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Recurring slope lineae in equatorial regions of Mars

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The presence of liquid water is a requirement of habitability on a planet. Possible indicators of liquid surface water on Mars include intermittent flow-like features observed on sloping terrains. These recurring slope lineae are narrow, dark markings on steep slopes that appear and incrementally lengthen during warm seasons on low-albedo surfaces. The lineae fade in cooler seasons and recur over multiple Mars years. Recurring slope lineae were initially reported to appear and lengthen at mid-latitudes in the late southern spring and summer and are more common on equator-facing slopes where and when the peak surface temperatures are higher. Here we report extensive activity of recurring slope lineae in equatorial regions of Mars, particularly in the deep canyons of Valles Marineris, from analysis of data acquired by the Mars Reconnaissance Orbiter. We observe the lineae to be most active in seasons when the slopes often face the sun. Expected peak temperatures suggest that activity may not depend solely on temperature. Although the origin of the recurring slope lineae remains an open question, our observations are consistent with intermittent flow of briny water. Such an origin suggests surprisingly abundant liquid water in some near-surface equatorial regions of Mars.

Pure water is highly unstable on the surface of Mars today[1–6] but the possibility of present-day habitable conditions near the surface, accessible to exploration, has been enhanced by recent results. In addition to the recurring slope lineae[3] (RSL), there is evidence for the presence of thin films of water in the shallow subsurface, associated with ice deposits in the middle to high latitudes[4,5]. However, RSL are found in the warmest areas of the planet, typically extending downslope from bedrock outcrops, and often associated with small gullies. The preferred explanation for these features is brine flow, but the source of the putative water remains unclear. Brines are far more likely than pure water because they have lower freezing temperatures and evaporation rates[2,6], and because the martian surface has been found to be highly salty at every successful landing site[7].

Observations

Seven RSL sites were identified in the initial report[3]. Here, we describe new observations by the High Resolution Imaging Science Experiment[8] (HiRISE) on Mars Reconnaissance Orbiter (MRO) of active RSL inside Valles Marineris (latitude 6°–15° S), and in a few other equatorial locations. A number of candidate equatorial RSL sites were previously identified[3], but continued monitoring has now led to confirmed sites. At present, 13 sites have been fully confirmed in the southern mid-latitudes and 20 sites are partially confirmed[9]. We consider RSL 'fully confirmed' if we observe simultaneous incremental growth of multiple ($\geq$10) flows on a warm slope, fading, and recurrence of this sequence in multiple Mars years. We consider them 'partially confirmed' if we have seen either incremental growth or recurrence, and 'candidate' if an image shows $\geq$10 slope lineae that resemble RSL but we lack observations needed for partial confirmation. Episodic mass wasting processes also create dark lines on steep slopes, so observation of the temporal behaviour is required to confirm RSL. There are now 12 fully confirmed and 10 partially confirmed RSL sites in the tropics (25° S–25° N), and 1 confirmed site at 35° N latitude (Fig. 1 and Supplementary Table 1).

The global distribution of RSL (Fig. 1) shows that they favour the southern hemisphere, which has the highest peak surface temperatures because perihelion occurs at $L_s = 250°$, close in time to the southern summer solstice ($L_s = 270°$; L_s is the areocentric longitude of the sun). Confirmed RSL occur only in low-albedo regions, which absorb more heat from insolation and are free of an insulating layer of dust so the heat is conducted further below the surface. The confirmed or partially confirmed equatorial RSL (Supplementary Table 1) extend from central Valles Marineris to the eastern canyons, and are especially concentrated in Coprates Chasma. They have not been seen in far western Valles Marineris where the slopes are dust-covered and at other higher altitudes, that is, >2.1 km above the datum established by the Mars Orbital Laser Altimeter[10] (MOLA). Slope streaks are common in these high areas where steep slopes are mantled by dust, but are distinctly different from RSL in terms of absolute albedo (Supplementary Fig. 1), seasonality and flow trajectory[3]. The absence of RSL may be explained by the high elevations and low atmospheric pressure or by the dust cover itself with its very low thermal inertia, which creates an especially steep thermal gradient and would inhibit seasonal melting of ice (if present) at depths greater than a few centimetres.

