Sinuous rilles and permafrost on a wet Moon

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Abstract (150 word limit)

About 200 rilles with remarkably Earth-like meander patterns extend for 100s of km across the lunar surface. Flowing lava is the only candidate agent on a bone-dry Moon but one impossible to reconcile with absence of large volumes of downstream-drained lava and many other observations. An alternate mechanism is hot volcanic gas melting meandering tunnels through permafrost ice and vanishing along with its meltwater. This explains downstream absence of lava but is impossible on a dry Moon. Here I show that thick permafrost ice is mechanically possible on a wet Moon and that hot-gas/permafrost melting mechanisms can replicate most photo-geologic details. Current origin models cannot produce the required truly wet Moon but lunar fission as a blob of volatile-rich Earth’s mantle driven by Earth-core formation can produce one. This largely forgotten but potentially viable model can explain the minor rille mystery and other, more fundamental lunar problems.

The Moon’s sinuous rilles are a minor but enduring mystery. Their meander patterns, remarkably like those of terrestrial rivers, require a fluid agent with lava as the only apparent candidate on a dry Moon. An interpretive atlas¹ (Harwitz) catalogues 195 examples, the longest is 566 km, the largest near its source is ~7 km wide and ~700 m deep (Fig. 1). Two competing origin models.²,
Drained lava tube models have strong support from collapse pits and uncollapsed segments much like terrestrial examples but their continuous passage through lava units that differ in age by > 2 Ga makes them impossible. 2) Channel erosion by surface lava flows can explain the age problem by cutting across multiple aged units to but the collapse pits require lava tube origin for some segments. Neither model explains the almost complete absence of any downstream-drained lava. Authors still struggle with these and other troublesome details. This study proposes an outrageous alternative: that rilles are collapsed tunnels melted through permafrost ice by hot gas diffusion from distant volcanic sources. Photo-geologic details are the basis of a proposed model in which meltwater ponds in these tunnels create the meandering paths as they drain through the floors to leave no downstream evidence. Given a wet Moon for which there is increasing evidence thick permafrost is possible based on terrestrial examples, thermal data, and current geophysical data. The tectonic history of central Procellaraum suggests an age and an origin: melting by hot gas expelled during that basin’s climatic crustal collapse at ~ 1 Ga. The source of these and many other lunar problems may be the dry Moon paradigm. Since Apollo days it has forced lunar origin models to focus on only one end of a spectrum of excess angular momentum possibilities; the other or fission end remains essentially unexplored. An updated version from that end would begin in the early solar system when a small but still giant impact homogenized the Earth while spinning it almost to the limit of rotational stability. Much later core formation accelerated it through a differentiated body’s unstable rotation for viscous separation of the Moon as a blob of volatile-rich mantle. Immediate trapping in close orbit allowed tidal resonance to transfer the excess angular momentum to the Sun and develop a new dry crust within a tidally generated, roasting atmosphere. At orbital escape, angular momentum was near modern values, near-surface volatiles were depleted, the Moon’s isotopic ratios were nearly identical to Earth’s mantle, both the iron deficiency and nearside-farside asymmetry were explained and the dry exterior over a wet interior was that required by the hot gas/permafrost model.
The greatest concentrations of all sinuous lunar rilles are in central Procellarum’s Aristarchus Plateau, the Harbinger Mountains / Prinz area (Fig. 1 inset & Fig. 2) ~ 150 km to its E and the Marius Hills ~ 350 km to its S. This paper focuses on the plateau’s young, crisp-edged rilles superposed upon or terminating in ~ 1.2 to ~ 1.0 Ga mare lavas1,15 (Hurwitz, Heisinger). Relatively young rilles occur in other regions, an example is Hadley Rille at the Apollo 15 site in Mare Imbrium, ~ 1,250 km to the NE. In many areas, older sinuous rilles occur as degraded depressions that fade into the local surface. The N-flowing member of a pair that flowed in opposite directions from nearly coincident source craters is an example (Fig. 1-E).

