Estudio del permafrost de Marte a partir de los datos de temperatura superficial del sensor Mini-TES, Spirit MER mission.

Studying Martian permafrost from surface temperature data of Mini-TES, Spirit MER mission.

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Abstract

Specialists ensure that Mars remains a high volume of water frozen forming the permafrost. Phoenix mission confirmed the presence of frozen soils, with frozen water solutions, and other missions provided images and spectrometrical data what support the permafrost existence. On the other hand, Mini-TES, a spectrometer instrument onboard the Spirit rover, acquired surface and atmospheric data since 2004, along its track in the inner plain of Gusev Crater. Here, we contrast this information with THEMIS (the spectrometer onboard the Mars Odyssey orbiter) data and a climatic empiric model for Mars (Mars Climate Database). We observed that THEMIS data are around 10 degrees lower than Mini-TES ones for the same dates. We also calculate the ground freezing front position (0ºC isotherm), with some of the geothermal gradients proposed for the planet, obtaining depths from 10 to 40 km for the study area in Gusev Crater.

Keywords: Mars, permafrost, surface temperature, Mini-TES, Spirit MER

Resumen

Numerosos investigadores aseguran que en Marte existen grandes cantidades de agua congelada bajo la superficie en forma de permafrost. La misión espacial Phoenix (NASA) confirmó la presencia de estos suelos congelados, y la presencia de soluciones acuosas en ellos, lo que resulta consistente con la existencia de permafrost. Por otro lado, un instrumento a bordo del vehículo Spirit (MER, NASA) denominado Mini-TES, lleva desde el año 2004 tomando datos de la superficie y la atmósfera de Marte a lo largo de su viaje por la llanura interior de Gusev Crater. En particular, está tomando datos de temperatura. En este trabajo, se contrastan estos datos con los derivados de los datos del adquiridos por el instrumento THEMIS (un espectrómetro a bordo de la sonda Mars Odyssey) y un modelo climático de Marte (*Mars Climate Database*). Esta comparativa muestra que los datos de THEMIS son, en general, 10 grados menores a los tomados por Mini-TES, en la misma fecha y lugar. En este trabajo, también se calcula la posición del frente de congelación (isoterma de 0ºC), mediante algunos de los gradientes geotérmicos que se han propuesto para el planeta, habiendo obtenido profundidades que oscilan entre los 10 y los 40 km para la zona de estudio dentro de Gusev Crater.

Palabras clave: Marte, permafrost, temperatura superficial Mini-TES, Spirit MER

Introduction: Mars' permafrost and thermal data

Today is known that early Mars had more water than we can found nowadays, even more than early Earth had in those times (Carr, 2008). The water on Mars was liquid above the surface in other times, as revealed by different geological, geomorphological, and geochemical evidences (e.g., Fairén et al., 2003, and references therein). However, most of the water existing on Mars (1) was lost into space by diffusivity, (2) is frozen in the polar caps (and also in other glaciers of the planet) and, also, (3) it could be all around the planet, frozen underground, forming permafrost (Forget et al., 2006). The widespread existence of this permafrost would explain where could be located nowadays the high volume of the water of early Mars, and its existence was confirmed with the Phoenix's and Mars Exploration Rovers' data (Smith et al., 2009) and supported by the data from other sensors (e.g., Byrne et al., 2009). In spite of that, the behavior and distribution of Martian permafrost is really unknown. Different models has been proposed (e.g., Clifford, 1993; Clifford and Parker, 2001; Faure and Mensing, 2007) and it is expected to have been very different in the past (e.g., Kreslavsky et al., 2008).

Present Martian climatic conditions allow the existence of frozen water near the surface only above 40º in latitude (N or S). On those areas have been identified periglacial features such as gelifraction and frost heaving, what is a geomorphologic evidence of permafrost existence (Baker, 2001; de Pablo, 2009). At lower latitudes, because the atmospheric conditions (essentially, the lower H_2O pressure and temperature values), the water near to the surface sublimes (diffusive contact with the atmosphere; Forget et al., 2006). Owing to these conditions, the active layer on Mars is expected to have a thickness lower than one centimeter (Baker, 2001). However, the high variability on these parameters between day and night (a Martian day, or "sol", has practically the same duration than terrestrial ones) and annual in lesser measure (the Martian year have double length than Earth's) makes it very variable. On the other hand, the change on cryoscopic fusion point produced in salts dissolutions would cause the presence of liquid water on surface or subsurface at temperatures below 0ºC. Furthermore, if Mars is still active (Márquez et al., 2004; Dohm et al., 2008; de Pablo, 2009), the geothermal energy could melt the deeper boundary of permafrost (Clifford, 1993; Hoffman, 2001; Hoffman, et al, 2002), delimiting the distribution of underground ice. For that reason it is important to work with real data instead only with models, for reach the understood of realistic permafrost depths distribution.

