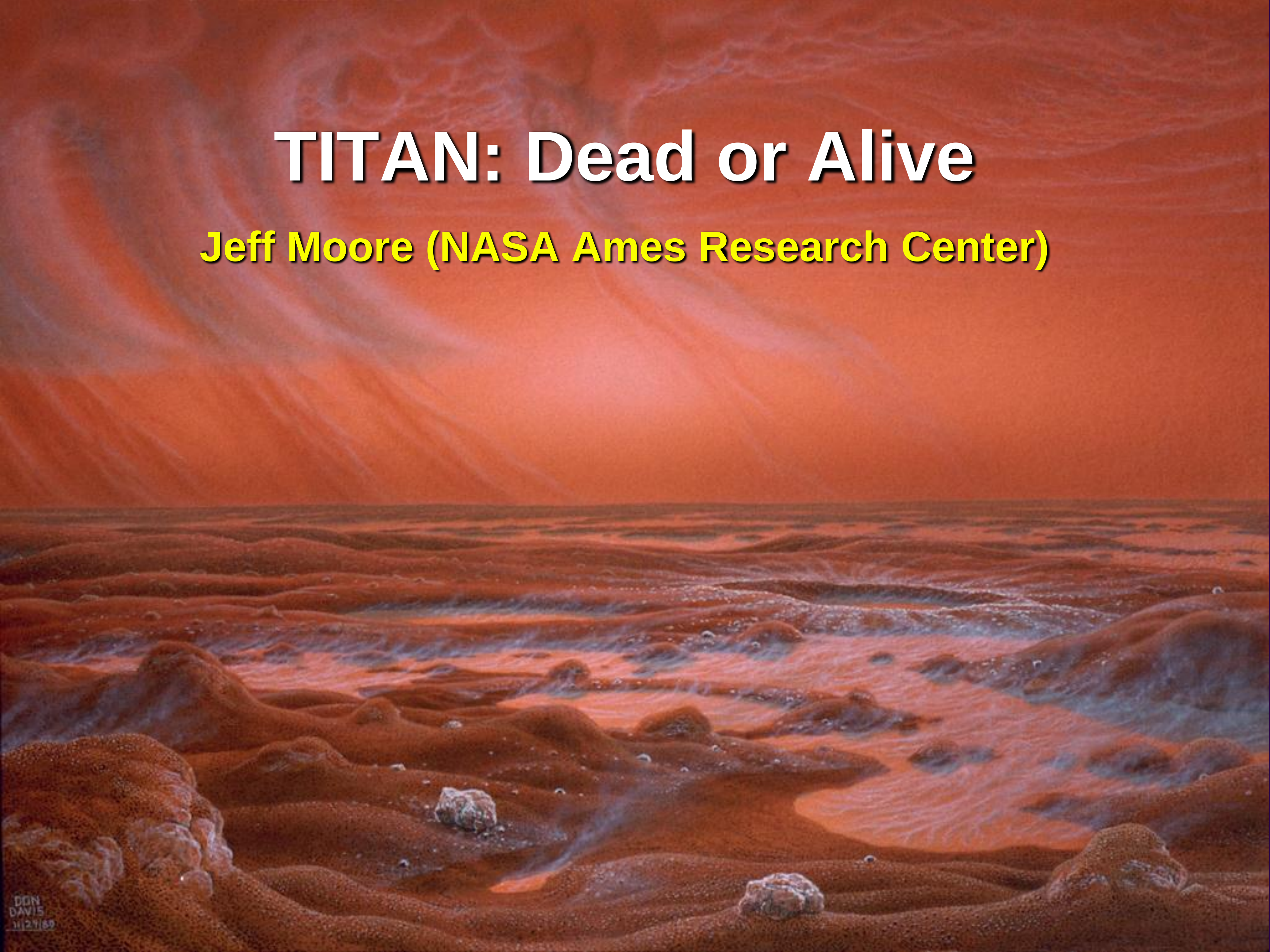
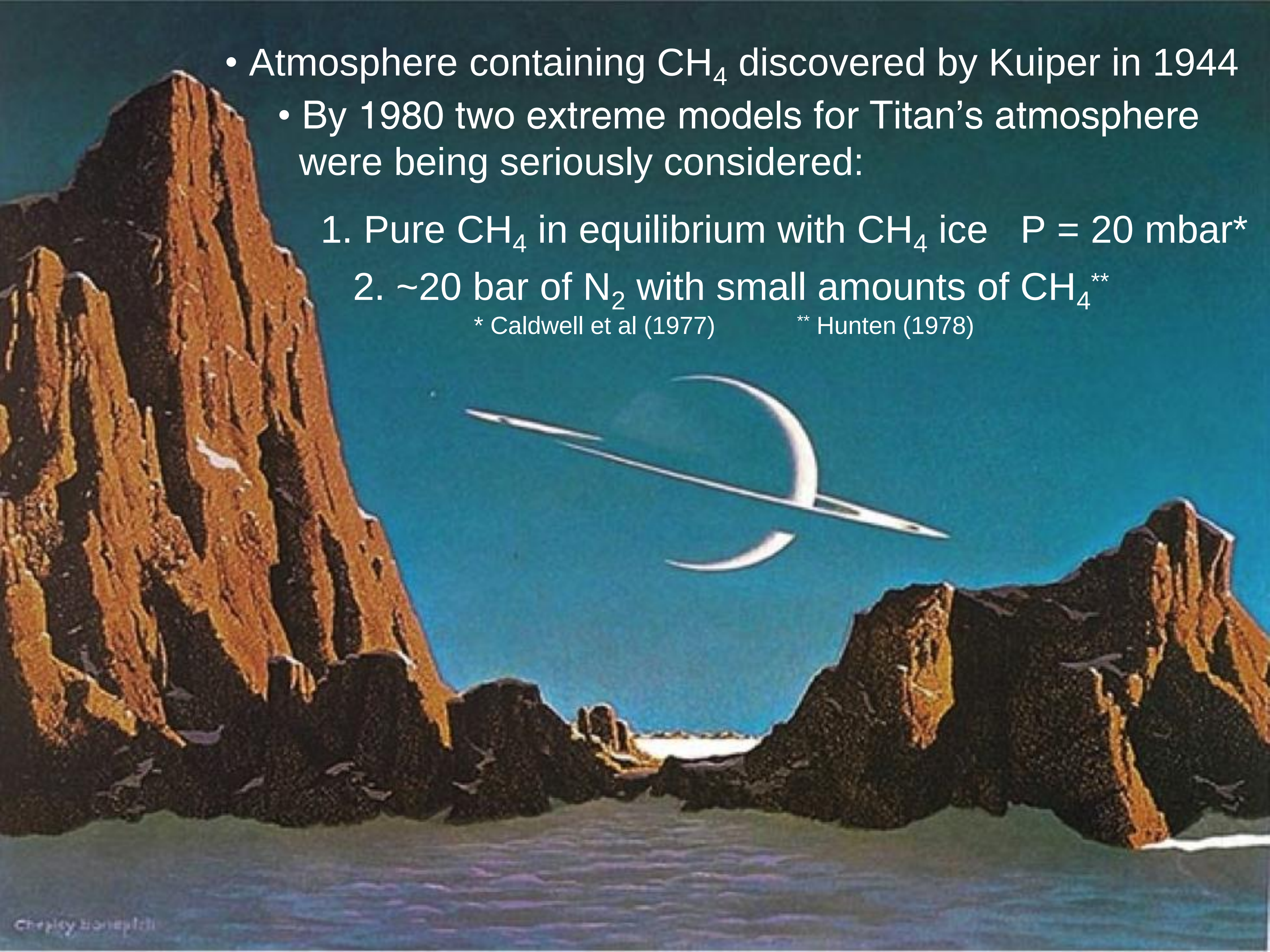
# TITAN: Dead or Alive

Jeff Moore (NASA Ames Research Center)