Almost all rilles taper downstream in width and depth to disappear by merger with their regional surface; none show clear evidence of surface or sub-surface downstream-drained lava. Some continue unchanged through lava units with greatly different ages: Rima Sharp is mostly in a 2.14 Ga mare unit but both ends are in 1.33 Ga mare units; Schroeter’s Valley (Fig. 1) is mostly in a 3.7 Ga mare unit but ends in a 1.14 Ga mare basalt1 (Hurwitz). Sinuosity (length along the meandering channel / straight line length) ranges from 1.03 to 2.09 with a median of 1.19. The value for > 2/3 of the rilles is between 1.3 and 1.51 (Hurwitz). Fig. 1 and Online Suppl. #1 include higher sinuosity examples.

Two classes of rilles are based on characteristics of roof failure, separable at widths of ~1 km. That approximate value is based on photo-geologic characteristics, the width distinction used in some of the catalog’s tables1 (Hurwitz) and the strength limit at lunar gravity for rock arches with thickness comparable to that in collapse pit exposures20 (Blair). Greater spans up to 5 km are possible but those 500 m thick roofs are difficult to reconcile with collapse-pit exposures or photo-geologic details.

**Class 1 rilles** are < 1 km wide and comprise ~ 88% of the population1 (Hurwitz). Their common characteristic is a floor covered with roof debris. This appears on floors of young rilles but talus aprons conceal it as age increases. Unconnected segments and natural bridges occur in some rilles, in others ~ 100 m diameter collapse-pits expose ~ 50 -75 m roofs of layered basalt above downward expanding cavities5,6,7 (Robinson-M.S., Kaku, Wagner). As described below, a special sub-class is restricted to the floors of Class 2 rilles (Fig. 1).
Class 2 rilles have widths > 1 km. Nearly identical surface texture on both a broad, flat floor and the adjacent rim is their diagnostic characteristic (Figs. 2 and 6). Crater count ages for Schroeter’s Valley show rim and floor textures are identical with ages of 3.65 (+/- 0.05) Ga\(^{21}\) (Zhang) and 3.61 (+0.07/-0.12) Ga\(^{22}\) (Li) respectively. That valley’s geometry leaves ~175 km\(^3\) or ~1/3 that of Lake Erie as volume missing from the plateau. Rima Prinz A\(^{23}\) (Hurwitz 2012) is missing ~17 km\(^3\) (Fig. 2). Wider members of this class have a single Class 1 rille extending through most or all of their length, hugging one or the other bounding walls and deeply embedded into their planar floors (Fig. 1B and Suppl. 2, &E).
Fig. 2. Examples of different rille classes in the Prinz Crater - Harbinger Mountain region. Class 1 rilles are K and distal ends of some Class 2 rilles. Class 2 rilles (B, C, D) host a special Class 1 rille within their walls; they began as Class 3 depressions in buried craters before developing exit channels to become sources of Class 2 rilles. Prinz Crater and E are Class 3 features. Suppl. Fig. 2 explains the seemingly impossible transit of D’s Class 1 rille through E while its Class 2 rille interrupted its passage. Arizona State University Image Library

Class 3 features are steep-walled, closed depressions that have no visible exit channel but share Class 2’s characteristic floor and rim textural similarity. Shapes vary from circular to irregular, to localization along fractures. Rille E is a fracture controlled example aligned along the E-W
trending Prinz system (Fig. 2). Both Herodotus and Prinz Craters are technically Class 3 features but are the probable source craters for their adjacent 3 largest sinuous rilles. Many Class 2 rilles appear to have started in similar ways but found surface exit channels. Rilles D, I, and H in Fig. 2D and Suppl. # 2 are examples.

**Permafrost**

This proposed rille model requires thick sheets of permafrost ice. In terrestrial cold regions permafrost can be in soil, rock or ice, just below the summer-winter freeze-thaw zone, typically at depths of 1 - 2 m. Temperature increases downward from the regional annual average at a gradient dependent on conductivity and heat flow until it reaches the 0º C isotherm. On time scales of $10^2$ s to $10^3$ yrs that isothermal surface migrates downward to establish a new gradient at an equilibrium depth to transport geothermal heat at the rate supplied from below $^{10}$ (Washburn). The maximum known thickness of terrestrial permafrost is 1,440 m in Siberia, probably a modified equilibrium relic of Pleistocene conditions that were about 10º C colder than that region’s present annual average temperature of -15.5º C. At Prudhoe Bay, Alaska, permafrost reaches 629 m while borehole data and estimated Pleistocene temperatures indicate the freezing isotherm should have reached 687 m in $7.75 \times 10^5$ yrs $^{11}$ (Lunardini). In a Polish sedimentary basin, the Pleistocene depth should have reached 550 m, based on similar borehole-based calculations and an assumed Pleistocene temperature of -10 ºC, approximately the same depth found in local drill holes $^{12}$ (Majorowicz). On the Moon, heat probes at mid-latitude Apollo 15 and 17 sites, show that diurnal temperature oscillations fade into annual average temperatures of -18 to -24 ºC at depths of ~ 1 m $^{24}$ (Langseth) or slightly warmer than Pleistocene Siberia.

