al., 2018) suggested that, even in the case of UV degradation of organic matter playing a role in methane production, this process is *not the dominant* one in methane emissions. A similar conclusion has been reached in Safi et al. (2019) concerning wind erosion and abrasion of methane inclusions trapped in basalts. Another possibility is that methane is released to the atmosphere from subsurface reservoirs, or subsurface production, through seepage in the regolith. Methane production by methanogenic microorganisms has been proposed (Atreya et al., 2007; Krasnopolsky et al., 2004; Mumma et al., 2009), living in the subsurface where ionizing radiation is less damaging for organic molecules (e.g., Blanco-López et al., 2018; Dartnell et al., 2007). However, other abiotic sources are perhaps considered more plausible (Webster et al., 2015, 2018; Yung et al., 2018). These include serpentinization of olivine and pyroxene in the crust (Oze & Sharma, 2005) (a process that would require liquid water), and the destabilization of clathrates containing trapped abiotic or biogenic methane formed in the past in quite a different climatological environment (Chassefière, 2009; Chastain & Chevrier, 2007; Prieto-Ballesteros et al., 2006). These or other physical processes would be releasing methane to the atmosphere along regolith and/or bedrock faults and fractures and could develop as macroseeps (such

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as gas vents, commonly found on Earth) or microseepage (diffuse emanations lacking surface expression) (Oehler & Etiope, 2017).

However, methane origin by these processes does not explain either the observed seasonal variation of methane or the daytime methane spikes detected by MSL. An additional mechanism that regulates methane emissions must be involved in order to explain the methane abundance variation in Gale crater. The lack of a methane detection by TGO (Korablev et al., 2019) to date suggests that the abundance of this gas detected by MSL could be localized or perhaps regional-scale in origin.

The regolith could also temporarily store methane by means of physical and chemical sequestration (Webster et al., 2018; Yung et al., 2018). Moores et al. (2019) proposed that methane adsorption in the regolith regulates the seasonal variation observed by MSL, considering a deep subsurface reservoir releasing methane at a constant rate. Regardless of whether adsorption/desorption is playing a role in the path between atmosphere and a hypothetical subsurface reservoir of methane, the release of methane to the atmosphere by means of seepage (microseepage or macroseepage) should be strongly affected by winds and pressure fluctuations, a process known as pressure pumping that has been demonstrated for Earth. In particular, near-surface atmospheric pressure fluctuations should increase the emission of gases through the generation of time-varying pressure fields in soil (Bowling & Massman, 2011; Colbeck, 1989; Maier et al., 2012; Massman & Lee, 2002; Scott, 2000; Weeks, 1994), which can strongly increase the release of gases from soil by advective fluxes. Atmospheric turbulence also contributes to time-varying pressure fields in soils (Kimball & Lemon, 1972; Maier et al., 2012). The interaction between winds and topography has been demonstrated to generate pressure gradients at the surface that are propagated within soil and can generate even greater advective fluxes than time-varying pressure fields (e.g., Colbeck, 1989), driving the emission of gases to the atmosphere. Also, winds produce ventilation of fractures (Kimball & Lemon, 1971, 1972; Maier et al., 2012; Nachshon et al., 2012, and references herein), which has the direct consequence of increasing the effective area through which this mechanism occurs (Nachshon et al., 2012). The expected extensively fractured subsurface, for example, in Gale crater and the dichotomy boundary could promote this possibility. Advective fluxes due to pressure pumping (e.g., produced by storms and winds) have also been recently suggested by Etiope and Oehler (2019) as a possible mechanism to provoke methane emissions in Mars.

Therefore, advective fluxes in Martian regolith may drive gas emissions. However, Mars's atmosphere is thinner than Earth's atmosphere and the ability of pressure pumping to enhance diffuse fluxes could be weaker. We have developed a regolith model described in the Methods section in order to test the strength of this family of mechanisms, driven by pressure and/or winds, including its penetration depth in the Martian regolith.