After working only with orbital data on the distribution of permafrost in depth (Molina, 2009), there is the need to study the reliability of these data, to data directly acquired from the surface of Mars. Here, we propose the study of permafrost from available surface temperature data, coming from many sources, but mainly from the Spirit Miniature Thermal Emission Spectrometer (Mini-TES) Brightness Temperature Records (BTR), a sensor onboard the Spirit rover.

Data and Method

On the last forty years, many mission have been sent to the planet Mars. The successful ones give us a huge volume of data about the physical characteristics of both the atmosphere and the surface. Most of the data come from orbital sensors, but a few missions had reached the surface of the planet. The importance of the Spirit's sensor, called Mini-TES, is that it provides most direct data (more reliable therefore), and allows to compare them with orbital ones (such as THEMIS) and empiric models (such as the Mars Climate Database; Forget et al., 1999).

Mini-TES sensor was designed for derive mineralogical and thermophysical properties of the area surrounding the Mars Exploration Rovers (MER), with a spectral range of 5-29 micrometers (339.50 to 1997.06 cm^{-1}) (Christensen et al., 2003). It is installed on Pancam Mast Assembly

(PMA), on its head, located ~1.5 m above the ground. It has 60 degree of azimuth travel and views from 30 degrees above the nominal horizon to 50 degrees below. It allows us to take a record from soil and another from atmosphere on the same place and practically at the same time. We use only the Spirit data (not the Opportunity ones), what delimiting our study area. This vehicle landed into Gusev crater (Figure 1), and is still travelling in the inner plains. On Figure 1 is marked the position and time (sol since the landing) were taken each data. Gusev crater was selected as the landing site because of the possibility that it once held a lake. Studies of the materials provide evidence for limited but unequivocal interaction between water and the volcanic rocks (e.g., Haskin et al., 2005).

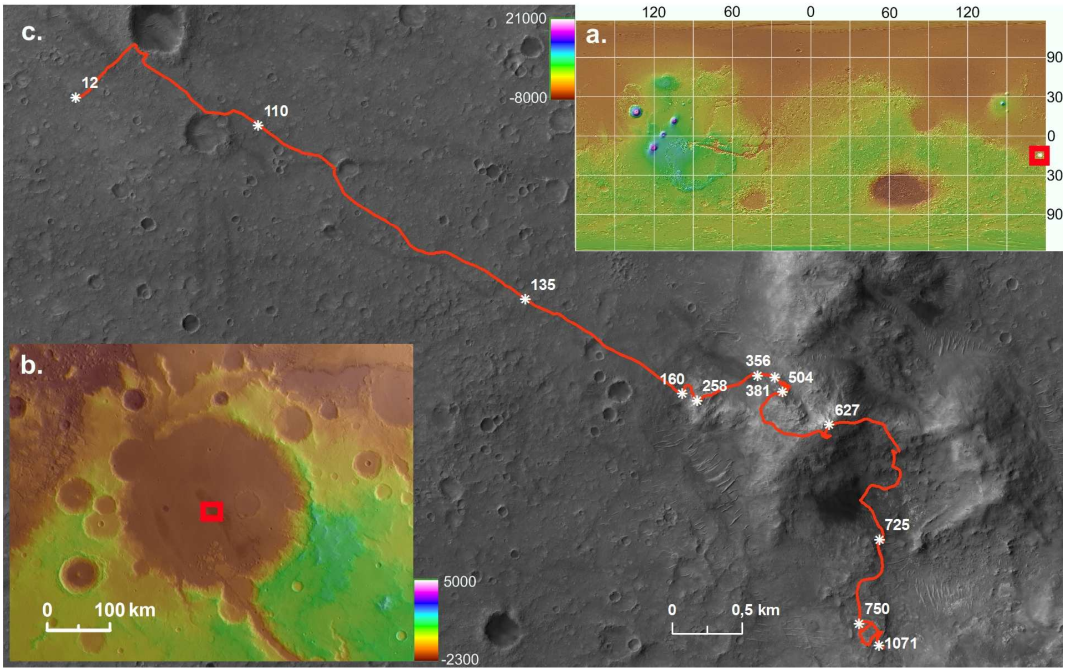

Figure 1.- *(a) Localization of Gusev crater on Mars, and (b) the Spirit`s track on it. (c) Spirit`s track (red line) and sol (from mission start) when every measurement were taken. Spirit landed on 175º 28' E; 14º 34' S.*