RSL in Valles Marineris (Figs 2 and 3) seem similar to those in the southern middle latitudes. Some of the largest RSL occur in Valles Marineris, up to 1.2 km long in a site near Eos and Capri Chasma. RSL are commonly associated with 'small' (1–20 m wide) gullies, actually more similar in size to terrestrial gullies than the larger martian landforms commonly referred to as gullies[11]. The close fit between the widths and lengths of the gully channels and

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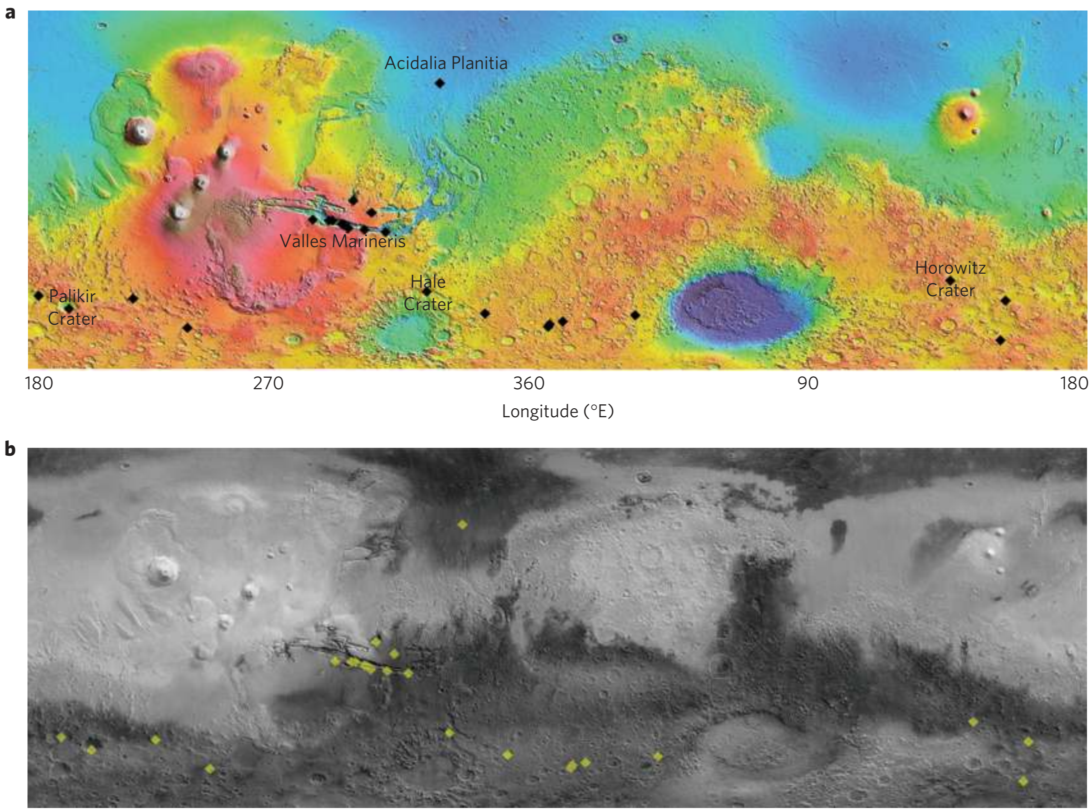

Figure 1 | Locations of confirmed recurring slope lineae (RSL). a, Confirmed RSL sites (black diamonds) on MOLA (ref. 9) colour-coded altimetry (latitude 60° S–60° N). MOLA elevation colours range from blue (low elevations) to red and white (high elevations). **b**, The same set of RSL (yellow diamonds) on a global bolometric albedo map from the Thermal Emission Spectrometer[40]. Both maps show MOLA shaded relief and are in simple cylindrical projection. All RSL sites plotted here are in areas with Thermal Emission Spectrometer albedo < 0.2.