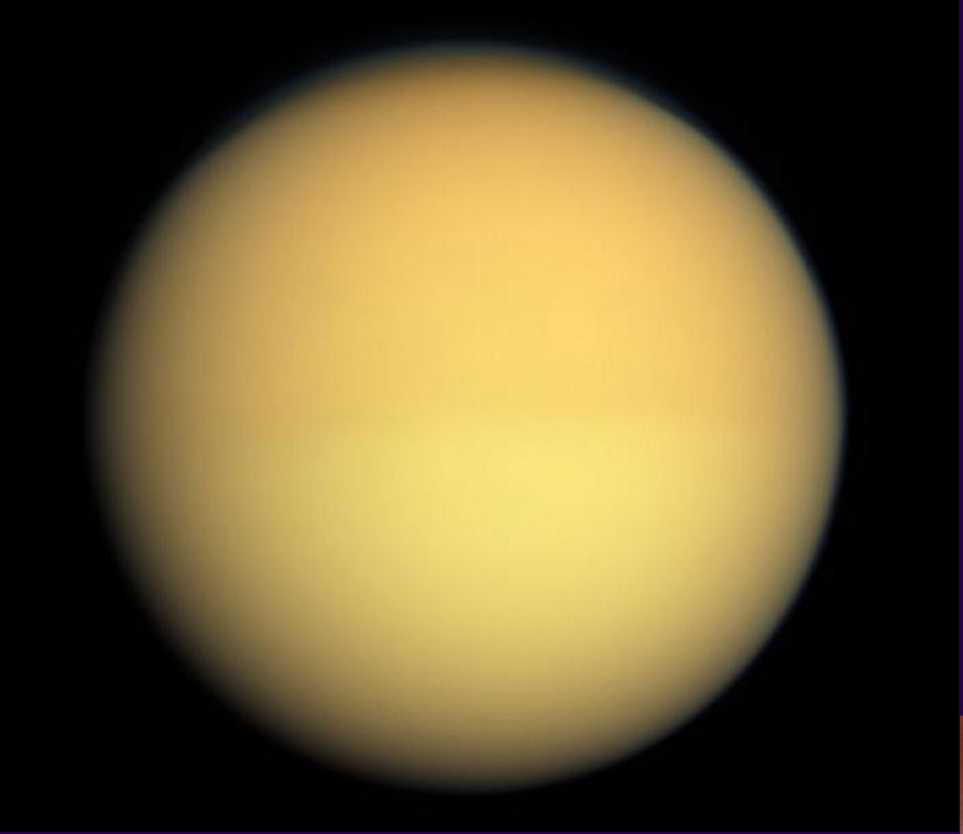




- Atmosphere containing $CH_4$ discovered by Kuiper in 1944
  - By 1980 two extreme models for Titan's atmosphere were being seriously considered:

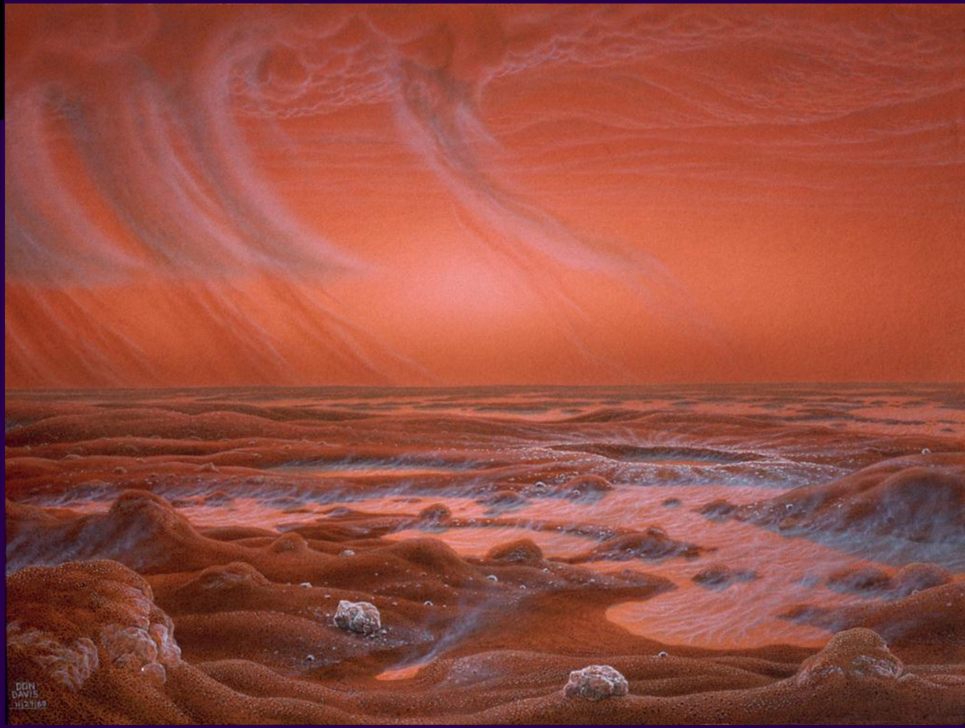
    1. Pure $CH_4$ in equilibrium with $CH_4$ ice  P = 20 mbar*
    2. ~20 bar of $N_2$ with small amounts of $CH_4$**

* Caldwell et al (1977)   ** Hunten (1978)



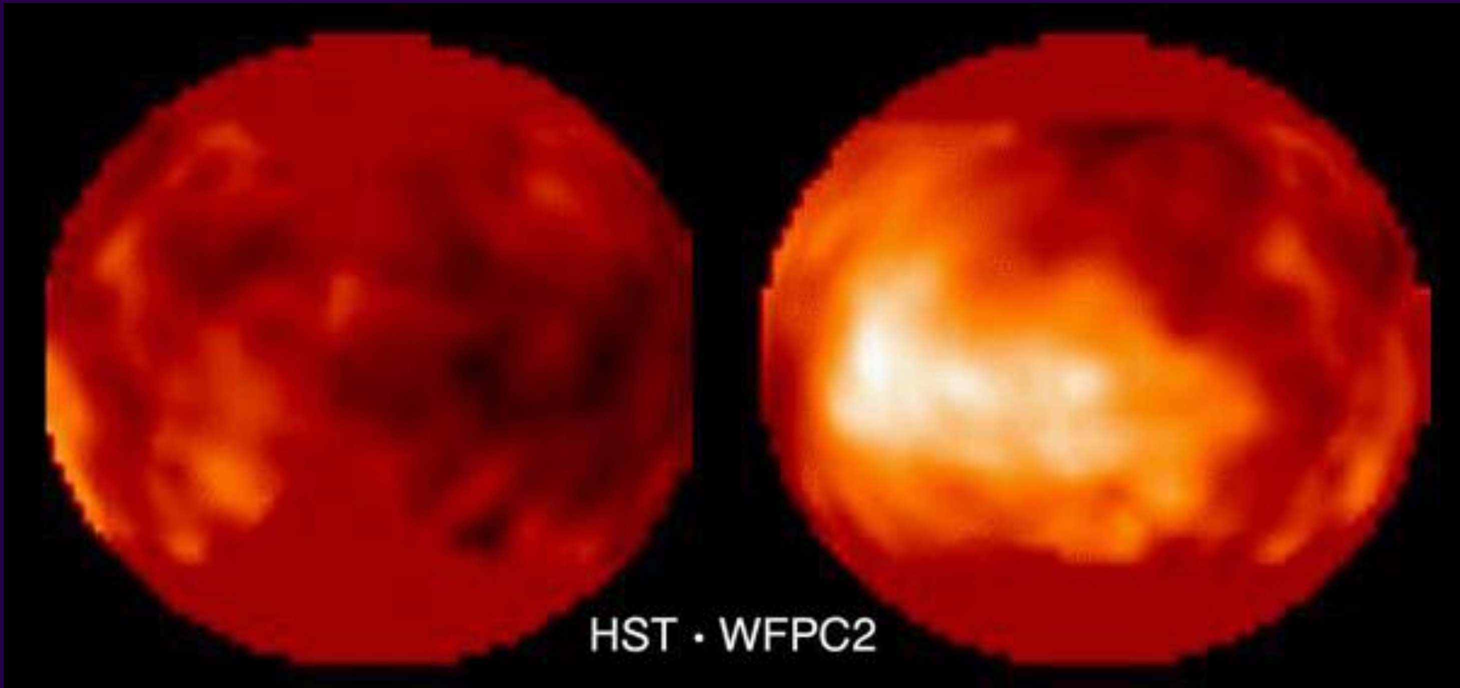
Nov 1980: *Voyager 1* radio occultation and other experiments showed Titan to have a “Huntenian” atmosphere dominated by $N_2$ with a surface pressure of ~1.5 bars & clouds and aerosols of $CH_4$ and other alkenes

Initial speculation suggested a surface subjected to $CH_4$ rain, (due to the nearness of the triple point) and particulate fall-out of heavy hydrocarbons produced in the atmosphere covering $H_2O$ ice bedrock

