

Martian hydrogeology sustained by thermally insulating gas and salt hydrates

Jeffrey S. Kargel* Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona 85721, USA
Roberto Furfaro Department of Aerospace and Mechanical Engineering, University of Arizona, Tucson, Arizona 85721, USA
Olga Prieto-Ballesteros Centro de Astrobiología–Instituto Nacional de Técnica Aeroespacial, Consejo Superior de Investigaciones Científicas, 28850 Torrejón de Ardoz, Madrid, Spain
J. Alexis P. Rodriguez National Astronomical Observatory of Japan, Mizusawa 023-0861, Japan, and Planetary Science Institute, Tucson, Arizona 85719, USA
David R. Montgomery } Quaternary Research Center and Department of Earth and Space Sciences,
Alan R. Gillespie } University of Washington, Seattle, Washington 98195-1310, USA
Giles M. Marion Desert Research Institute, Reno, Nevada 89512, USA
Stephen E. Wood Department of Atmospheric Sciences, University of Washington, Seattle, Washington 98195-1640, USA

ABSTRACT

Numerical simulations and geologic studies suggest that high thermal anomalies beneath, within, and above thermally insulating layers of buried hydrated salts and gas hydrates could have triggered and sustained hydrologic processes on Mars, producing or modifying chaotic terrains, debris flows, gullies, and ice-creep features. These simulations and geologic examples suggest that thick hydrate deposits may sustain such geothermal anomalies, shallow groundwater tables, and hydrogeologic activity for eons. The proposed mechanism may operate and be self-reinforcing even in today's cold Martian climate without elevated heat flux.

Keywords: Mars, heat flow, hydrous sulfates, clathrate hydrates, Aram Chaos.

INTRODUCTION

Resurfacing driven by hydrologic processes on Mars has been attributed to warm-wet climatic excursions (top-down processes) and elevated heat flow due to magmatism or impacts (bottom-up processes) (Baker et al., 1991; Parker et al., 1993; Malin and Edgett, 2000; Kargel, 2004; Marquez et al., 2005; Montgomery and Gillespie, 2005; Rodriguez et al., 2006). A warmer surface or crust may soften ice and cause ductile deformation of volatile-bearing strata, or it may generate groundwater and cause surface discharges.

Tens to thousands of meters of bedded sequences of hydrated magnesium sulfates, gypsum, jarosite, and other hydrated salts have been mapped from orbit by Mars Express OMEGA (Gendrin et al., 2005; Glotch and Christiansen, 2005) and investigated in situ by the Opportunity rover (Squyres et al., 2004). There are ~2-km-thick sequences of light toned layered rocks in Juventae Chasma and Candor Chasma in which OMEGA has detected gypsum or kieserite from top to bottom; some other light toned deposits are not obviously sulfate enriched. Outcrops of hydrates occur across Mars, particularly in layered deposits within the chasmata of eastern Valles Marineris and the chaotic terrains of circum Chryse. The fact that some sulfate deposits form layers exposed along scarps indicates that they may form stratigraphically extensive deposits. Other Martian hydrates may include methane and carbon dioxide clathrates (Prieto-Ballesteros et al., 2006).

Compared to most anhydrous silicates, anhydrous salts, and water ice, salt hydrates and gas hydrates have low thermal conductivities (Fig. 1) (Horai, 1971; Clauser and Huengas, 1995; Ross and Kargel, 1998; Prieto-Ballesteros and Kargel, 2005). They melt at eutectics or dissociate incongruently at low temperatures, which can cause volume change, brine generation, and landform development (Hogenboom et al., 1995; Kargel, 2004; Montgomery and Gillespie, 2005; Marion and Kargel, 2007). Hydrates have lower water-vapor pressures than ice, which extends hydrate stability across Mars beyond regions of ice stability (Feldman et al., 2004). Here we examine the effects of hydrates on steady-state heat conduction. We find that thick hydrate layers can produce thermal conductive anomalies and sustain hydrogeologic activity independently of regional volcanic activity or changes in climate, although a hydrogeologic event, possibly coupled to climate change, is needed to form the hydrates.