## 2. Methods: Regolith Model and Simulations

The objectives of the regolith model are (i) to test the strength of the pressure pumping mechanisms, driven by pressure and/or winds, and (ii) evaluate their penetration depth in the Martian regolith. Consider a Darcy flow (Whitaker, 1986) through the regolith with seepage flux $\boldsymbol{q}$:

$$\boldsymbol{q} = -\frac{k}{\mu}\nabla P, \tag{1}$$

where $k$ is the effective intrinsic permeability of the medium, $\mu$ is the air viscosity, and $P$ is pressure. The mass conservation is defined by

$$\phi\,\frac{\partial \rho}{\partial t} - \nabla(\rho \boldsymbol{q}) = 0, \tag{2}$$

where $\phi$ is the porosity of the medium, and $\rho$ the air density that can be approximated by the ideal gas law $P = \rho RT$, $R$ is the gas constant of air, and $T$ its temperature. Substituting (1) in (2), a PDE with an analytical solution under certain assumptions can be obtained.

The magnitude of advective fluxes in methane emissions can be estimated by the Péclet number $Pe = \overline{v}\,L/D_{eff}$, where $\overline{v} = \overline{q}/\phi$ and $\overline{q}$ is the mean air flux in the domain, computed by (1); $L$ is the depth of the hypothetical methane reservoir, and $D_{eff}$ is the effective diffusivity coefficient. $D_{eff} = D_{ab}/\tau_d$, where $D_{ab}$ is the molecular diffusion coefficient for methane in air and $\tau_d$ is the tortuosity factor in regolith. $\tau_d$ can be estimated as a function of $\phi$ by means of (Ghanbarian et al., 2013)

$$\tau_d = 1 - \theta \ln(\phi) , \tag{3}$$

where we consider $\theta = 0.5$, which fits well with tortuosity values reported for Martian regolith analogs for $\phi < 0.5$ (Sizemore & Mellon, 2008). Thus, for the previously mentioned Pe numbers, if Pe $\ll 1$ emissions are fully controlled by diffusion (e.g., Costanza-Robinson & Brusseau, 2002; Fityus et al., 1999; Hassanizadeh, 2006; Huysmans & Dassargues, 2005). If Pe $\geq 1$ (threshold T1), advective fluxes can be significant and therefore shape the gas emissions. For Pe $> 10$, advective fluxes can increase the gas emission even by more than an order of magnitude (e.g., Fityus et al., 1999; Hassanizadeh, 2006; Huysmans & Dassargues, 2005), and the contribution of diffusion to gas transport is significantly reduced, even negligible.

Two different mechanisms were considered that would induce pressure gradients in regolith and enhance methane and other trace gas emissions by advective fluxes: (i) time-varying atmospheric pressure fields and (ii) pressure gradients induced by wind's interaction with topography. In order to obtain affordable analytical solutions of (2), we considered a homogenous and isotropic regolith for which analytical solutions are easily derived and can be found, for example, in Colbeck (1989). For mechanism (i), a one-dimensional time-varying pressure field $P$ is forced at the surface by a sinusoidal pressure wave $P' = P - P_0$, where $P_0$ is the mean pressure in the time domain and $P'$ is defined by the wave amplitude $A_p$ and frequency $\omega_p$. For mechanism (ii), a two-dimensional surface topography scenario is subjected to steady-state horizontal wind speeds, which perturb the atmospheric surface pressure field, and hence the near-surface regolith pressure field. The topographic feature is defined by its wavelength $\lambda$ and height $H$ and generates a surface pressure perturbation $P' = A_p \cos(2\pi x/\lambda)$, where $x$ is the coordinate along the surface, and $A_p$ the pressure amplitude. This means that winds induce a pressure gradient; that is, they roughly increase the pressure in the windward side of a topographic feature and reduce it on the leeward side (Nachshon et al., 2012; Scott, 2000). The pressure amplitude for this case can be defined by $A_p = 2.9\rho {v_{10}}^2 H/\lambda$ (Colbeck, 1989), where $v_{10}$ is the wind speed at 10 m of altitude and can be obtained from the observed wind speed by MSL $v_{1.6}$ at 1.6 m by means of the definition of friction velocity: $v_z = \frac{v_*}{K} \ln\left(\frac{h}{z_0}\right)$ (Bagnold, 1941), where $v_z$is the wind speed at the altitude $h$, $v_*$the friction velocity, $K$ the von Karman constant, and $z_0$ the roughness length. Thus, evaluating the aforementioned expression for $v_{10}$and $v_{1.6}$, and making the ratio between the resulting expressions for both levels, after rearranging, $v_{10}$can be computed by means of

$$v_{10} = v_{1.6} \frac{\ln(10/z_0)}{\ln(1.6/z_0)} \tag{4}$$

Assuming $z_0 = 0.05$ m, (4) results in $v_{10} \approx 1.53\, v_{1.6}$.