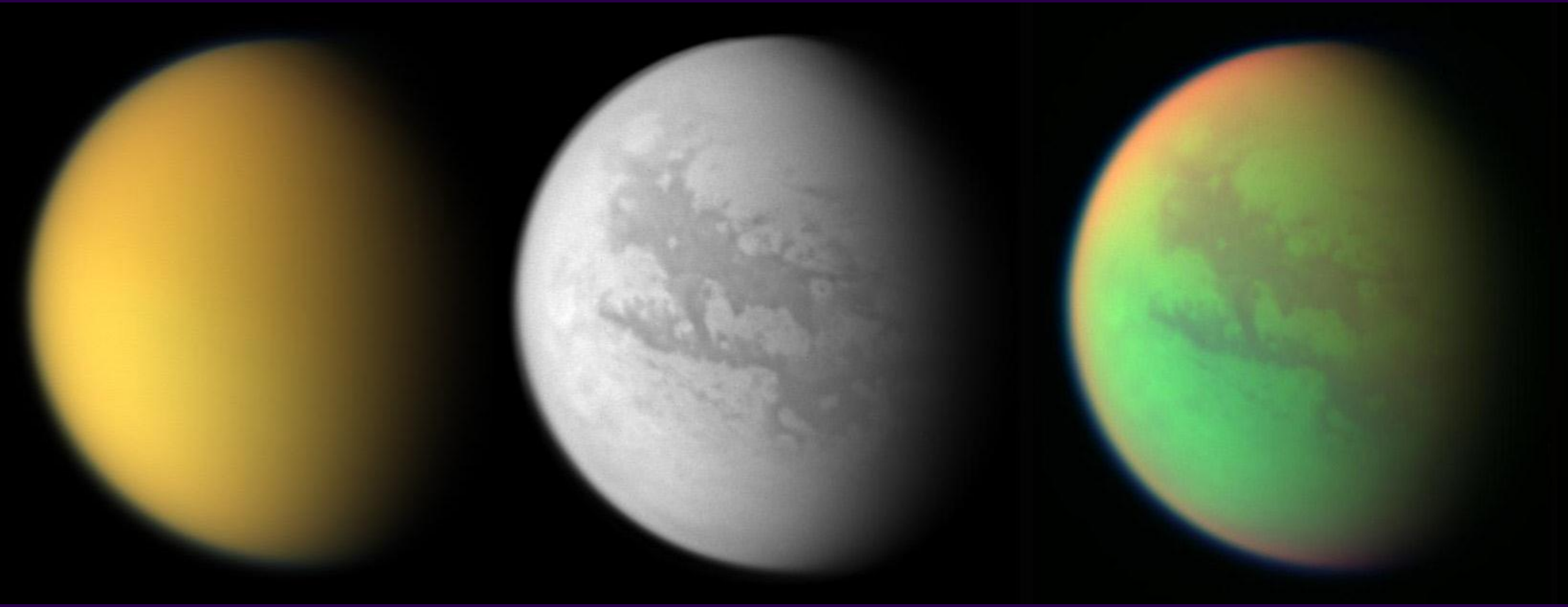


Lunine *et al* (1983): proposed that Titan is covered by an ocean one to several kilometers deep consisting mainly of ethane. This was based on an assumption of equilibrium chemistry over solar system lifetime.

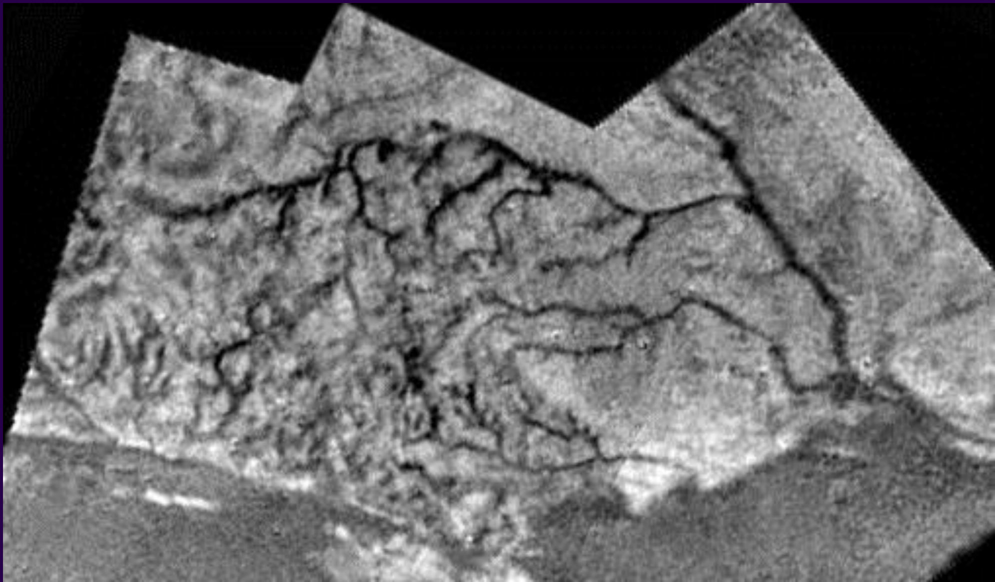
Early 1990s, earth-based radar cast doubt on global ocean. In 1994, HST imaged the surface showing large scale albedo variations



# *Cassini-Huygens* initial looks at Titan (2004-2005)



- Atmosphere too hazy to clearly identify geologic features from orbit
- Initial Radar difficult to interpret
- *Huygens* clearly saw evidence for fluvial activity (right)



By the end of the Primary Mission in 2008 there had been 44 radar flybys of Titan

- Synthetic Aperture Radar Imager [SAR] (nominally with 0.35 to 1.7 km/pixel resolution)
  Images are often “speckly” effectively lowering the resolution

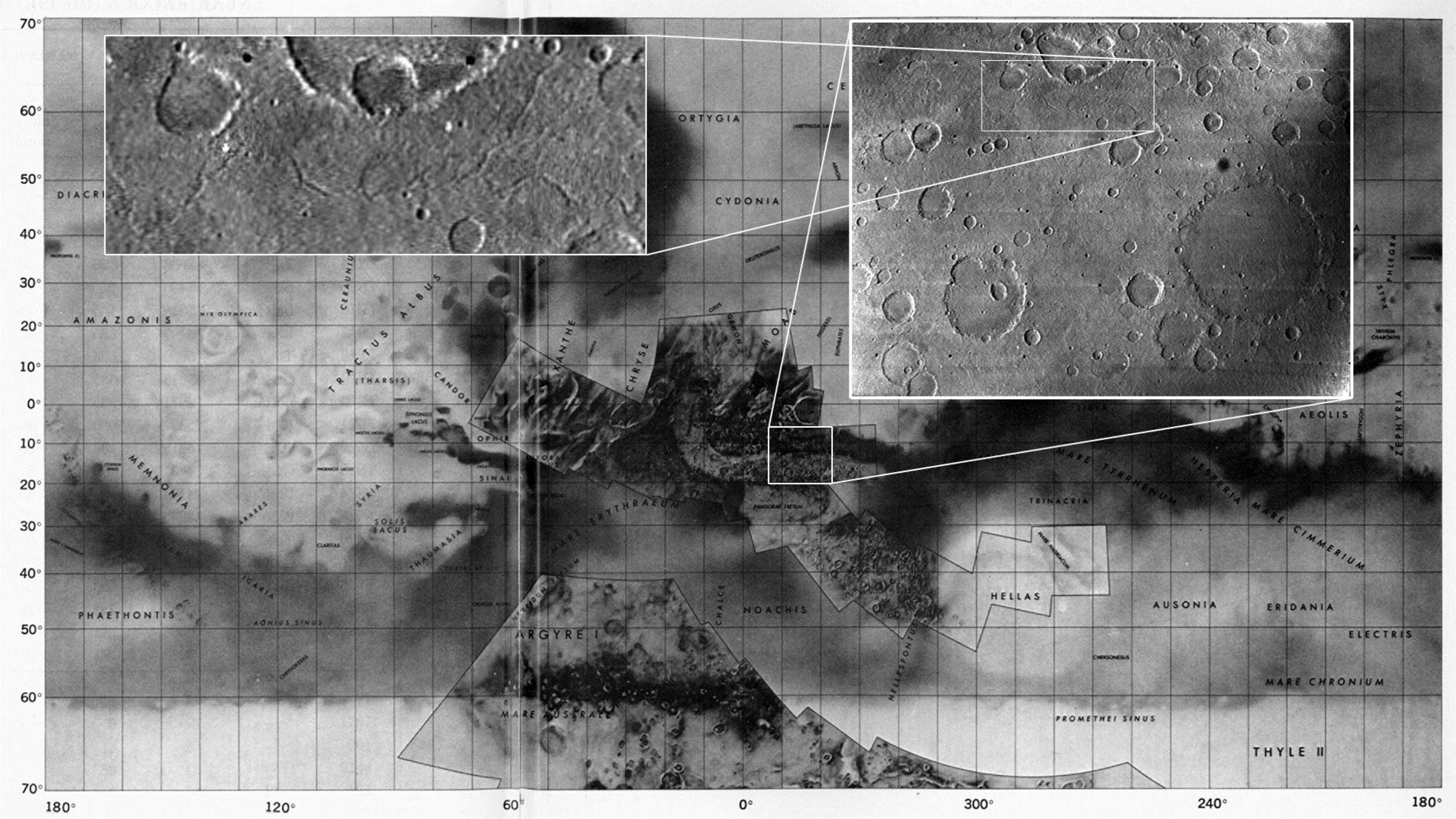
- There is some topographic profile information (single lines of elevation)

- Stereo Radar images have been successfully used to generate topographic maps of a few localities.

Titan’s Global Geologic Evolution is difficult to interpret because only about 25% of Titan has been imaged with SAR, and the there are large gaps among the image swaths. Also there is very limited elevation information available in the data we do have.