CRUSTAL THERMAL SIMULATION

We have modeled the thermal environments of two types of hydrate deposits, epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) and methane clathrate hydrate ($\text{CH}_4 \cdot 5.75\text{H}_2\text{O}$), both thought to be common on Mars (Feldman et al., 2004; Prieto-Ballesteros et al., 2006). Steady-state two-dimensional heat transfer models of the Martian crust simulate crustal thermal perturbations due to (1) hydrate lenses and (2) ice lenses in an ultramafic host (Fig. 2). Temperature was computed using a Matlab toolbox with the Laplace equation using

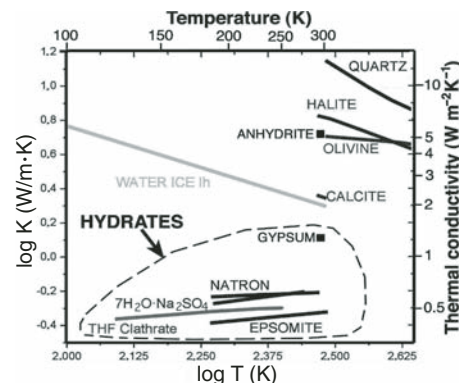


Figure 1. Thermal conductivity of hydrates and other minerals (for sources, see text).

an iterative finite element method. Each model region is homogeneous with temperature-dependent thermal conductivity and no internal heating. We imposed fixed temperature at the top and constant heat flux at the bottom. On the sides, we imposed the steady-state temperature profile for heat conducted through ultramafic rock distant from perturbing insulators.

Results of simulations using 4× estimated current global average Mars heat flow reveal large steady-state thermal anomalies for simplified geometries (Fig. 2A) and predict an annular thermal structure for epsomite crater infill of a complex crater (Fig. 2B). Water ice bodies (Fig. 2A, top) have little impact on geothermal structure, because their thermal conductivity is similar to the ultramafic matrix. In contrast, hydrates produce large geothermal anomalies.

Remarkable attributes of the models include: (1) high-amplitude variations in the depth of melting; (2) steep geotherms within the insulating lenses; (3) steep geotherms in the host adjoining the edges of the lenses, where heat leaks from below; and (4) perturbations to heat flow above the lenses, especially above their edges, up to the surface. Detailed phenomenology depends on the thickness, burial depth, and lateral extent of hydrate beds and rock matrix properties.

*E-mail: kargel@hwr.arizona.edu.