Both mechanisms were simulated for the first meters of regolith under two different scenarios, in order to determine the relative contribution of each in the resulting advective fluxes: (a) well-sorted gravel as a first-order analog to the Martian regolith, with $k$ in the range $10^{-7}$–$10^{-9}$ m$^2$, and $\phi$ in the range 0.30–0.40 (De Bortoli et al., 2015; Pinder & Gray, 2008). Here, we consider $k = 10^{-8}$ m$^2$ and $\phi = 0.35$; and (b) a fractured medium, defined by its equivalent continuum parameters $k$=$10^{-9}$ m$^2$ and $\phi$= 0.01 (Pinder & Gray, 2008). Note that for (b), we assume that the fracture network is well connected and can be homogenized as a continuum (Berkowitz et al., 1988). These choices are meant to demonstrate the reality of the processes hypothesized in the work and will be followed by more detailed regolith and fractured media (i.e., bedrock) characteristics based on MSL's observations.

Each mechanism was modeled for different assumptions of pressure perturbation. For mechanism (i) (Figure 1, left), four different sinusoidal perturbations were considered, corresponding to idealized scenarios from those present in the Mars's atmosphere: high-frequency perturbations corresponding to the effect of atmospheric turbulence; 1 and 0.1 Hz waves with amplitude of 0.1 Pa; a "seasonal" perturbation with a period of 1 Mars year and amplitude of 100 Pa; and a "diurnal" perturbation with a period of 1 sol and amplitude of 40 Pa. The diurnal perturbation is not relevant under Earth's conditions, but in Mars, pressure presents a large diurnal cycle due to thermal tides. Tides are driven by the solar cycle and modulated by the presence of dust loading, topography, surface albedo, and thermal inertia, in addition to water ice clouds (Kleinböhl et al., 2017), which largely determine the amplitude of the thermal tide signature (Hess et al., 1977; Leovy

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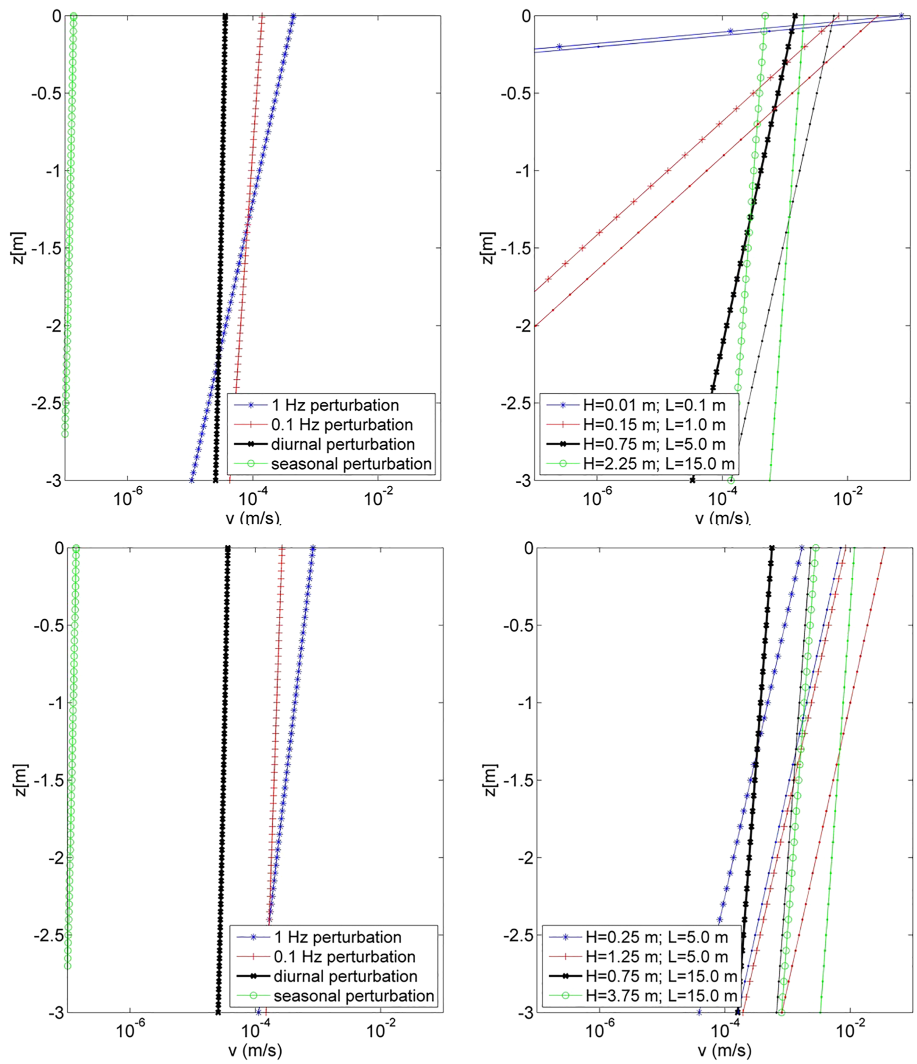