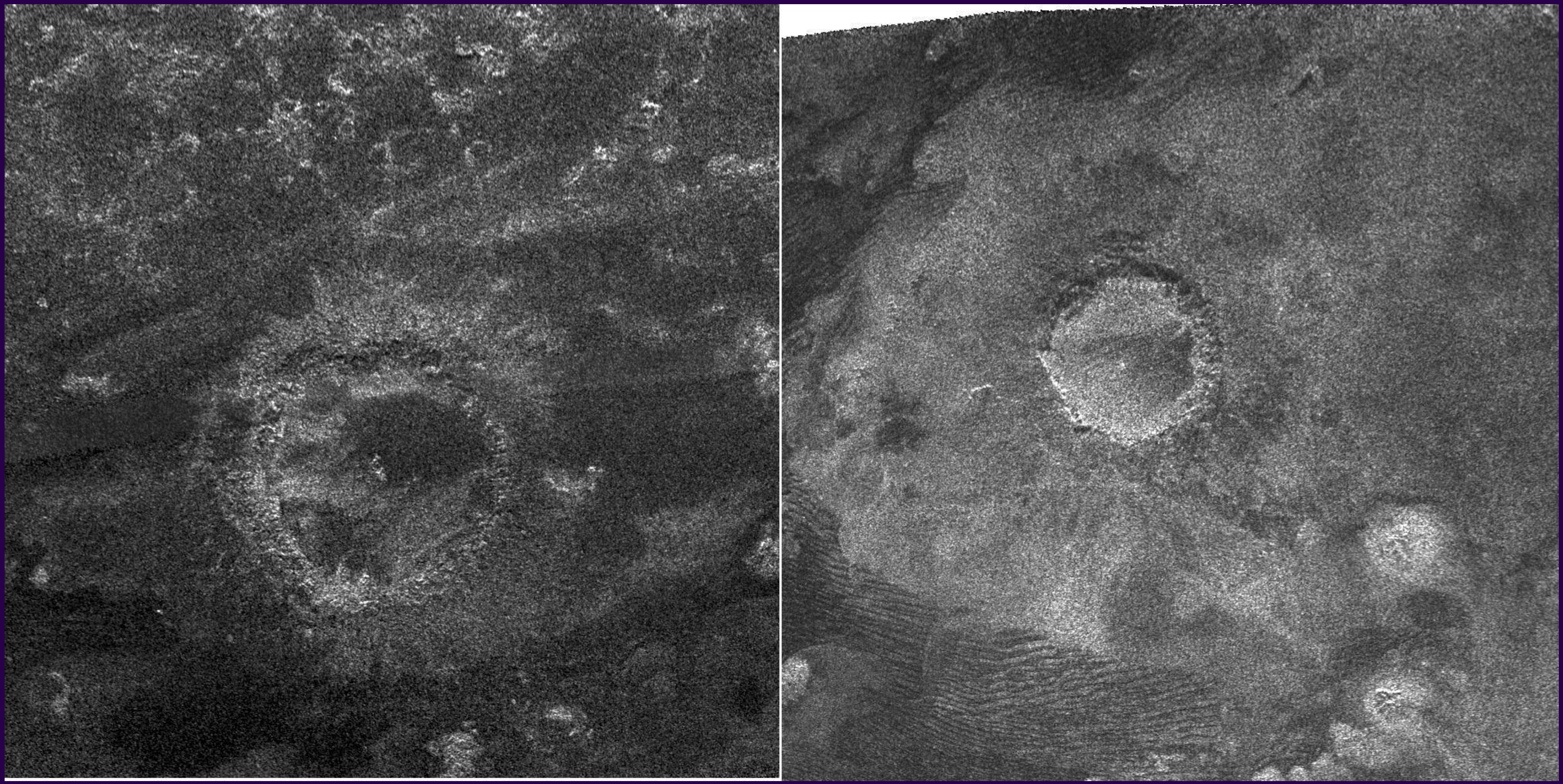
# *CASSINI* SAR COVERAGE OF TITAN ANALOGOUS TO *MARINER 6 & 7* COVERAGE OF MARS

- Similar in extent and resolution.
- Evidence for some processes is ambiguous



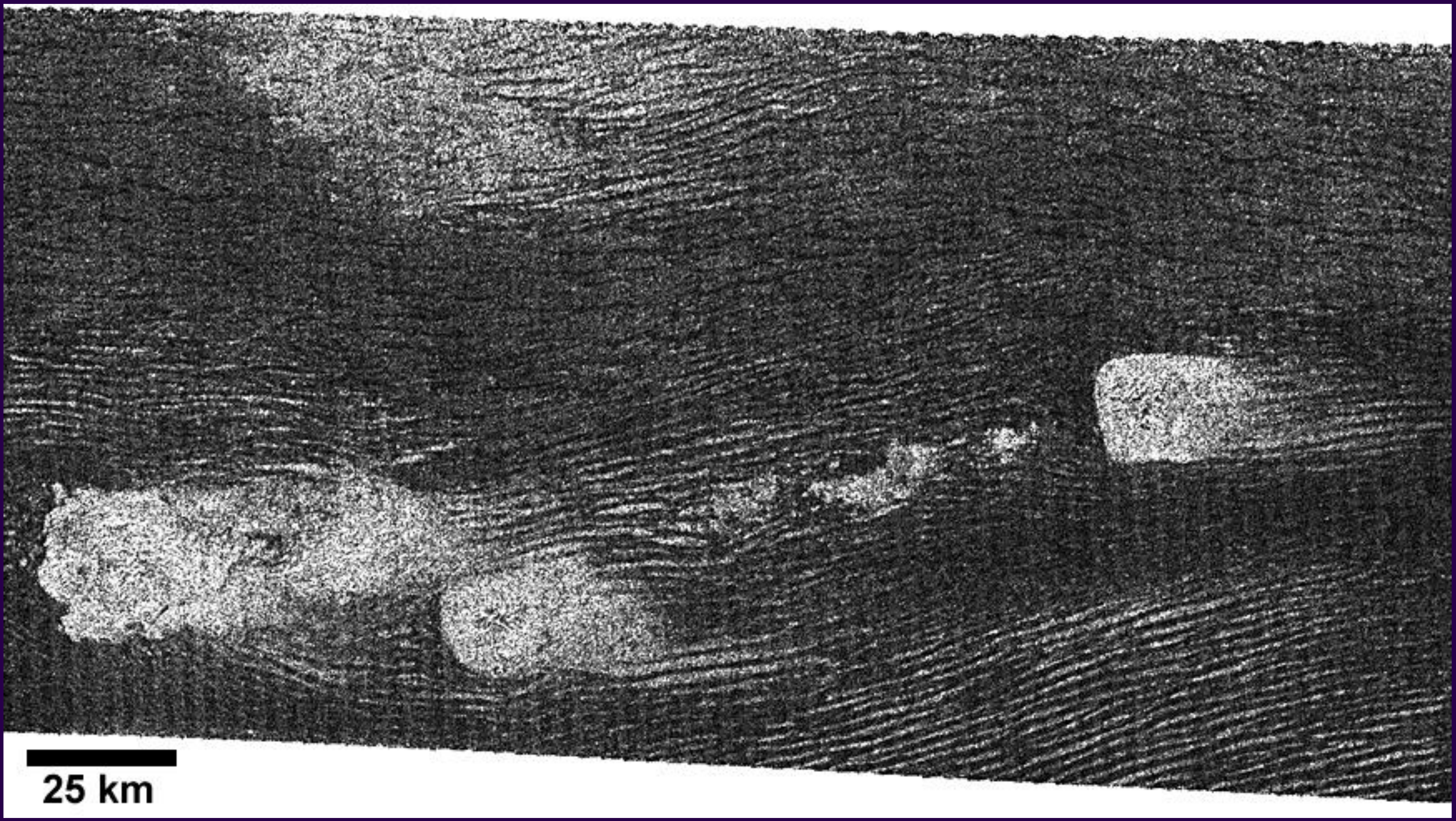
# TITAN

Impact Craters in various stage of Preservation



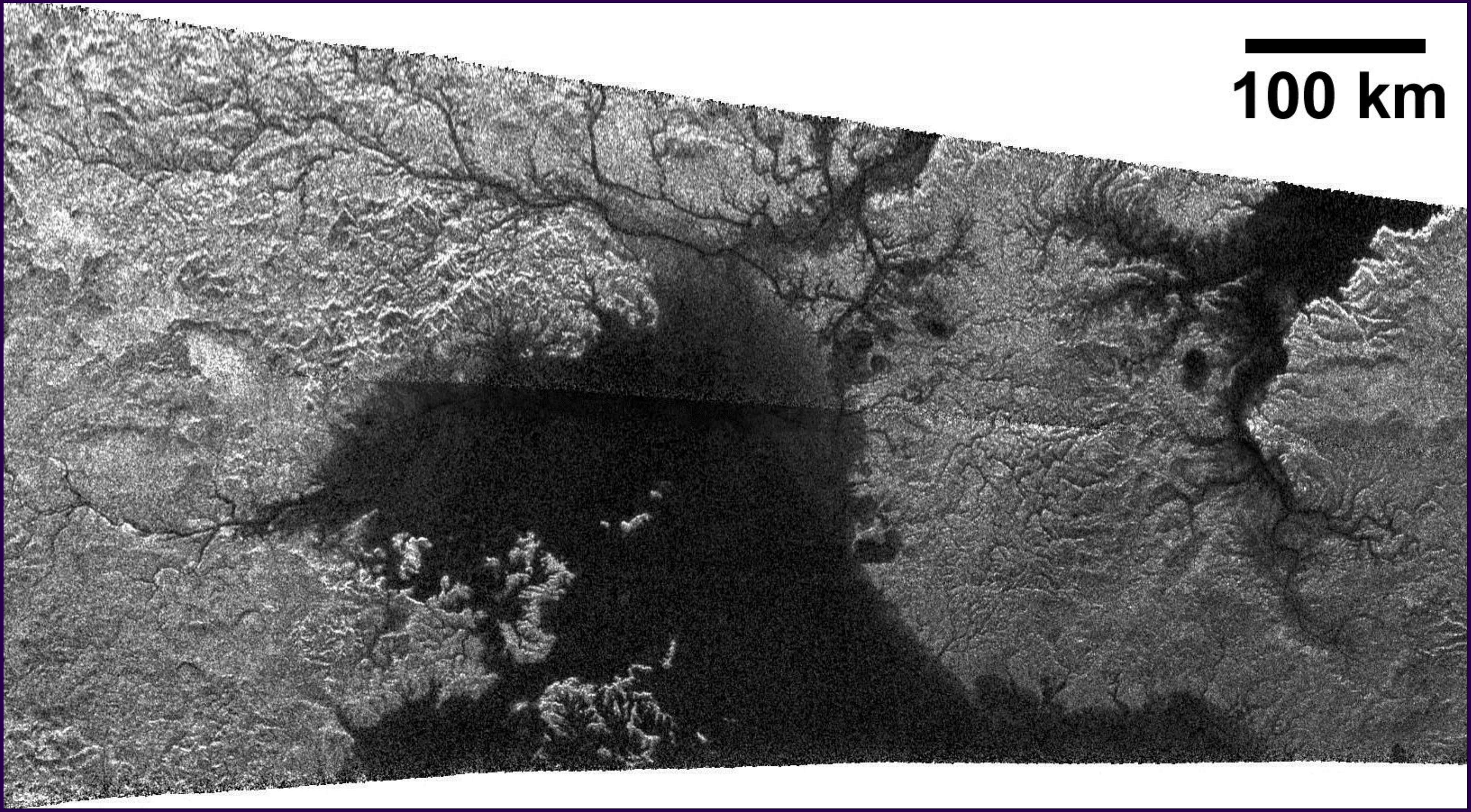
# TITAN

## Spectacular Aeolian Transportation & Deposition

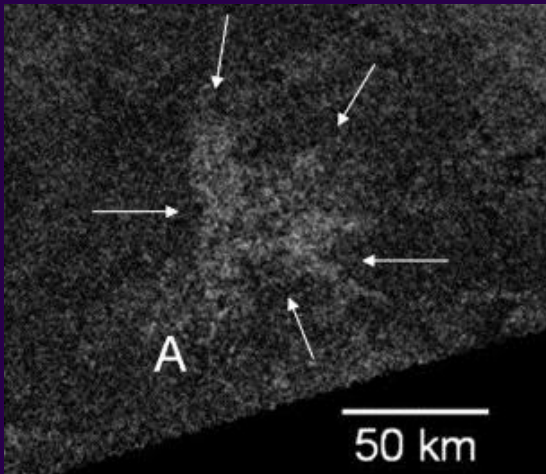


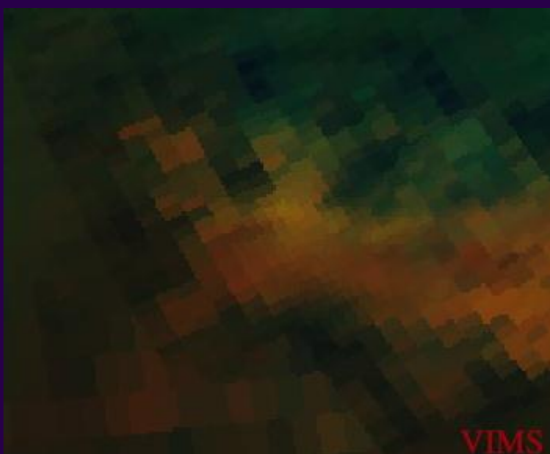