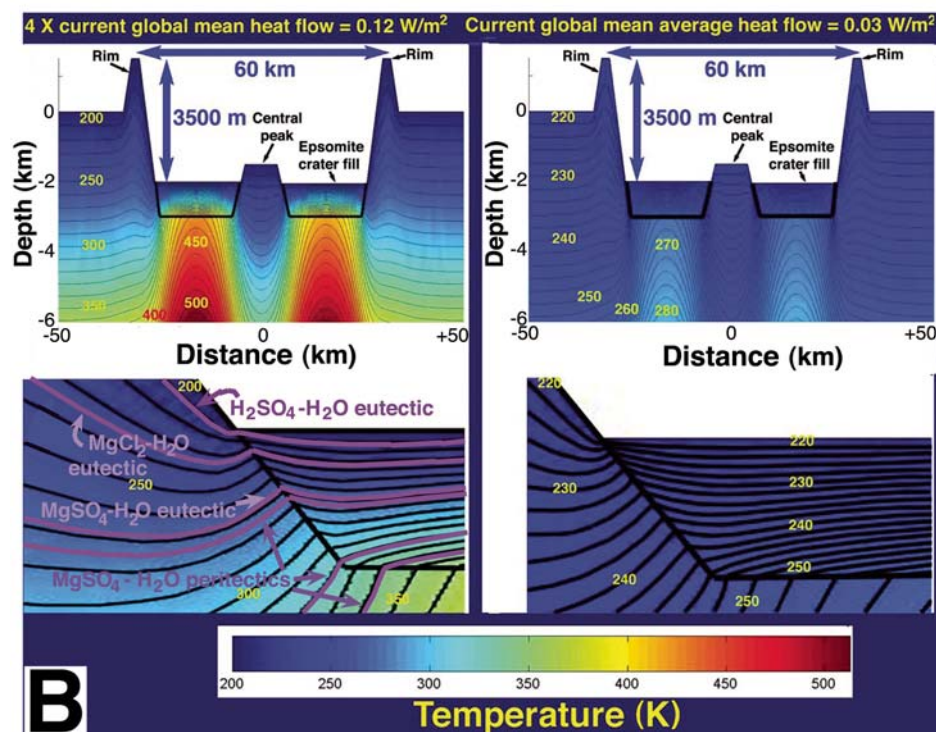
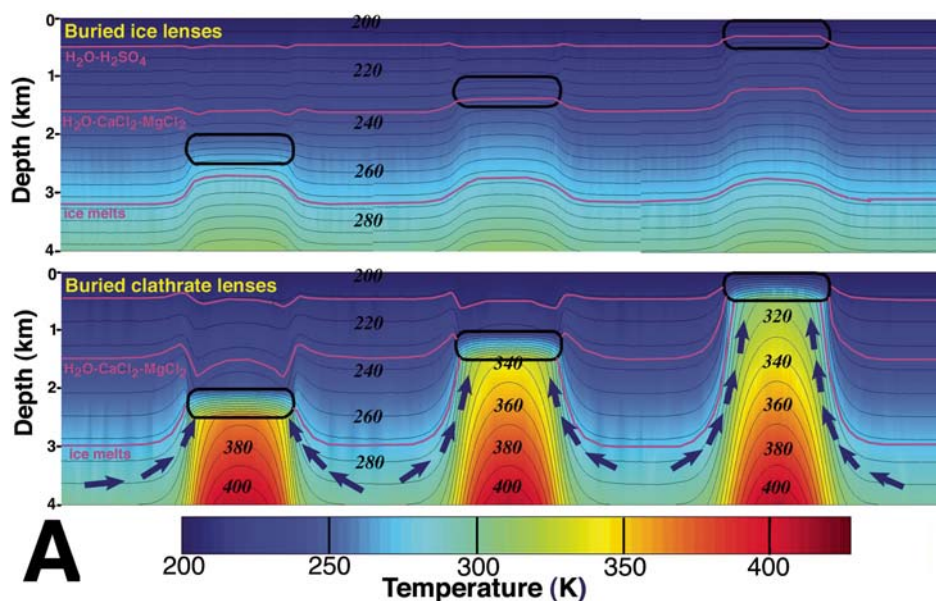


Figure 2. Steady-state conductive thermal anomalies associated with insulating lenses. Isotherms in Kelvin. **A:** Black ovoids in top two panels: lenses of ice or clathrate hydrate embedded in ultramafic rock matrix. Each lens is 20 km long, 0.5 or 1.0 km thick, and has its upper surface 2 km, 1 km, or 0 km deep. Vertical exaggeration ~13:1; panels cover 4 km × 200 km. Basal heat flow 0.12 W m^{-2} (estimated Mars global average during the Late Hesperian or Early Amazonian, ca. 2.6 Ga; Kargel, 2004; see also Spohn, 1991). Pink: key melting transitions. Blue arrows: schematic groundwater flow, which would naturally arise, given sufficient permeability, due to the thermal anomaly. **B:** Thermal anomalies due to 1 km of epsomite crater infill. Left pair of panels: surface temperature 200 K (low-latitude temperature for reduced solar luminosity ca. 2.6 Ga), heat flow 0.12 W m^{-2} (Mars' global average ca. 2.6 Ga). Right pair of panels: surface 220 K (for modern climate at low latitudes), heat flow 0.03 W m^{-2} (modern average, scaled from Earth's by planetary radius and density). Bottom pair of panels: crater wall detail showing heat leak around insulator edges and highlighting some aqueous eutectics and peritectics. Thermal conductivities (k , $\text{W m}^{-2} \text{ K}^{-1}$) for nonporous materials are as follows (temperature, T , in Kelvin). Ultramafic rock: $\log k = 1.50 - 0.35 \log T$. Ice: $\log k = 2.7154 - 0.97520 \log T$. Methane clathrate: $\log k = -2.23337 + 1.44624 \log T - 0.27371 (\log T)^2$. Epsomite: $\log k = 0.44$ (see text for sources).