**Figure 1.** Vertical profiles of air flux $v$, for different cases forcing the pumping of gas into and out of the regolith under two scenarios (top row: $k$=$10^{-8}$ $m^2$ and $\phi$= 0.35; bottom row: $k$=$10^{-9}$ $m^2$ and $\phi$= 0.01). (left column) Time-varying pressure waves (seasonal, diurnal; 0.1 Hz, 1 Hz) forcing variable pressure field in regolith; (right column) wind-induced pressure gradients for four topographic features with different heights and wavelengths, considering both the average REMS wind speed (thick lines) and a high wind speed case with $v_{1.6}$= 10 m/s (thin lines).

& Zurek, 1979; Zurek, 1976; Wilson & Hamilton, 1996). The diurnal pressure range is also strongly enhanced by the topographic slopes found in Gale Crater via hydrostatic adjustment flows (e.g., Richardson & Newman, 2018). The seasonal perturbation is due to the deposition and sublimation of carbon dioxide in the polar caps.

For mechanism (ii) (Figure 1, right), the effect of $v_{1.6}$=5 m/s (the average MSL REMS wind speed, Viúdez-Moreiras et al., 2019a, 2019b) and $v_{1.6}$=10 m/s (a windy case) on surface topography was considered, applied to four topographic features with different $H$ and $\lambda$. Note that the aspect ratio of the feature was assumed to be sufficiently small that the flow field can reasonably be calculated as if this pressure distribution exists beneath a flat surface, and therefore, results only represent a rough estimate of the flow (Colbeck, 1989).

The effect of advective fluxes on the methane emissions is evaluated making use of the Péclet number. Wind-induced pressure gradients (mechanism ii) are suggested to be the most relevant in the regolith's advective fluxes (see Figure 1 and next section); therefore, we focused this analysis on wind-induced pressure gradients. Substituting (1) in (2) and solving the PDE, air fluxes in regolith for this mechanism are computed by (Colbeck, 1989)

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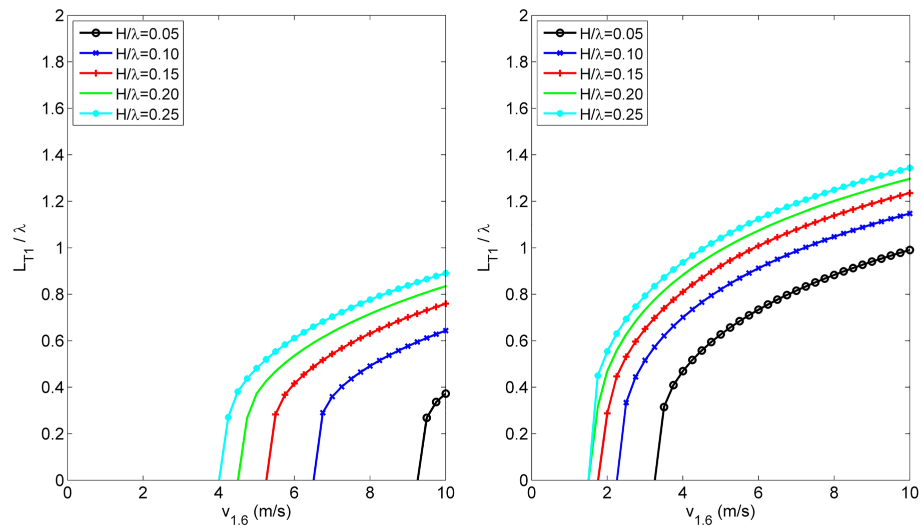