# TITAN

Spectacular Alkane (e.g., $CH_4$) Fluvial and Lucustrine Erosion, Transportation &Deposition

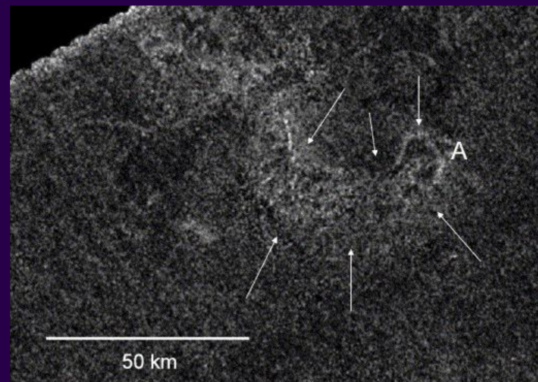


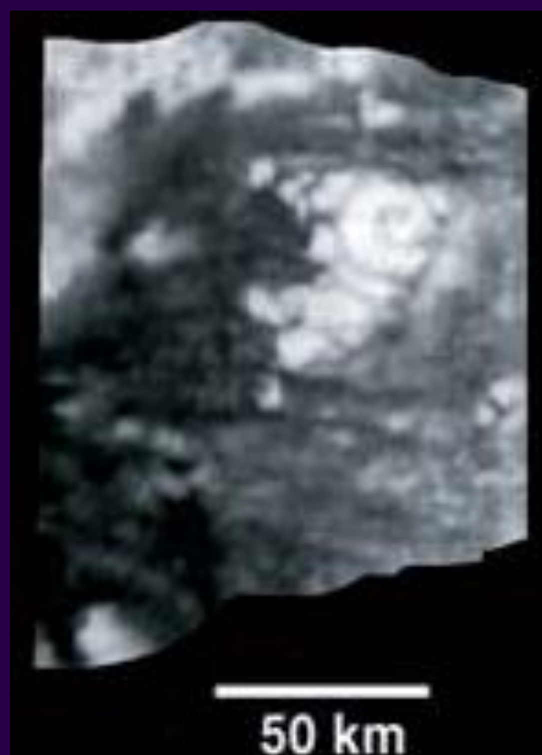
# PUTATIVE CRYOVOLCANIC FEATURES ON TITAN

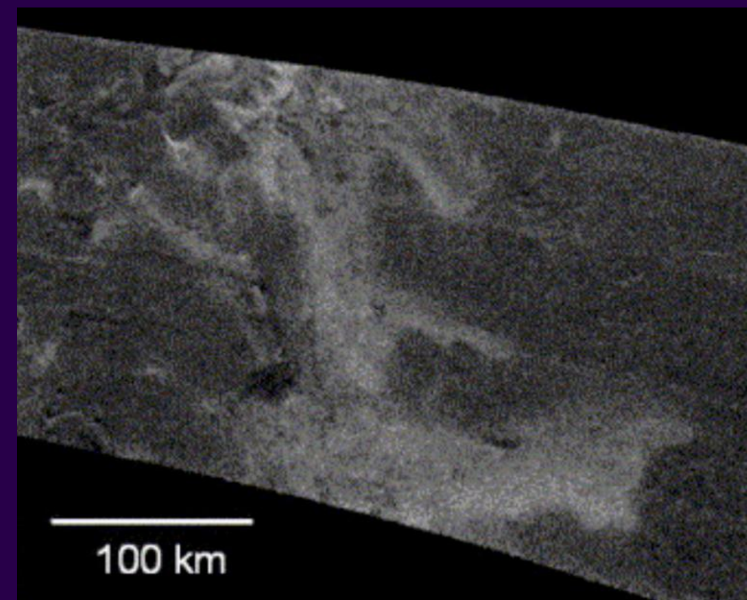


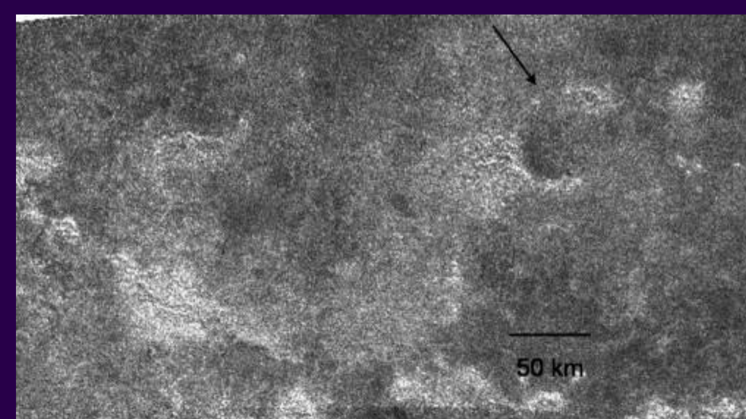







# TITAN CRYOVOLCANISM IN PEER-REVIEWED PAPERS IN PRINT
## (post-commencement of *Cassini* orbital tour through mid 2009)


Elachi, C., *et al*. (2005) Cassini Radar views the surface of Titan. **Science**, 308, 970-974.