THEMIS sensor (THermal EMission Imaging System; Christensen et al., 2005) is onboard of the Mars Odyssey spacecraft, and is still acquiring (for more of ten years) visible and infrared multispectral images all over the planet, with a mean resolution of 18 and 100 m/pixel, respectively. Here, we use derivates Brightness Temperature Records (BTR) product, what provides surface temperature information derived from the IR images.

We analyzed (1) the BTR from THEMIS images available of the area of Spirit's track and (2) Mini-TES BTR information from concordant date, local time and coordinates. On the second case, it was analyzed the information acquired at 798.82 cm^{-1} wavelength (generally Band 81); similar to the 795.54 cm^{-1} from Band 9 of THEMIS-IR. For the area, there are available 13 THEMIS BTR data, but one of them is overexposed and it has been discarded. It was taken on the 15th sol of the mission (the measurement number 1), and the sensor could have been bad calibrated yet. The images are taken from early 2004 to early 2007 on irregular intervals of time. For comparing, we use the Mars Climate Database (MCD) data to obtain the evolution of mean surface and near surface temperatures.

Mars Climate Database (www-mars.lmd.jussieu.fr) is a climatic statistical database, based on general circulation model of Martian atmosphere. This has been validated exhaustively with Thermal Emission Spectrometer (TES) for surface temperature and the ultrastable oscillator onboard Mars Global Surveyor (MGS) for atmospheric temperature (Millour et al., 2008). We use a scenario with the mean conditions (density of particles in suspension) of the 24th Martian year (1999-2001; Clancy et al., 2000).

Finally, THEMIS images were taken each few days and months, and we have only 12 BTR images for the zone on three Martian years (four Earth's ones). These average data allow us to study possible trends, and the adjustment among THEMIS and Mini-TES data.

Results

Temperature surface values derived from Mini-TES and THEMIS are similar and concordant with the MCD trends (Figure 2). In all cases (except on the measurement number 9, from the left; 627th sol), Mini-TES temperature is higher than THEMIS, probably owing to the effect of thin Martian atmosphere (the data have not any correction on this way).

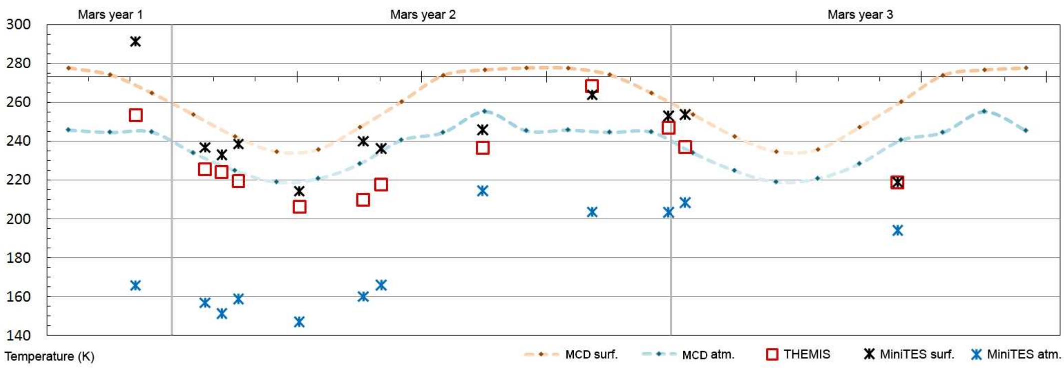

Figure 2.- *Comparative plot of surface and atmospheric temperatures derived from two different sensors (THEMIS, an orbital one and Mini-TES, into the Spirit' rover) and Mars Climate Database (MCD).*

On the first seven measurements (from the left) of Mini-TES atmospheric data, there is a difference of about 70 K respect to the data obtained from MCD model. On the next measurements the difference is lower, but still about 40 K. It could be caused by the different orientation on the soil surface. In some measurements, the angle of the sensor varies between 0.5 and 0.2 degrees above the horizon. The inclination of the sensor affects to values of temperature; and the lower the angle, the higher the temperature value obtained by the sensor. In spite of this, this difference is only about 10 K.