In this proposal, lunar permafrost began its accumulation in young mare basalt by trapping upward migrating water vapor at the extant 0 ºC paleo-isotherm, interpreted as the ~50 – 75 m roof thickness exposed in collapse-pits $^{5, 6}$ (Robinson,M.S., Kaku). That depth combined with the Apollo heat probe surface temperatures would yield a crude estimate of ~ 0.25 – 0.4 ºC/m for the mid-latitude, near-surface, paleo-geothermal gradient in mare basalts. As new ice accumulated to lift the roof as a broad ice laccolith or giant pingo while the isotherm remained at the bedrock contact (Suppl. Fig. 3). If the vapor supply was episodic in time or migrated in irregular fashion, the isotherm migrated downward through bedrock to become the future roof of a new, deeper ice
sheet when vapor percolation resumed. This mechanism for creation of Christmas-tree ice
laccoliths may have played a significant role in the origin and isostatic survival of broad, low-
gradient, shield-like domes of the Aristarchus Plateau, Harbinger Mountains, and Marius Hills.25

Spudis.

Thick ice sheets on the Moon are compatible with existing geophysical data, especially radar for
which ice is almost as transparent as empty space. The SELENE radar sounder found missing
echo returns, interpreted as cavern floors, at depths of ~100 to ~250 m for ~10% of locations in
Procellarum and other western mare basins14 (Koyabashi). In the Marius Hills, the radar recorded
linear zones of no shallow returns near collapse pits located on 10-20 km-wide, 100 km–long
negative gravity anomalies6 Kaku. These large features far exceed the 5 km span limit for 500 m-
 thick rock-arched caverns at lunar gravity20 (Blair), the obvious tunnels must be in some much
larger mass of low density material. Alternatives are tunnels of unknown origin in low density
igneous rock or transparent tunnels in permafrost ice with the underlying ice-bedrock contact
providing the radar echoes.

Interpretations and explanations

Fig. 3. Idealized half-section of a Class 1 permafrost tunnel. The input-output or
hot gas-drainage equilibrium explains why rilles have no volume problems at
their termini. The text explains roof rise by permafrost growth while the freezing
isotherm remains at the top of bedrock.
The proposed hot-gas/permafrost mechanisms explain the major problems of lava-based models. 1) Permafrost can develop across multiple rock units independent of age. 2) Absence of downstream lava or excavated waste at rille termini is the result of an input-output, volumetric equilibrium (Fig. 3). 3) The characteristic rille sinuosity is the mechanism for maintenance of that equilibrium. It increases the exit channel’s length within the trailing tunnel so that total channel loss for a given floor permeability /km matches the rate at which the advancing face creates new tunnel length. When floor permeability changes with tunnel advance through or along fracture zones, sinuosity makes abrupt changes (Suppl. #1). 4) Similarity of Class 2 floor and rim textures is the result of gentle roof subsidence immediately behind the slowly advancing melt face (Fig. 4). 5) Special Class 1 rilles follow a wall of their Class 2 hosts because the roof’s lateral spreading along the arcuate face creates a transient linear cavity for the exit channel along the border fault. 6) The special Class 1, single, non-branching rilles that extend the entire length of the largest Class 2 rilles emphasize their critical role for all rilles, they are the power link between source and active face. For Class 2 rilles, the exit channel uses residual heat to etch its path into the planar floor, when roof subsidence is complete it remains as a tunnel to power the Class 1 and Class 2 tandem advance.