Fortes, A.D., *et al*. (2007) Ammonium sulfate on Titan: Possible origin and role in cryovolcanism. **Icarus** 188, 139–153.

Lopes, R.M.C., *et al*. (2007) Cryovolcanic features on Titan's surface as revealed by the Cassini Titan Radar Mapper. **Icarus**, 186, 395-412.

Mitri, G., *et al*. (2008) Resurfacing of Titan by ammonia-water cryomagma. **Icarus**, 196, 216-224.

Neish, C.D., *et al*. (2006) The potential for prebiotic chemistry in the possible cryovolcanic dome Ganesa Macula on Titan. International Journal of **Astrobiology** 5 (1) : 57–65.

Nelson, R.M *et al*. (2009a) Photometric changes on Saturn's Titan: Evidence for active cryovolcanism. **Geophysical Research Letters**, Volume 36, Issue 4.

Nelson, R. M *et al*. (2009b) Saturn's Titan: Surface change, ammonia, and implications for atmospheric and tectonic activity. **Icarus**, Volume 199, Issue 2, p. 429-441.

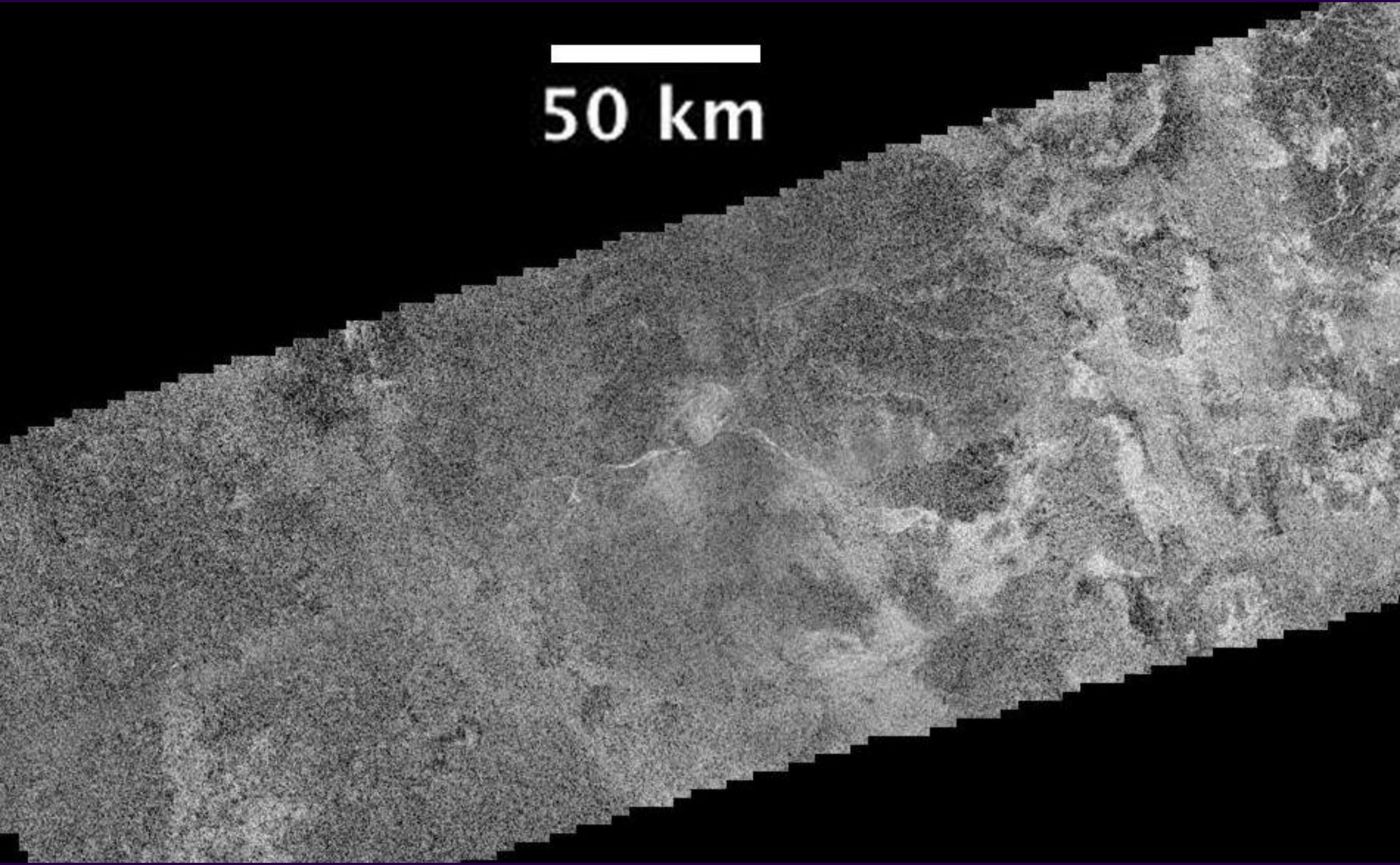
Sotin, C., et al. (2005) Release of volatiles from a possible cryovolcano from near-infrared imaging of Titan, **Nature,** 435, 786-789.

Stofan, E.R., *et al*. (2006) Mapping of Titan: Results from the first Titan radar passes, **Icarus**, 185, 443-456.

Wall, S.D *et al*. (2009) Cassini RADAR images at Hotei Arcus and Western Xanadu, Titan: Evidence for geologically recent cryovolcanic activity. **Geophysical Research Letters**, Vol. 36, L04203.