Only on two measurements the temperatures are close to 0ºC: on the 15th sol of Spirit mission (the measurement number 1; with could be a wrong data, because its difference with THEMIS one), and on sol 627 (measurement number 9). On the second case, also THEMIS-derived temperature approximates to 0ºC, and it is higher than Mini-TES-derived surface temperature.

We used the maximum and minimum values for Mini-TES surface temperature to calculate the deep of the 0ºC isotherm (French, 2008), by the use of different geothermal gradient proposed for Mars (Table I). The lower geothermal gradients had been proposed in Hoffman (2001), and are 6.4

K/km for saturated on ice soils and 10.6 K/km for dry materials; being probably the most appropriate for the area the second. In Hoffman, et al. (2002) the geothermal gradients proposed are higher, from 12 to 15 K/km (the latter also having been proposed in Clifford [1993]) and 20 K/km as locally extremely high values. The formula that we use to calculate the deep of the 0ºC isotherm is (French, 2008):

$$T_z = T_s + g_g \cdot z \qquad [1]$$

where T_z is the underground temperature, in our case 273 K (0º C), T_s is surface temperature, g_g is geothermal gradient and z is the deep for T_z temperature. We modified the equation [1] to extract the z value for a given temperature (in this case 0º C).

Geothermal gradient (K/km)	6.4 [1]		10.6 [1]		12.0 [2]		15.0 [2, 3]		20.0 [2]		30.0 [1]	
Surface temperature (K)	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
	214.3	264.0	214.3	264.0	214.3	264.0	214.3	264.0	214.3	264.0	214.3	264.0
Deep of 0ºC isotherm (km)	33.5	41.3	20.2	24.9	17.9	22.0	14.3	17.6	10.7	13.2	7.1	8.8

Table I.- *Depths calculated for the 0º C isotherm, based on maximum and minimum Mini-TES data and the different geothermal gradients proposed for planet Mars and the Earth's one (grey).* [1]*Hoffman, 2001;* [2]*Hoffman, et al. 2002;* [3]*Clifford, 1993.*

We calculated the depth of 0ºC because at this isotherm, interstitial pure ice would melts, and water may be liquid below it, however could find liquid water associated a lower values of ground temperatures sub-zero (ºC) in the case of water solutions. The first data measurement was discarded, because it was considerate an atypical record. For the higher geothermal gradient (6.4 K/km; Hoffman, 2001) the 0ºC isotherm is expected to reach between 33.5 and 41.3 kilometers.

Table 1 shows the results obtained by this methodology. For the lowest (20 K/km; Hoffman et al., 2002), we calculate values between 10.7 and 13.2 kilometers for the freezing front. With the Earth's geothermal gradient (30 K/km; Hoffman, 2001), the deep of the zero (ºC) isotherm would be between 7.1 and 8.8 kilometers.

Discussion

In spite of the results obtained (Table I) could not be regionally representatives because from they were derived from a few data, we could use them to obtain a general idea about the possible distribution of permafrost in the ground. In this sense, results reveal important differences for the deep of the 0ºC isotherm, depending of the geothermal gradients (but in any case the different is higher than 10 km). At these deeps, the materials have a compact structure and the water (or ice) content would be insignificant. Moreover, such as we mentioned in the introduction, frozen water near the surface nowadays is only above latitudes of 40º, such as recently confirmed by Phoenix mission (e.g., Mellon et al., 2008, 2009), and our study area is located on 15º S. In areas close to equator, the ice is not expected to be stable at less than 1 km deep (Forget et al., 2006). In polar areas, the ice layer would be thicker (instead it could be also nearest to the surface).

On the other hand, if liquid water exists at the resulting deeps (Table I), it could be under high pressure conditions, and it could migrate toward the surface in order to reduce the pressure. This could be related to some periglacial processes such as pingos (see de Pablo and Komatsu, 2009 for an example), whose have diverse origins for groundwater (Gurney, 1998). However, in general, low quantities of water could reach the surface by this process, so the real implications of liquid water under the calculated 0º C isotherm could not be relevant on the periglacial morphologies at the Martian surface. Nevertheless, ice might have been at shallow depths during periods of high obliquity, then melted and risen (in response to warming of the surface) as transient water (Richardson and Mischna, 2005). These results also have astrobiological implications, because in the less deep case (10.7 km), the liquid water could be located so deep, since the deepest bacteria described living below the terrestrial surface were located at 2.8 km (Wanger et al., 2006).