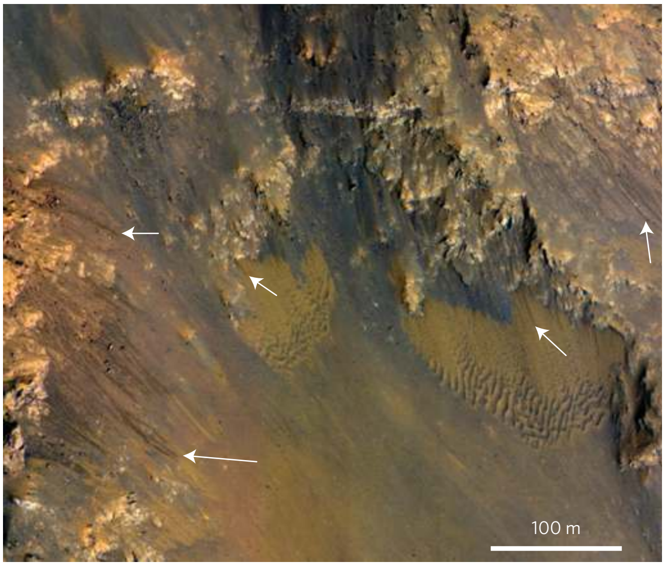

Figure 2 | Portion of Coprates Chasma showing RSL on generally north-facing slopes in northern summer and southern winter. North is down, and most slopes face northwest. IRB colour (near-infrared, red and blue-green band passes shown as red, green and blue, respectively) with min–max stretch illustrates the 'greenish' fans and deposits associated with RSL. Two of these fans transition downslope into ripples. All of the lineae here and in the larger scene seem to originate from relatively bright bedrock outcrops. The white arrows point out a few of the $\sim$100 lineae in this subscene from HiRISE image ESP_027815_1670.

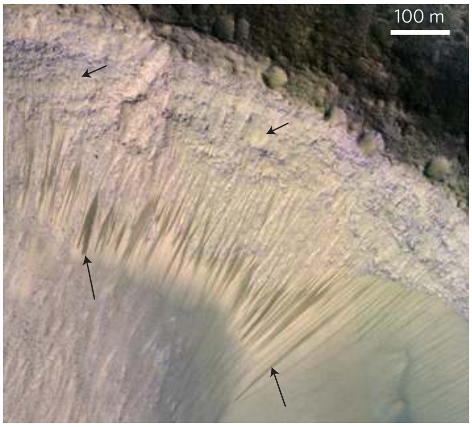

Figure 3 | RSL on the south-facing slope of a crater on the floor of Melas Chasma. IRB colour with minimum–maximum stretch as in Fig. 2, but north is up. Black arrows point to some of the many individual lineae. The RSL begin in narrow channels on the steep, rocky crater slope and spread out on the smooth fans. They were active on this portion of crater wall in early southern spring and summer (Table 1 and Supplementary Table 1). See http://www.uahirise.org/sim/ for a set of animated GIF files illustrating the activity. Portion of image ESP_031059_1685.

RSL suggests that RSL activity may gradually erode the channels, but no topographic changes have been confirmed. The large gullies observed to be active today are in times and places where seasonal CO_2 frost is present on the ground[12]. CO_2 frost is insignificant at