Cross-sections, elevations and gradients of most rilles are propagated downstream from those established by the heat supply in the source cavity (Fig. 5). At inception, the hot gas melts upward through increasingly colder ice to terminate at the bedrock ceiling and condense on that coldest surface. Some condensate drops to form a meltwater pond, hereafter condensate is assumed to be part of meltwater. At the roof, surface tension and gravity transport the condensate to the downslope edge and initiate melting advance in that direction. As this continues, a rearward sloping face develops in permafrost to drain into the pond while a slightly warmed roof always trails that front to maintain it as the system’s coldest point and the focus of downslope tunnel advance.
Fig 4. Mechanics of Class 2 rille advance. As described in the text, the wide tunnel’s slow melting advance allows the subsiding roof to sag gently onto the floor. Lateral spreading along the arcuate face creates a transient cavity along the border fault in which the exit channel develops its characteristic sinuosity. Final subsidence transforms the rille into a tunnel as the critical link for hot gas diffusion to power face advance.

Continuing heat input also expands the meltpond laterally and downward (Fig. 5) to form the active face with a height to width ratio of ~ 1:10, the same approximate ratio preserved in the rilles (Hurwitz). The pond’s ratio of downward to forward melting rates establishes the floor gradient while its lateral melting produces the planar tunnel floor. That gradient, along with input volume and floor permeability, determines how far the pond back along the tunnel the exit channel can extend and with that, the sinuosity needed to maintain volumetric equilibrium.

Roof gradients steeper than floor gradients make ceiling-floor convergence an integral part of downslope advance. If heat input and resulting face area remained constant, the tunnel would increase downstream in width and depth but rilles do the opposite. Heat supply and meltwater production must have declined more rapidly than downslope advance drove ceiling-floor convergence. Lava-based models explain the taper by downstream decrease in velocity,
turbulence, and erosional efficiency\(^1\) (Hurwitz).

Secondary processes modify the overall direction of downslope advance. Multiple fracture sets in the roof slabs can torque that direction. Original fracture-related thermal conductivity differences changed the \(\mathbf{C}^0\) depth and thus warped the local ceiling depth and future direction of its downslope advance. The resulting rille path is a series of loosely connected linear segments that advance down the regional topographic slope with zig-zag deviations of 10\(^\circ\) to 30\(^\circ\). The best example is Schroeter’s Class 2 valley (Fig 1 and Online Suppl. # 1).

Upstream halves of the three largest rilles are exceptions to this dominant downslope control. These followed linear but somewhat zig-zag paths at high angles to the topographic slope before passing through a big bend to join the downslope parade (Figs. 1 & 2). High rates of early stage, hot-gas input followed fracture systems in the underlying deep bedrock to override the roof gradient’s downslope control. When heat input declined sufficiently, Class 2 control reverted to downslope roof control modified by its local fracture deviations (Suppl. #1).

Another style of deep bedrock fractures produced the greatest concentrations of both types of rilles and the largest three examples. Ancient impacts for Herodotus and Prinz Craters drove deep fractures into Proceirllarum’s anomalous KREEP and volatile-rich crust. Combined with locations near the basin’s center, these were prime sites for the greatest rates of water percolation and accumulation of the thickest permafrost. When a later pulse of maximum rate of hot gas release followed those fractures through the crater floors, the meltwater pond and meltwater formed very large Class 3 depressions within the less permeable crater rims. Instead of finding surface escape paths, the large flow of hot gas followed deep fractures beneath the rims to become sources for the largest rilles and for their greatest concentrations. The same escape process operating at surface levels made many Class 3 depressions the source craters for Class 2 rilles.

An example of this Class 3 to Class 2 evolution, and much more, is the “frying pan” crater with a Class 2 rille as its “handle.” As shown in Fig. 2 and described in Suppl. #2), the frying pan began as a Class 2 rille evolved from a Class 3 crater depression to begin downslope advance along
with its hosted Class 1 rille. At the intersection with the older “tongue depressor” the Class 1 rille continued to melt through intact ice beneath the floor whereas the ice at the Class 2 rille’s elevation was already melted. It halted advance but resumed it in intact ice on the far side powered by hot gas through the Class 1 tunnel, still visible as a sag in the old floor.

Fig. 5. Determinates of tunnel geometry. Gradients, cross-sections and elevations established by hot gas in the source cavity propagate downstream to control the geometry of tunnel advance as described in the text.