From other point of view, those results are based on a simple methodology what includes only the surface temperature such as an input parameter. To derive more detailed and accurate results requires the introduction of these and more parameters, both climatic and geological. For example, it may be interesting to include hydrogeological parameters such as porosity and transmissive of the subsurface materials; as well as physical parameters, for example water vapor pressure and phenomena of transmission of energy (Gori and Corasaniti, 2004; 2008). Even, it could be interesting consider the salts dissolution or the effect of the different surface warming produced by the relief effect. It could be used a model that relates the surface temperature with other variables such as topography and air temperature values (e.g., Abramov et al., 2008). However, the differences in height for the Spirit rover’s transect is about 100 m, and therefore it is not expected to be an important factor.

New missions projected, such as Mars Science Laboratory (marsprogram.jpl.nasa.gov/msl/), will provide, thanks to the Rover Environmental Monitoring Station instrument, meteorological data for studying other areas with more direct and diverse data. With these data, and the above considerations, we expect to continue working in future on the study of permafrost distribution on the Martian surface through the use of surface temperature data, improving the here showed methodology and model.

Conclusions

In this work we show that the values of surface temperature, coming from orbital and landing sensors could be comparables, with a mean difference of about 10 K. We also observed that both the surface and atmospheric temperature values follow the trends expected by the climatic models, like the MCD. This information is important for understand how reliable are the studies based on them, and how they fit to the reality. From this data it will be possible to derive maps of the freezing front (0ºC isotherm), what will be useful in the study of Martian permafrost distribution, and its relation to the surficial periglacial morphologies. In the area the calculated depths are considerably deep to have influence on the periglacial landscape of the area, but in the past, the amount of water had to be higher, and being an important factor for geomorphology and even for the possible microbiological life.

Furthermore, because of its proximity to the Martian equator, the area it is not the most appropriate for the study of near-surface ice. At higher latitudes, and also by the inclusion of geological and physical parameters, we could derive more interesting and realistic results, for understanding the today’s Martian permafrost. The upcoming launches of new missions, that will bring higher quality and diversity new information, will be a good opportunity to further advance on the research in this field.

On one hand, the study of permafrost on other planets (as on Mars) is difficult owing to the absence of continuous data, the different and unexpected conditions that we found and the impossibility for making ordinary fieldworks and analysis. But, on the other hand, we have the chance of work with high quality and free data, interesting conditions that would allow us to compare later the result with what we know and understand about the Earth. Mars is not so far nor is so different from Earth than we could think, and its study is a good way to know how was the Earth and how may it would be in the future.

References

Abramov, A., Gruber, S. and Gilichinsky, D. (2008), Mountain Permafrost on Active Volcanoes: Field Data and Statistical Mapping, Klyuchevskaya Volcano Group, Kamchatka, Russia. Permafrost and Periglacial Processes, 19. 261–277.

Baker, V.R. (2001), Water and the Martian landscape. Nature, 412. 228-236.

Byrne, S., Dundas, C.M., Kennedy, M.R. et al. (2009), Distribution of Mid-Latitude Ground Ice on Mars from New Impact Craters. Science, 325. DOI: 10.1126/science.1175307.

Carr, M.H. (2006), The Surface of Mars. Cambridge University Press. New York. ISBN: 978-0-521-47201-0.

Christiensen, P.R., Mehall, G.L., Silverman, S.H. et al. (2003), Miniature Thermal Emission Spectrometer for the Mars Exploration Rovers. Journal of Geophysical Research, 108 (E12). DOI: 10.1029/2003JE002117.

Christiensen, P.R., Ruff, S.W., Fergason, R., et al. (2005), Mars Exploration Rover candidate landing sites as viewed by THEMIS. Icarus, 176. 12–43.

Clancy, R.T., Sandor, B.J., Wolff, M.J. et al. (2000), An intercomparison of ground-based millimeter, MGS TES, and Viking atmospheric temperature measurements - Seasonal and interannual variability of temperatures and dust loading in the global Mars atmosphere. Journal of Geophysical Research, 105 (E4). 9553-9571.

Clifford, S.M. (1993), The role of the geothermal gradient in the emplacement and replenishment of ground ice on Mars. LSPS XXIV. 313-314.

Clifford, S.M. and Parker, T.J. (2001), The evolution of the Martian hydrosphere: implications for the fate of a primordial ocean and the current state of the Northern Plains. Icarus, 154, 40-79.