**Figure 2.** Maximum required depths of a hypothetical methane reservoir ($L_{T1}$, for Pe numbers at threshold values $T_1$, see text), where advective fluxes can be significant and therefore shape the gas emissions, normalized to the wavelength $\lambda$ of the topographic feature, as a function of the characteristic wind speeds (1.6 m). Several aspect ratios ($H/\lambda$) of the feature (see section 2) were simulated. (left) $k$=$10^{-8}$ $m^2$ and $\phi = 0.35$; (right) $k$=$10^{-9}$ $m^2$ and $\phi = 0.01$.

$$v = \frac{5.8\,\pi}{\lambda^2}\frac{k\,\rho}{\mu}\,\frac{H}{\phi}{v_{10}}^2\,e^{-2\pi\,z/\lambda}, \tag{5}$$

where $z$ is the vertical coordinate. The mean air flux, $\bar{v}$, is derived integrating (5) along the vertical axis from the surface to the depth $L$ in which the hypothetical methane reservoir is located. It results in a Péclet number:

$$Pe = \frac{11.6\pi^2}{\lambda^3}\frac{k\,\rho}{\mu}\,\frac{H\,{v_{10}}^2}{\phi}\frac{L^2}{D_{eff}}\frac{1}{e^{2\pi\,L/\lambda}-1}, \tag{6}$$

Thus, considering a reservoir at depth $L$, which emits to the atmosphere through a combined effect of diffusion and advection, the relative contribution of each transport mechanism depends on the Péclet number, which also depends on the depth of the reservoir (6). Considering that the wind-induced pressure gradients are the mechanism that drives gas emissions, the advective fluxes generated by this mechanism must be strong enough to shape the methane emissions, that is $Pe > Pe_{T1}$. Thus, solving (6) for $Pe_{T1}$, a roughly maximum depth for the hypothetical methane reservoir can be obtained. Note that (6) implies a decreasing trend in Pe very close to the surface, that is, for a hypothetical reservoir with $L \approx 0$, diffusion is the dominant transport mechanism.

## 3. Discussion and Conclusions

Within the first pressure pumping mechanism, results (Figure 1) suggest that the seasonal cycle of pressure has a negligible effect on the advective fluxes within regolith. Also, the strong diurnal cycle of pressure in the Martian atmosphere does not reach the required advective fluxes to significantly enhance regolith emissions. Atmospheric turbulence, modeled by high-frequency waves, experiences a strong advective flux attenuation in regolith, but they are greater than the diurnal perturbation in the first meters of depth. However, wind-induced advective fluxes resulting from the interaction between surface winds and topography are orders of magnitude greater than those produced by time-varying atmospheric pressure fields, particularly in the near-surface regolith. As can be seen in Figure 1, air fluxes are higher for smaller topographic features (characteristic length of the topographic feature $\lambda < 1$ m), although the penetration depth is constrained to the near surface.