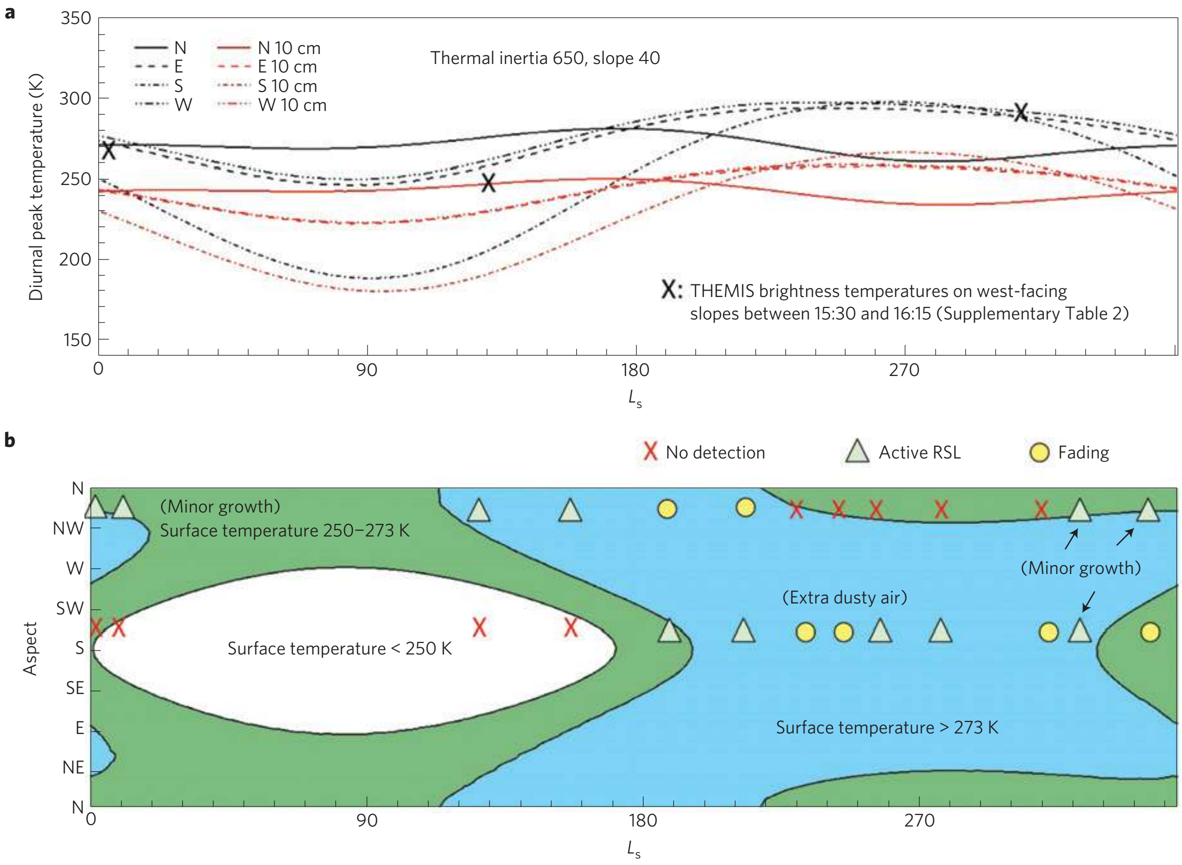

Figure 4 | Thermal model for the crater on the floor of Melas Chasma (11.5° S, 290.3° E). Model assumed bolometric albedo 0.134, emissivity 1, thermal inertia 650 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$ and a 40° slope for the steep rocky slopes where RSL originate; other reasonable choices produce similar results. **a**, Peak diurnal temperature for several slope aspects, for surface (black) and 10 cm depth (red). THEMIS (Supplementary Table 2) data are shown (crosses) for comparison with the west-facing slope model. **b**, Plot of slope aspect versus L_s, coloured to show three temperature ranges. Symbols indicate when RSL were either active (lengthening), fading or not detected.

present in equatorial regions or on the generally equator-facing slopes where RSL are seen in the southern middle latitudes, so a different formation mechanism is needed if these small gullies are now forming. There is no sign of modification of these small gullies by aeolian bedforms, impact craters or other morphologies that might imply an age greater than 10^3–10^5 yr, less than or comparable to the expected timescale for orbitally driven climate variations.

RSL activity clearly favours slopes with relatively warm daytime temperatures, with brightness temperatures[13] in the late afternoon from ~250 to 300 K in the southern mid-latitudes[3,8]. We have checked the temperatures for RSL sites in Valles Marineris from the Thermal Emission Imaging System[13] (THEMIS), and again the brightness temperatures range from ~250 to 300 K when RSL are active on west-facing slopes (Supplementary Tables 2 and 3). THEMIS usually observes in the late afternoon on Mars, after the time of peak temperature for flat areas, so these are minimum peak temperatures but probably near the peak temperatures for steep west-facing slopes (Fig. 4).

RSL activity on north-facing slopes in the southern mid-latitudes strongly favours the warm season between $L_s = 250°$ and 340°. The only confirmed northern hemisphere site seems most active from $L_s = 0°$ to 170°. Activity is now documented throughout the year in equatorial Valles Marineris. In five well-monitored Valles Marineris sites (Table 1) we have seen activity cease on north-facing and commence on south-facing slopes approximately when the subsolar point crossed their latitudes. The south-facing slopes receive the most insolation (incidence nearly perpendicular to the surface) when the subsolar latitude is to the south, whereas north-facing slopes are better illuminated for the remainder of the Mars year (as opposed to the mid-latitudes where equator-facing slopes have a permanent thermal advantage). The new sites confirm the link between slope temperature and RSL activity. However, warm, steep and rocky slopes are not the only requirements for RSL activity, as most such locations on Mars lack RSL (ref. 9).