Real-world complications include compositional and thickness heterogeneities of deposits and complex subsurface structure. If brines are produced, heated fluid advection could modify temperature fields and heat flow. Smaller perturbations than modeled would be produced by lower hydrates (e.g., gypsum or kieserite) or hydrates dispersed within conductors. Thermal conductivity influences on Martian hydrogeology also are interlaced with variations in heat flow and climate through time, e.g., due to episodic volcanism (Fairén et al., 2003) and epochal and cyclic oscillations of obliquity and greenhouse gases (Baker et al., 1991; Clifford, 1993; Touma and Wisdom, 1993).

GEOLOGIC PROCESSES CONTROLLED BY PHYSICAL CHEMISTRY

The attainment of warm, steady-state crustal temperatures due to insulation is a key distinction with respect to heating by elevated heat flux, which provides geologically brief high heat flow due to igneous activity, impacts, or crustal thinning. Our proposed mechanism can operate in steady state for eons (responding mainly to decay of long-lived radionuclides), but also may produce interesting dynamic activity. Closed-system incongruent melting and dehydration involves a net volume increase including the brine. Open-system dehydration (or incongruent melting with brine expulsion) results in reduced volume of remaining salts. After water removal, dehydration of gypsum to anhydrite produces a 39% volume loss, epsomite to hexahydrate a 12% loss, and epsomite to kieserite a 64% loss; the dissociation of type 1 CO_2 clathrate to ice incurs a 16% loss. Confined hydrates may undergo closed-system hydraulic pressurization and volume increase during incongruent dissociation; however, if the fluid escapes, sink holes, graben, debris flows, and fluvial activity may result.

Depending on hydrologic circumstances, hydrate insulation may be self-reinforcing by evaporative precipitation (in hydrologically closed basins) or self-dispersing due to dissolution (in open basins). Hydrothermal circulation may reduce the thermal anomaly and produce a cooler steady state or cyclic activity. The time required to renew thermal equilibrium subsequent to an arbitrary cooling event is estimated by the hydrate layer's diffusion time scale, $\tau = d^2/\alpha$, where d is the layer thickness, the thermal diffusivity $\alpha = [k/(\rho C_p)]$, ρ is density, and C_p is heat capacity. For a 1-km-thick layer of epsomite, $k \approx 0.5 \text{ W m}^{-1} \text{ K}^{-1}$, $\rho C_p \approx 2.5 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$, $\alpha \approx 5 \times 10^7 \text{ m}^2/\text{s}$, and $\tau \approx 1.6 \times 10^5 \text{ yr}$; including rewarming of cooled rock underneath, τ may be several times greater.

Additional heat is consumed by dehydration. The enthalpy of epsomite relative to the enthalpy of water in dilute solution is -15.33 per mole of water. Summed with the heat of vaporization of