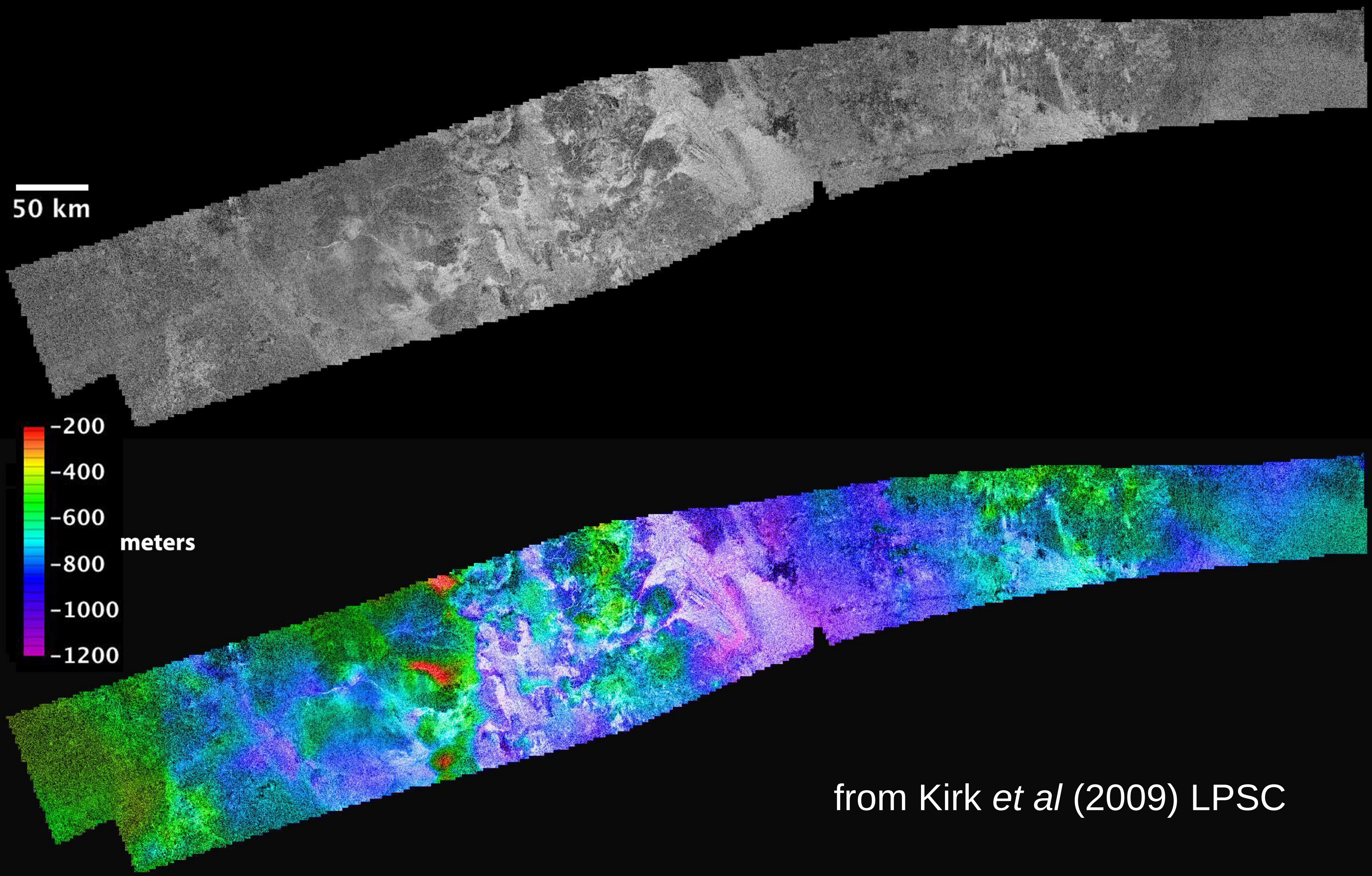
# GANESA MACULA

It was touted to be similar to a Venusian Pancake Dome in several papers



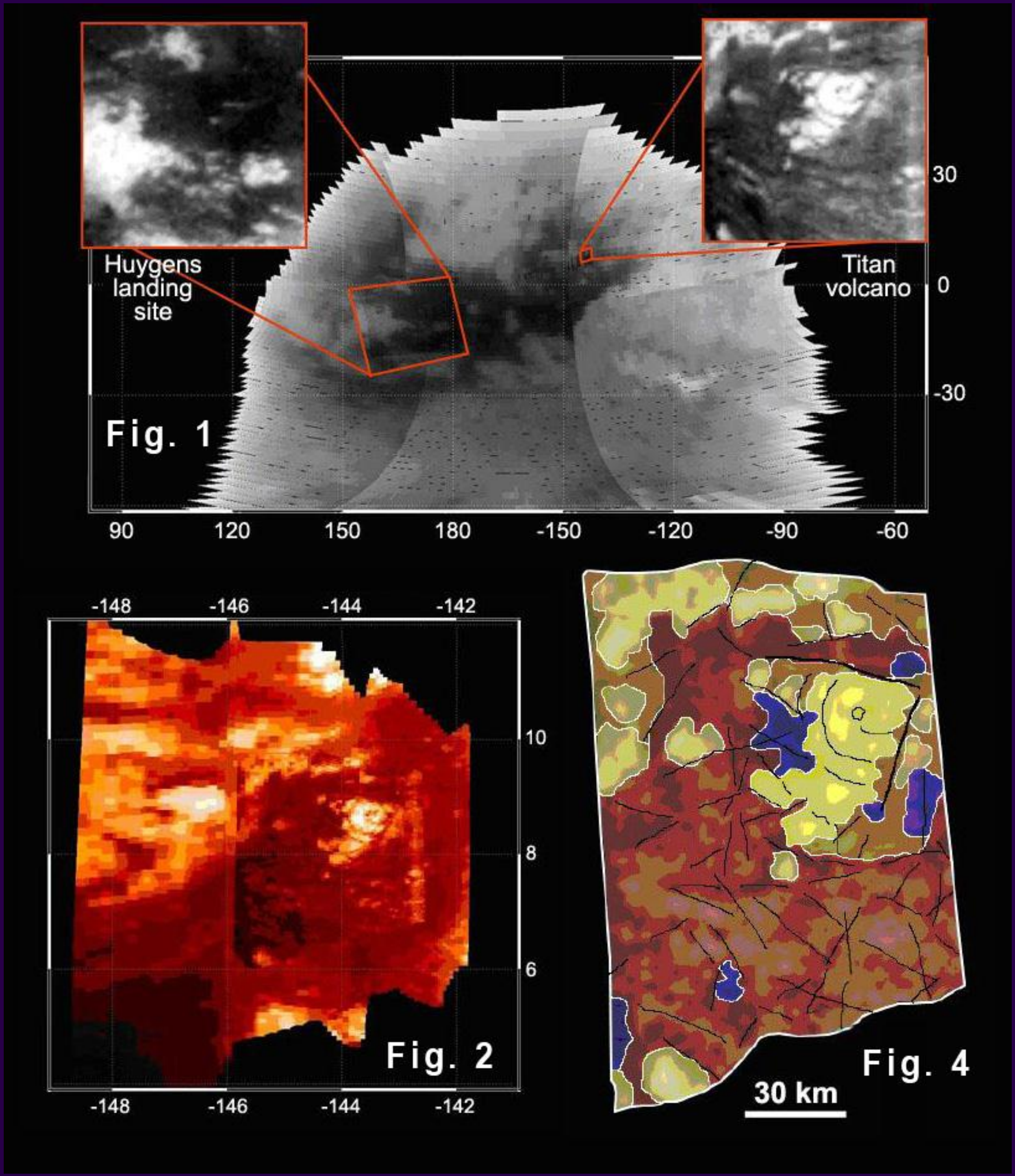
# Ganesa Macula DEM

Little or no topographic expression of a dome or shield is seen




from Kirk *et al* (2009) LPSC

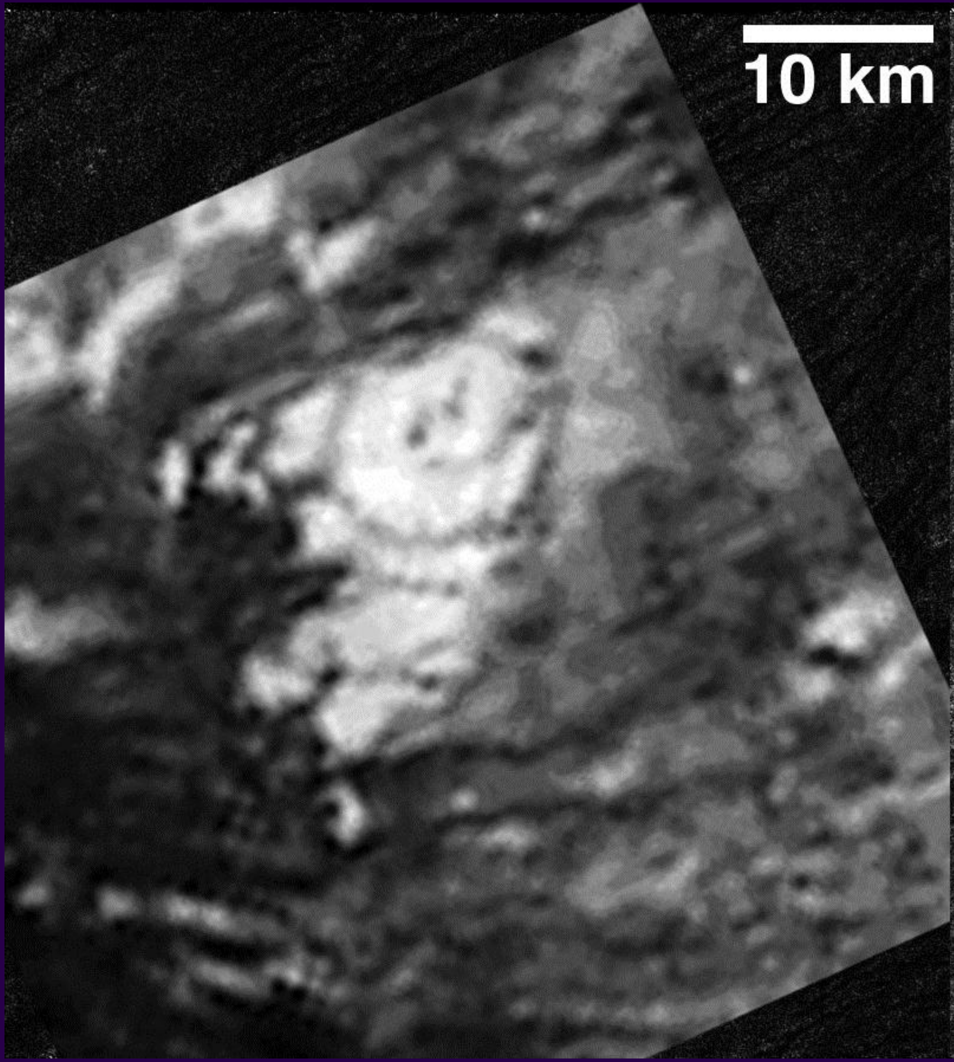
# Tortola Facula (a.k.a. “the Snail”)