Temperatures do not exactly follow the average daytime incidence angle, especially for equatorial north-facing slopes, because global insolation peaks at perihelion ($L_s = 250°$) when these slopes are most obliquely illuminated. Temperature variations were modelled for the symmetrical crater on the floor of Melas Chasma (Fig. 4). RSL on south-facing slopes behave as expected for a simple temperature-dependent process. However, temperatures vary little with season on the north-facing slopes, yet the RSL activity favours northern spring and summer. Warm temperatures are required for RSL activity, but there may be other influences on the timing of activity.

Where does the water come from?

The origin of RSL remains an open question. The seasonality and temperature correlation suggest a key role for a volatile, for which water is in the right temperature range. This includes the hypothesis that a volatile phase change triggers dry flows, as proposed for slope streaks on dust-mantled slopes[14], but this hypothesis does not explain the incremental growth or rapid fading of RSL. Another analogous process is the incremental growth of dark lines seen as

Table 1 | Activity of well-monitored RSL sites in Valles Marineris.

Site name	Latitude	Longitude (°E)	Elevation (km)	Slope aspect	Active on N-facing slopes (L_s)	Active on S-facing slopes (L_s)	Subsolar latitude to the south (L_s)
Slopes in E Coprates	−14.7	304.6	−2.1	N, E, S, W	50°–196°	213°–279°	217°–323°
Crater on Coprates floor	−14.1	296.9	−3.1	N, S, W	101°–110°	209°–278°	215°–325°
Coprates slope and dunes	−13.9	296.8	−1.8	N, S, W	?	225°–288°	215°–325°
S of large impact in Coprates	−12.6	294.7	−3 .1	N, E, S, W	69°–195°	246°–274°	211°–329°
Crater on central Valles Marineris floor	−11.5	290.3	−5.2	N, E, S, W	133°–161°	192°–281°	208°–331°

CO_2 defrosts over polar dunes, forming gullies[15], but RSL occur in places far too warm for CO_2 frost. Streaks on the avalanche slopes of active dunes sometimes resemble RSL, and may be seasonal owing to the changing atmospheric pressure[16], but in well-monitored locations such as Nili Patera the dune avalanching shows more abrupt rather than incremental growth (see links to animated GIFs in the Supplementary Information).

Flowing or seeping water or wet debris are attractive models for RSL as they can explain the seasonal darkening and fading. This seemed unlikely[3] on the basis of the lack of water absorption bands seen in Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data[17]. Furthermore, surface water is not expected near the 15:00 local observing time of MRO (ref. 6) unless it is actively being exposed or released. However, recent laboratory measurements of brine-wetted Mars analogue soil show that darkening persists when there is only a few per cent water present and H_2O spectral absorptions have greatly weakened or disappeared[18,19].

The hypothesis of melting shallow ice provides a good match to RSL observations, but is such ice actually present at these locations? In the southern middle latitudes RSL are active from $L_s = 250°–340°$ in most years, whereas surface temperatures peak between perihelion ($L_s = 250$) and the summer solstice ($L_s = 270°$). Seasonal temperatures peak at a later time in the shallow subsurface, $L_s \sim 290°$ at 20 cm[6], better matching the observations. Shallow, clean ground ice beneath flat terrain has been detected from new impact craters down to 39° N latitude[20,21] and is thought to also occur in the southern mid to high latitudes[22]. Such ice could provide a water source for the RSL by seasonal melting of frozen brines that are a remnant from a past climate[6]. However, the equator-facing slopes of middle latitudes should rapidly dry out, and the presence of shallow frozen brines from a former climate is even more difficult to explain in equatorial regions. Deeper and perhaps older brines[23] could play a role, especially deep in Valles Marineris.