**Tectonics, age and origin**

Clues to the age and driving tectonics of the greatest concentrations of sinuous rilles reside in Central Procellarum’s Aristarchus Plateau, the adjacent Harbinger Mountains-Prinz uplift and the Marius Hills Dome. Their mare-related history began at ~ 3.8 Ga with flows scattered across much of the lunar nearside; by ~ 2.0 Ga most of that activity was concentrated in Procellarum and ended with a burst of tectonic activity and mare flooding at ~ 1.0 Ga. Those penultimate mare events began with crustal break-up and definition of the Aristarchus Plateau’s ~ 180 x 200 km rectangular shape by NE and NW trending fault systems (Fig. 6). As the plateau rose, possibly aided by permafrost growth, younger lavas were deposited on its flanks, tilted...
slightly and then abandoned. The final events began with tilting to the NW and crustal foundering at ~ 1.14 Ga. The plateau’s NW end broke off for additional tilting as the Agricola Mountain block of upended crust while young basalts unconformably covered the lower flanks and lower elevation crustal exposures. The era of major mare tectonism ended with extrusion of the youngest lavas at ~ 1.0 Ga with the plateau having most of its present large-scale appearance with the exception of Aristarchus’s impact at ~ 175 myr\(^26\) (Zanetti).

The permafrost-related history began during the initial crustal breakup. Increased percolation of water vapor caused geologically rapid accumulation of thick permafrost to aid both the plateau’s isostatic rise and its physical doming. Most of the plateau’s young rilles are either superposed upon or terminate in the 1.14 Ga flank units that were part of the NW tilt and foundering, a rare few are superposed on the 1.0 Ga lavas. Most of the region’s young rilles originated with the final tectonic upheavals just before or during that 140 myr time gap. The low density ice that helped form the three domal regions\(^{25}\) Spudis, then aided their isostatic survival. Hot gas displaced by lava filling voids in deeper ends of the tilted blocks migrated up fracture pathways to power local melting of permafrost tunnels and rilles. Most gas came up along edges of the tilted plateau to form small rilles but the deeply fractured roots of Herodotus Crater provided an escape path beneath its rim for the Cobra Head to become the non-lava source for Schroeter’s Valley (Fig. 1A). Similar processes occurred for Prinz Crater: the rising Harbinger Mountain dome tilted that crater\(^{27}\) Jawin for lavas to flood the SW half to the rim (Fig. 2) while the displaced gasses migrated through deep fractures beneath the rim to become the NE ring of sources for the Prinz family of rilles.
Fig. 6. Oblique view across the Aristarchus Plateau. Herodotus is the ancient, 38 km crater whose deep fractures probably channeled hot gas for Schroeter’s Valley. The Agricola Mountains are a block of plateau crust, upended and foundered in a sea of ~1.0 Ga mare basalt. Archimedes Crater at 40 km and 175 myrs is the youngest significant feature. Arizona State University Image Library.

Discussion

If even partially correct, these permafrost models and explanations suggest the Moon contains vast amounts of water. Surviving ice on both sides of the plateau above Schroeters’s Valley floor plus unknown amounts at elevations beneath it may have a volume that approximates Lake Erie. Access through the wall of a Class 1 tunnel wall could be the starting point for a lunar base. Nuclear powered melting could form smooth-walled cavities as containers for fully pressurized bladders as large volume living spaces. Abundant water would supply all human needs, perhaps
even for fish ponds and gardens beneath artificial lights. Hydrogen/oxygen fuel would be abundant while condensate minerals from the roof or entrained in ice would provide many elemental requirements while the thick basaltic roof protected the base from solar storms and meteorite impacts.

A case for Martian permafrost grows with evidence of former wet climates, lakes and groundwater channels (Fassett, Dundas). The planet’s orbital location suggests it began with much more water than the Earth: ice in volumes equivalent to many Earth’s oceans may comprise some or even most of the sedimentary component of its older crust. Some of these lunar permafrost mechanisms might apply to Mars as examples of that process not complicated by precipitation and other atmospheric complications.