ARAM CHAOS: HYDRATE-INDUCED HYDROGEOLOGY

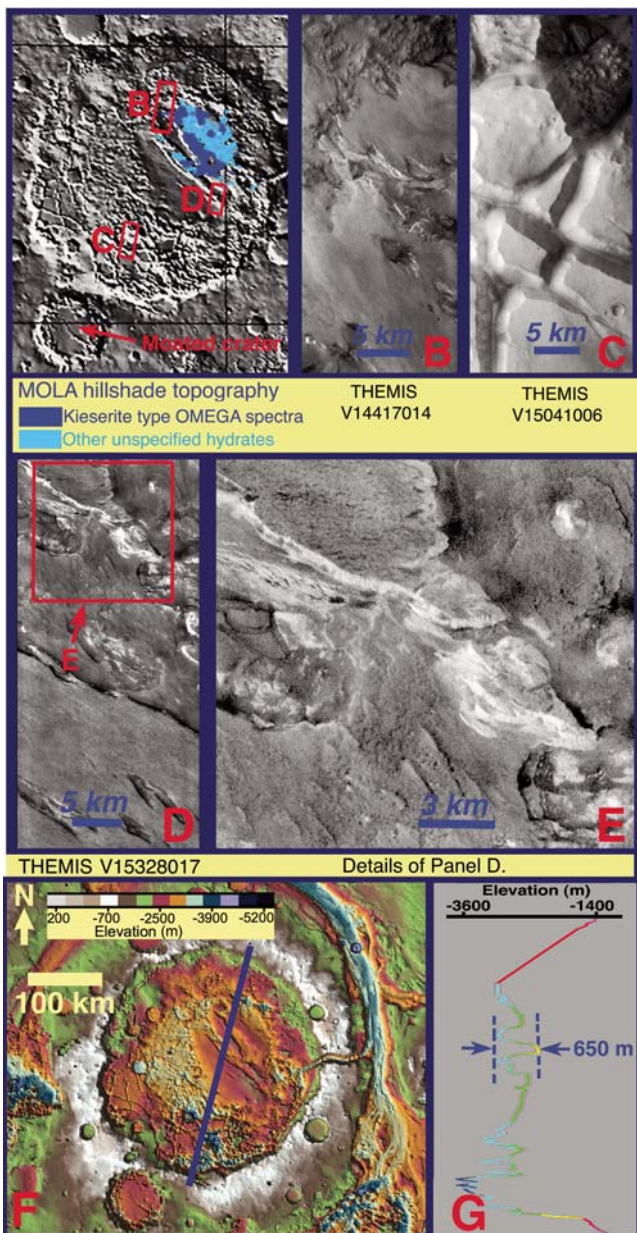
Aram Chaos is the disturbed fill, 300 km across, of an impact crater. Fractures, pits, and hummocky erosion mark two generations of bedded and massive infill, including a light-toned layer sequence >650 m thick, where OMEGA has identified hydrated sulfates (Fig. 3) (Gendrin et al., 2005; Glotch and Christensen, 2005). Minerals in Aram Chaos include kieserite type and unspecified other hydrates, as well as abundant hematite (Gendrin et al., 2005), which may be an oxidized alteration product of ferrous iron sulfate hydrates (Marion et al., 2006). The infill may have resulted from either (1) clastic and chemical deposition in a crater lake (Glotch and Christensen, 2005), or (2) interstitial precipitation of hydrated salts from saturated groundwater permeating clastic or other infill. In terms of our model, the difference is significant, because effective heating arises from beds of pure insulators (thick beds or multiple thin beds) rather than intimate granular mixtures of conductors and insulators.

Chaotic terrain morphologies in Aram Chaos are consistent with an initial stage of doming of the infill (Glotch and Christensen, 2005) followed by release of fluids and subsequent subsidence. This geologic history is consistent with the salt dissociation hypothesis for flooding suggested by Montgomery and Gillespie (2005), our model of a thermal anomaly produced by thick hydrated salts (Fig. 2), and the volume increase caused by hydrate dissociation and then volume decrease after release of evolved brines.

The sulfates and associated hematite occur mainly in one of the layers of the infill's upper unit; these fractured and/or etched rocks appear to have been deposited after the first episode of fracturing of the underlying basal unit (Glotch and Christiansen, 2005; Gendrin et al., 2005). Thus, at least two cycles of deposition and collapse have occurred. A rim-breaching channel extends from Aram Chaos into Ares Vallis, and debris-flow deposits mantle some troughs of Aram Chaos (Kargel, 2004), consistent with hydrate dissociation and fluid expulsion during the first cycle. The upper interior hydrate-bearing unit may represent upward mobilization and recrystallization of sulfates (then further dehydration) derived from the lower unit. The concentric morphological zonation of Aram Crater's interior (Fig. 3) may represent dehydration and collapse due to annular deposits and thermal structure (Fig. 2) or to annular variations in permeability related to impact fracturing and brecciation of the substrate (Rodriguez et al., 2006).

The origin, distribution, and evolution of salt hydrates are important. Ice-equilibrated brines generally precipitate higher hydrates, e.g., $\text{MgSO}_4 \cdot 11\text{H}_2\text{O}$. The abundance of kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) in Aram Chaos could reflect (1) climate-driven desiccation from primary higher

Figure 3. A: Complex disintegration and collapse deforms crater deposits, some of which are mapped as kieserite and other hydrates (blue overlays, from Gendrin et al., 2005) within Aram Crater and a nearby moated crater. B–E: Disrupted bedded deposits include light-toned rocks within or near area where sulfates and other hydrates have been mapped by OMEGA. F: Digital elevation model highlights annular topographic structure. Blue line is Mars Orbiter laser altimeter (MOLA) topographic profile line shown in G. G: Topographic profile across eroded interior dome of layered rocks in Aram Chaos. Layered sequence is minimally ~650 m thick in the hydrate region.