An alternative hypothesis is that water comes from the atmosphere, trapped by hygroscopic salts, analogous to water tracks in Antarctica[24,25]. To consider this hypothesis, we compiled CRISM water vapour data[26] over the specific locations with confirmed RSL (see Supplementary Table 4 and Figs 5 and 6). These data are from Mars year 28 to 29 when RSL were observed over some of these sites, but the yearly pattern in water vapour is very similar to that from Mars year 24 to 26 (refs 27,28); years begin at $L_s = 0°$) The data are normalized to a constant surface pressure of 6.1 mbar (by assuming a uniform mixing ratio) to remove the effects of elevation. In the southern middle latitudes the column abundances peak at 15 precipitable micrometres (pr.μm) at $L_s = 240°–270°$ and drop rapidly to ∼5 pr.μm by $L_s = 300°–330°$. As RSL activity continues to $L_s = 340°$, the atmosphere may not be the direct source of water, but could recharge shallow water or ice if there is a mechanism to concentrate more of it than subsequently evaporates. Deliquescent salts effloresce (phase change from liquid back to solid) at a lower relative humidity than they deliquesce[29], but it is unclear whether this could serve to accumulate subsurface water or ice.

The locations in Valles Marineris in general show normalized column abundances of H_2O near 5 pr. μm from $L_s = 0°$ to 120° and 300°–360°, peaking at 10–15 pr.μm at $\sim L_s = 210°–240°$. This is a poor match to the observation of RSL activity over most of the year, varying with slope aspect. Again, the period of higher water vapour could conceivably result in some recharge. There are also water ice fogs in Valles Marineris[30] that might facilitate deliquescence or the recharge of shallow subsurface ice by keeping the near-surface air more humid.

RSL activity seems to be influenced by the atmospheric dust content. RSL were apparently more extensive in Mars year 28 (ref. 3 and Supplementary Table 1), after a planet-encircling dust storm started near $L_s = 268°$. To some degree this may be an increase only in the visibility of active RSL, because they have greater contrast with the background when they disturb a bright, fresh coating of dust deposited by the storms. However, RSL growth also continued longer (into early Mars year 29) in the southern middle latitudes[9]. We have also seen some variation related to dust activity in Mars year 31. In particular, two craters on the floor of Valles Marineris paused RSL activity on south-facing slopes from $L_s \sim 220°–246°$, apparently a time of higher dust opacity based on the poor surface contrast in our images (Fig. 4 and Supplementary Table 1). Valles Marineris can be dusty around this time period because regional storms propagate southward from the northern tropics into eastern Valles Marineris before spreading into central Valles Marineris[31]. RSL activity resumed when the air became clearer after $L_s = 246°$. We also observed darkening of RSL fans in this same time period ($L_s = 241°$), as discussed in the Supplementary Information (Supplementary Fig. 2).

Greater atmospheric dust results in cooler daytime and warmer night-time temperatures of the surface, which changes the expected timing for breakouts of subsurface water[32]. To understand the near-surface water cycle, we need improved information on: water vapour abundance near the surface; how the water vapour varies with time of day; and near-surface winds. The high-resolution orbital data are dominated by mid-afternoon observations, and no past or present lander or rover has visited a confirmed RSL region.

If RSL are due to briny water, what are the most abundant salt compositions? $CaCl_2$ was favoured[6] because the eutectic temperature is about right if RSL originate from melting shallow (10–20 cm deep) frozen brines. This is an attractive hypothesis because $CaCl_2$ is expected to be abundant[23] and the regions of most RSL are consistent with the regions of putative chloride deposits[33]. However, there is no direct observation of an association between RSL and chlorides. Anhydrous chlorides lack distinctive absorption bands in either the near-infrared or thermal–infrared spectral regions[33]. Typical RSL extend down steep slopes and terminate on sediment fans that are slightly less steep (∼ 23°–30°; Supplementary Table 1). These fans often have a distinctive colour in HiRISE IRB products, consisting of the IR (800–1,000 nm), RED (550–850 nm) and BG (400–600 nm) band passes shown in red, green, and blue channels, respectively. The fans are relatively 'green' in IRB colour, meaning that there are absorptions reducing the BG and IR brightnesses (Fig. 2). Many of these fans are well resolved by ∼18m pixel^{-1} spectral maps from CRISM (ref. 17); the spectra are consistent with the presence of Fe^{3+} absorptions in the BG region combined with Fe^{2+} absorptions in the IR region[34]. Mafic minerals with Fe^{2+} absorptions are common in dark regions of Mars, but the Fe^{3+} absorption might be produced by RSL activity. Precipitates such as chlorides are spectrally bland[33], so minor iron phases could be the major colorants in precipitates from briny water. However, even a dry mechanism for RSL might deposit iron-rich material on the fans.