The preceding data and interpretations argue that a solution to the rille mystery may exist but only outside the dry-Moon paradigm. Two paths seem open: either find a non-lava, non-permafrost model that can explain the observations or accept the existence of extensive lunar permafrost ice, test and correct the proposed models with simulations, existing data and new probes while searching for an origin model that can produce a much wetter Moon. A variety of new data support such a Moon (Hauri, Robinson –K, Karato, Sarafian); a recent giant impact model forms one from the inner ring of its impact-produced orbiting disk (Nakajima). Like almost all current models, this focuses on the maximum or excess angular momentum (A-M) end of a spectrum of giant impact possibilities. “Excess” is the amount beyond that in a differentiated Earth spinning at its limit of rotational stability, the rate at which equatorial centrifugal force equals gravity.

At the other end of that spectrum, fission models (Ringwood, Wise) remain essentially unexplored. The A-M/g in the Earth-Moon system is ~ 4X that of any other terrestrial planet; fission must at least double that amount before dissipating the excess. In the 1960s the generally accepted lunar origin paradigm was Urey’s model of a captured survivor of the early solar system. This could import the ~ 4X excess and had no requirement for supporting geologic evidence; fission had only limited geologic evidence in its support and could suggest only vague mechanisms of ways to dissipate the excess A-M. As a result it acquired a stigma of mechanical impossibility that precluded its obvious explanation for similarity of returned Apollo samples.
and terrestrial rocks. That evidence also doomed the capture model and left lunar science for several years with no origin model. Relief came in 1975 with the giant impact model\textsuperscript{35} (Hartmann) that became the ruling paradigm for four decades. Early versions used very large giant impacts to inject a great excess of A-M before reassembling the Moon from part of that debris cloud. The excess escaped along with the cloud’s remainder but none could offered a credible explanations for the isotopic absence of any traces of the impactor. In 2012 a new mechanism of tidal resonance transfer of AM to the Sun showed models allowed even greater amounts of excess A–M\textsuperscript{18} (Cuk and Stewart) and produced a Moon relatively free of impactor contamination. This soon became the revised paradigm but all new models are unable to explain both volatile and isotopic signatures\textsuperscript{36, 37, 38} (Stevenson, Melosh, Jacobsen). If these large excess models are generally accepted the same reduction mechanism should be available to reduce fission’s far smaller amounts but illogically, that Apollo era stigma survives to preclude serious consideration of such models\textsuperscript{39} (Wise, 2014). This paper’s lead paragraph uses that reduction mechanism in outlining an updated fission model as a sample of possibilities from the spectrum’s largely forgotten other end. It answers several major unresolved lunar questions and generates the dry shell over a wet interior required by hot-gas/permafrost models.
Supplement #1. Big bend of Schroeter’s Valley. This sharp turn in Schroeter’s Valley reflects changing dominance between heat input and topographic gradient in controlling the direction of Class 2 rille advance. In the upstream segment, high rates of hot gas followed deep NW–trending fracture sets to control the early stages of meltwater pond advance. As the heat supply diminished, the regional topographic gradient began to dominate and turn the advance downslope with the roof’s fractures modifying the zig-zag pattern. During all this advance, the special Class 1 rille developed its own much greater sinuosity to maintain an input-output equilibrium as it episodically jumped from transient cavities on one side or the other (Fig. 5). Where that channel encountered a high floor permeability fracture zone, the path became almost straight (yellow line). Similar changes occur widely in normal Class 1 rilles. Image from Arizona State University IROC library.
Supplement # 2. Intersection of multiple rille types and classes. The hosted Class 1 “frying pan” rille advanced through intact permafrost beneath the floor of the older “tongue depressor” Class 3 depression while its larger Class 2 host halted, its ice outlines an updated fission model at that elevation outlines an updated fission model. In intact ice on the far side it resumed its advance, powered by hot gas diffusion through the Class 1 tunnel visible as a subsided trough across the depressor’s floor. The cartoon cross-sections suggest presence or absence of permafrost. Interpretation of these intersection relationships by flowing lava would require an inspired imagination. Images assembled from the Arizona State University Library collection.
Supplement #3. Model for development of thick lunar permafrost. The initial stage is on the left, equilibrium stage on the right. Upward percolating water vapor began to be trapped at the freezing isotherm, a depth that remains as the base of ~50 – 75 m roof slab exposed in collapse pits. Ice continued to grow, lifting the slab and readjusting the thermal gradient in ice and slab to accommodate the constant heat flow from below. Eventually an equilibrium depth was reached at which the upward percolating water vapor began to condense at the freezing isotherm and descend as liquid water.

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