De Pablo, M.A. (2009), Cartografía geológica de la región volcánica de Elysium, Marte. Interacciones magma-agua-clima. Doctoral Thesis. Universidad Rey Juan Carlos, Departamento de Biología y Geología. 500 pages (in press).

De Pablo, M.A. and Komatsu, G. (2009), Possible pingo fields in the Utopia basin, Mars: Geological and climatical implications. Icarus, 199. 49-74.

Dohm, J.M., Anderson, R.C., Barlow, N.G. et al. (2008), Recent geological and hydrological activity on Mars: the Tharsis/Elysium corridor. Planetary and Space Science, 56. 985-1013.

Fairén, A.G., Dohm, J.M., Baker, V.R. et al. (2003), Episodic flood inundations on the northern plains of Mars. Icarus, 165. 53-67.

Faure, G. and Mensing, T.M. (2007), Mars: the little Planet that could. Springer, the Netherlands. 532 pp.

Forget, F., Hourdin, F., Fournier, R., et al. (1999), Improved general circulation models of the Martian atmosphere from the surface to above 80 km. Journal of Geophysics Research, 104. 24,155–24,176.

Forget, F., Costard, F. and Lognonné, P. (2006) Planet Mars, Story of another world. Springer – Praxis (Berlín). 229 pp.

French, H.M. (2008), The periglacial environment (3rd Ed) John Willey & Son. ISBN: 978-0-470-865688-0.

Gori, F. and Corasaniti, S. (2004) Theoretical prediction ofthe thermal conductivity and temperature variation inside mars soil analogues. Planetary and Space Science, 52. 91-99.

Gori, F. and Corasaniti, S. (2008) Detection of a dry–frozen boundary inside Martian regolith. Planetary and Space Science, 56. 1093-1102.Gurney, S.D. (1998), Aspects of the genesis and geomorphology of pingos: perennial permafrost mounds. Progress in Physical Geography, 22. 307-324.

Haskin, L.A., Wang, A., Jolliff, B.L. et al. (2005), Water alteration of rocks and soils on Mars at the Spirit rover site in Gusev crater. Nature, 436. 66-69.

Hoffman, N. (2001), Modern geothermal gradients on Mars and implication for subsurface liquids. Conference of the Geophysical Detection of Subsurface Water on Mars, Abstract #7044.

Hoffman, N., Kargel, J. and Tanaka, K. (2002) Basal melting of a CO_2-rich icecap on Mars. LPSC XXXIII, Abstract #1509.

Kreslavsky, M.A., Head, J.W. and Marchant, D.R. (2008) Periods of active permafrost layer formation during the geological history of Mars: Implications for circum-polar and mid-latitude surface processes. Planetary and Space Science, 56. 289-302.

Márquez, A., Fernández, C., Anguita, F. et al. (2004), New evidence for a volcanically, tectonically, and climatically active Mars. Icarus, 172. 573-581.

Mellon, M.T., Arvidson, R.E., Marlow, J.J., et al (2008), Periglacial landforms at the Phoenix landing site and the northern plains of Mars, Journal of Geophysical Research, 113. doi:10.1029/2007JE003039.

Mellon, M.T., Arvidson, R.E., Malin, M.C., et al., (2008), Permafrost and polygons at the Phoenix landing site. LPSC Abstract #1904.

Millour, E., Forget, F., Gonzalez-Galindo, F. et al. (2008), The latest (Version 4.3) Mars Climate Database. 3rd International Workshop on the Mars Atmosphere: Modeling and observation, #9029. Williamsburg, Virginia.

Molina, A. (2009), Caracterización geológica, física y climática de la zona de amartizaje de la sonda Mars Science Laboratory (NASA). BSc Thesis. Departamento de Geología, Universidad de Alcalá. 160 pp.

Richardson, M. and Mischna, M. (2005), Long-term evolution of transient liquid water on Mars. Journal of Geophysical Research, 110. DOI:10.1029/2004JE002367.

Smith, P.H., Tamppari, L.K. Arvidson, R.E., et al. (2009), H_2O at the Phoenix Landing Site. Science, 325. 58-61. DOI: 10.1126/science.1172339.

Wanger, G., Southam, G. and Onstott, T. (2006), Structural and Chemical Characterization of a Natural Fracture Surface from 2.8 Kilometers Below Land Surface: Biofilms in the Deep Subsurface. Geomicrobiology Journal, 23. 443-452.