water at 273.15 K, the enthalpy of water molecules in epsomite relative to water vapor gives a heat of hydration of -60.37 kJ/mole of water. Depending on which salts, phase states, and temperatures are compared, different values are obtained. Dehydration to water vapor of a 600 m column of epsomite consumes 1.7×10^{12} J m^{-2} , equivalent to 1.8 m.y. of current global average Martian heat flow. The dehydration of geologically significant deposits requires a lot of energy, but the geothermal flux over tens of millions of years is much greater. Thus, repetition of hydration-dehydration cycles is thermodynamically possible if water remains accessible.

In closed basins, transport of solutes from adjacent terrain and precipitation of additional hydrated salts may reinforce the insulation. If the thermal anomaly becomes excessive, the

deposit's average hydration state will decline, thus reducing insulation. If water remains available, salts may rehydrate (Hogenboom et al., 1995), and, as global heat flow gradually declines and the crust cools, they may acquire higher hydration states, thus tending to self regulate. Lacking losses of water from the system (water is recycled into hydrates or is replaced by water added from elsewhere, e.g., the atmosphere or aquifer), then oscillatory behavior can occur. Hydrates may repeatedly form, heat, dissociate, cool, rehydrate, and reheat. If dispersal of solutes occurs or if rehydration potential is lacking, especially with dissociation of gas hydrates, these systems may self-destruct in one event. Continuing slow dissociation of methane clathrate may explain Martian atmospheric methane (Formisano et al., 2004; Prieto-Ballesteros et al., 2006).

hydrates, (2) geothermally driven desiccation, or (3) primary deposition by hot aqueous solutions or cold solutions of high ionic strength, perhaps acid sulfate brines (Marion and Kargel, 2007). Polyhydrated sulfates, e.g., hexahydrate, epsomite, and gypsum, have been detected in similar nearby terrains (Gendrin et al., 2005), so dehydration may be likely in Aram Chaos. In any case, the current low-latitude Martian climate favors dissociation of higher hydrates to low-hydration phases, e.g., kieserite (Feldman et al., 2004).

Fitting a curve to the upper, hydrate-bearing infill unit of Aram Chaos (Glotch and Christensen, 2005) and the underlying tabular, fractured, pitted unit reveals a minimum 20% average volume loss of crater infill. This is attainable by incongruent melting and dehydration, which likely would have produced brine-filled karstic cavities.

Areas of potential application of our model are widespread. Light-toned units similar to those in Aram, some of which also contain abundant sulfates, occur at Aureum, Iani, and Arsinones Chaos, in several interior layered deposits in Valles Marineris, and in Meridiani Planum (e.g., Gendrin et al., 2005; Glotch and Rogers, 2007). These areas have similar chaotic terrain or etching and/or pitting and erosion, suggesting similar deposits and modification processes. Some paleohydrologic models suggest that hydrates may underlie much of the northern plains and may be patchy but widespread in the highlands (Baker et al., 1991; Kargel, 2004).

CONCLUSIONS

Thermal insulation due to hydrate-rich parts of the Martian crust may support shallow groundwater even without extreme solute-induced freezing-point depressions, climate warming, or high heat flow, although these dynamics also are part of the Martian montage of processes. Eruptions of water, dissolved salts, and gases may occur especially above the edges of buried hydrate bodies. Insulation-activated debris flows, hot and cold springs, surface icings and rock glaciers extruded from the crust, evaporitic mounds, mud volcanoes, mud diapirs, pingos, collapse structures, salt domes, and salt glaciers may be current active phenomena in hydrate-rich regions. Beneath hydrate insulators, low-grade rock metamorphism and release of metamorphic gases, e.g., methane (Oze and Sharma, 2005) or sulfur dioxide, are likely. Hydrate insulation heating might support moist subsurface conditions, possible life, and transfer of subsurface life or frozen remains to the surface. The proposed mechanism requires initial formation of hydrates, so this mechanism does not circumvent major paleohydrology or argue against warm climate excursions; however, it does provide a novel mechanism coupling bottom-up and top-down hydrogeology and

extending hydrogeologic activity and perhaps life into more recent, cold climatic periods in areas where thick hydrate deposits exist.

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