Figure 2 presents results for several topographic features, as a function of wind speed. Note that although $L_{T1}$ is related to $\lambda$ (i.e., an increase in $\lambda$ implies an increase in $L_{T1}$ for these conditions) from a pure mathematical perspective, the permeability in soils decreases in practice with depth, and therefore, advective fluxes decrease accordingly. Thus, Scenario 1 (gravel) would be constrained to the near surface, below ~1 m, even for the higher aspect ratios $H/\lambda$. It would require a methane or trace gas reservoir at depths, $L_{T1}$, not greater than a few centimeters, and results suggest that diffusion is the dominant transport mechanism in regolith for low wind speeds. However, Scenario 2 (fractured medium) allows greater air fluxes and therefore hypothetical reservoirs as far down as depths greater than the topographic wavelength $\lambda$. Thus, for $H/\lambda = 0.15$ and $\lambda = 5$ m, a reservoir subjected to a characteristic wind speed equals to 5 m s$^{-1}$ (roughly the MSL REMS average wind speed, acquired at 1.6 m) will require depths not greater than 4.6 m; and 13.8 m in case the topographic feature has $\lambda = 15$ m. $L_{\mathrm{T1}}$ is allowed to be higher for greater aspect ratios $H/\lambda$ and wind speeds (Figure 2).

Note that these simulations, performed on idealized topographic features, give only a rough estimate for the range of depths of a hypothetical reservoir. Also, we assume for Scenario 2 that the fracture network is well connected and can be homogenized as a continuum (see section 2). A numerical discrete-fracture approach, with the exact fracture's geometry and features, should be used for modeling a particular fractured system with high accuracy.

It is expected that sharper topographic features could enhance the pressure perturbations, and thus increasing the impact in air fluxes and therefore in methane and other trace gas emissions. Also, low-permeable topographic features will create their own pressure fields in their vicinities by the interaction with winds, provoking advective fluxes in soil. In addition, unsteadiness of winds, both in wind speed and directions, could play a significant role in the mechanism enhancement, continuously varying the pressure field in regolith. Given that this mechanism experiences a strong attenuation as a function of depth, it requires that trace gas should be produced or stored in the near-surface regolith (e.g., by shallow gas accumulation after seepage from a deeper reservoir), in order to shape gas emissions. Other mechanisms to induce advective fluxes, such as thermally driven convection, which is dependent on the air and ground temperatures, could also influence on the total venting fluxes (Weeks, 1994).

This paper evaluates for the first time the relevance of advective fluxes in soil emissions into the atmosphere of Mars, which could be applied for methane and other species. Results suggest that, even in the Mars's thin atmosphere, the air exchanged between the regolith and the near-surface atmosphere by the interaction between surface winds and topography can be the dominant process in the first centimeters of depth for gas transport in a high-permeable regolith. Other kind of regolith with lower permeabilities, such as poorly sorted or even well-sorted sand, commonly found to date by MSL and previous missions (Banham et al., 2018; Sizemore & Mellon, 2008), would be mostly dominated by diffusion. However, for fractured media, the advective transport mechanism can be dominant in the first meters of depth (Figure 2).

This mechanism could regulate gas emissions into the atmosphere as a function of winds and meteorological conditions and thus reconcile the methane abundance variation detected by MSL and several emission mechanisms proposed to date from subsurface reservoirs (Yung et al., 2018), which have difficulties to match the observed variation in methane abundance (Webster et al., 2018; Yung et al., 2018); that is, the observed variation could be mostly driven from local meteorology around the hypothetical reservoir(s), instead of from the mechanism emitting or producing gas *in origin*. Atmospheric chemistry and dynamics could also play a significant role in the resulting gas abundance in the atmosphere. The methane reservoir, or the methane production, should be located in the near-surface, or perhaps methane could be accumulated in near-surface traps and temporary reservoirs (Oehler & Etiope, 2017), after seepage from a production or emission at a higher depth. The expected extensively fractured subsurface in Gale crater could promote this possibility. Focusing on the vicinity of MSL in the slopes of Aeolis Mons, the highly fractured Murray outcrops observed by MSL could exhibit the needed permeability characteristics within the polygonal fractures where not covered or just thinly covered by regolith. Another possibility is that some of the sulfate-bearing strata on Aeolis Mons exhibit layers with a very blocky weathering pattern, again suggesting dense fracturing throughout these layers. Also, the floors, walls, and ejecta deposits from impact craters may be other potential methane sources.

Regolith transport simulations suggest that pressure pumping, a well-known mechanism to enhance gas emissions on Earth can also induce methane and other trace emissions to the Mars's atmosphere by means of advective fluxes in highly permeable soils such as fractured media, at relatively low depths.

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