If the abundant RSL in Valles Marineris are due to flowing water, then there must be much more water available near the surface in equatorial regions than predicted by equilibrium models[20–22]. The alternative is that there is some unknown active process on Mars that mimics the behaviour of flowing or seeping water.

Implications to future Mars exploration

The Committee on Space Research has defined 'Special Regions' on Mars as any regions experiencing temperatures >248 K for a few hours per year and with a water activity >0.5, safely below the limits for reproduction of terrestrial organisms[35]. Special regions need added planetary protection during future surface exploration or sample return. On the basis of the best available information up to 2010, the Committee on Space Research concluded that there are probably no special regions in the equatorial latitudes of Mars[35]. The discovery of RSL in equatorial regions suggests that it is time to reconsider this question. High salt concentrations may produce a water activity <0.5, depending on salt composition, but the surface temperatures do not rule out fresh water in some locations[36], so these are not necessarily eutectic brines with very low water activity.

More importantly, the surprising abundance of apparent water near Mars' equator should renew interest in the search for extant life. Although steep slopes with RSL cover a very small fraction of Mars' surface (<0.1%), there may be shallow water hidden from view over more substantial regions. Future remote sensing experiments designed to address this objective are needed to map the distribution of near-surface water on Mars[37], followed by landed investigation.

Methods

Intensive monitoring of equatorial RSL from MRO began with the discovery of RSL recurrence in the crater on the floor of Coprates Chasma in ESP_026905_1660 acquired 22 April 2012, after candidate RSL were seen in ESP_018123_1660 in the previous Mars year. A search for candidate RSL elsewhere in Valles Marineris and other equatorial regions, and for similar geologic settings (such as the crater on the floor of central Valles Marineris), produced a list of high-priority monitoring sites. There were also monitoring sites in the northern mid-latitudes that we observed during northern summer, one of which has been confirmed. The HiRISE team maintains a list of special requests for each two-week planning cycle, which are given high priorities in the process of resolving conflicts between imaging targets, resulting in many more observations than would be realized in the normal process. CRISM and Context Camera (CTX) typically ride along with HiRISE observations for coordinated observing. In addition, the CRISM team targeted some of the sites with large and extensive RSL during the CRISM-focused cycles, with HiRISE and CTX riding along. Calibrated HiRISE images are inspected for possible RSL using the HiView tool for rapid panning, zooming and stretching of these large images.

We have tried to get high-quality stereo coverage of each of the key monitoring sites, although not all are complete. Digital terrain models (DTMs) have been produced over eight of the sites, following standard procedures[38]. The DTMs in turn were used to orthorectify the images for better documentation of changes and production of animated GIF files, and to measure slopes (Supplementary Table 1). THEMIS brightness temperature images[13] at 100 m pixel^{-1} scale were used to extract surface temperatures of RSL slopes. Brightness temperature assumes unit emissivity and zero atmospheric optical depth, so these are minimum values for actual kinetic temperatures of the surface, and they were acquired in middle to late afternoon, past the peak daily temperatures except on steep west-facing slopes. The THEMIS images were found using the overlap tool in the Java Mission-planning and Analysis for Remote Sensing system[39]. CRISM column abundances of H_2O were extracted as described in ref. 26.

Data. All of the original spacecraft data used for this study are available from the Planetary Data System (http://pds.nasa.gov) and are also available from team web sites such as http://hirise.lpl.arizona.edu/, http://crism-map.jhuapl.edu/and http://themis.asu.edu/maps. Further materials such as animated GIFs of RSL sites are available from http://www.uahirise.org/sim/.

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Author contributions

A.S.M. and C.M.D. planned many of the HiRISE observations to search for and monitor the equatorial RSL. Image analysis to locate and track candidate RSL was performed by A.S.M. with significant help from C.M.D. and L.O. S.S.M. led production of DTMs and orthorectified images. M.C. assisted with DTM production and measurements, RSL reconnaissance and image analysis. A.D.T. extracted column abundances of water vapour from the CRISM data. S.B. contributed the thermal analyses. S.L.M., J.J.W. and L.O. contributed to CRISM observations and compositional analyses. N.T. contributed photometric analyses. All authors contributed to discussions, interpretations and writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.S.M.

Competing financial interests

The authors declare no competing financial interests.