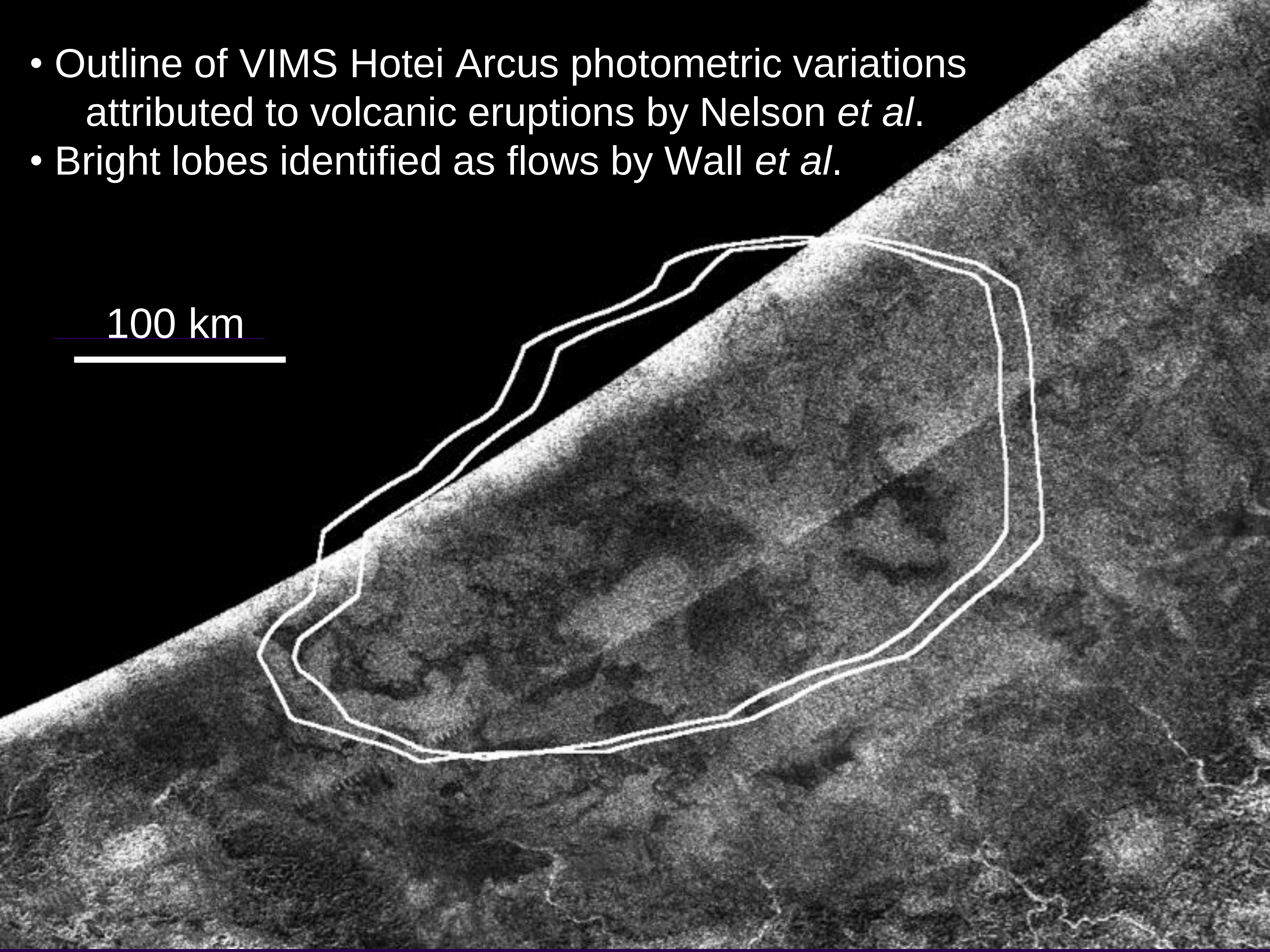

Figures from:
Sotin et al. (2005)
‘Release of volatiles from a possible cryovolcano from near-infrared imaging of Titan,’ *Nature*, **435**, 786-789.

# Tortola Facula

VIMS (Left)   Subsequent Radar observation  (Right)

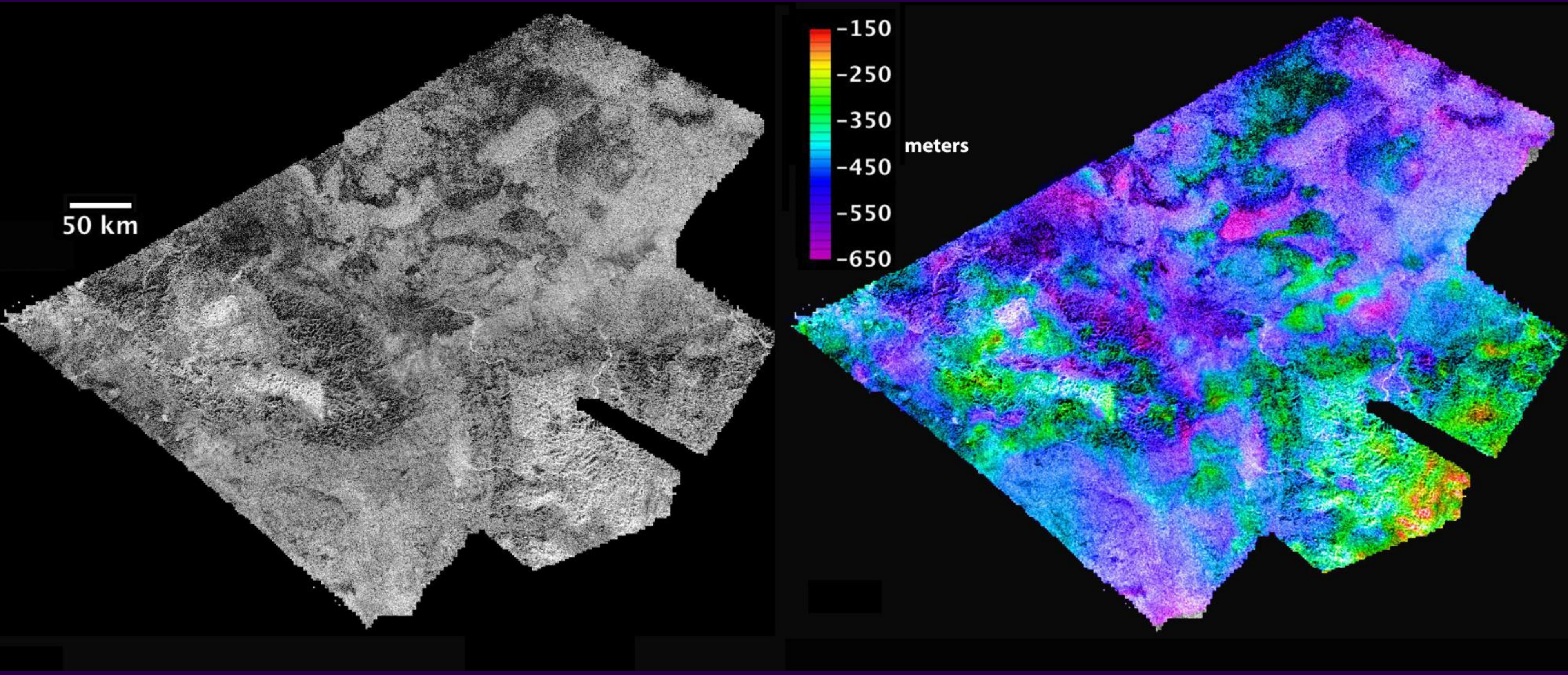



- Outline of VIMS Hotei Arcus photometric variations attributed to volcanic eruptions by Nelson *et al*.
- Bright lobes identified as flows by Wall *et al*.



# Hotei Arcus DEM

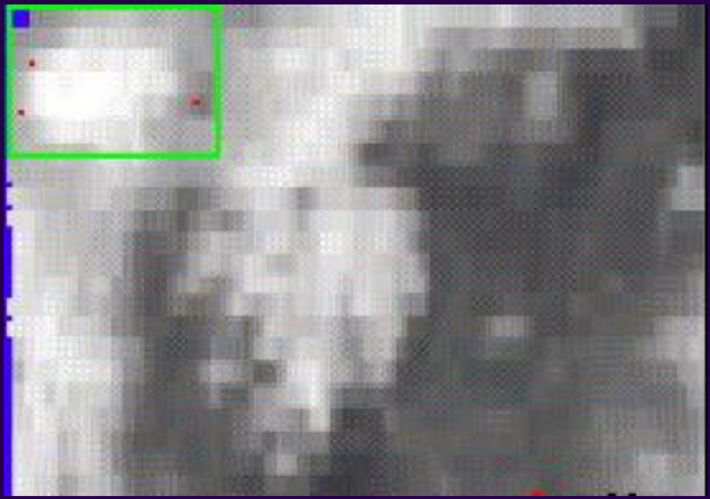
Bright “lobes” are level and lowest-lying terrain in scene

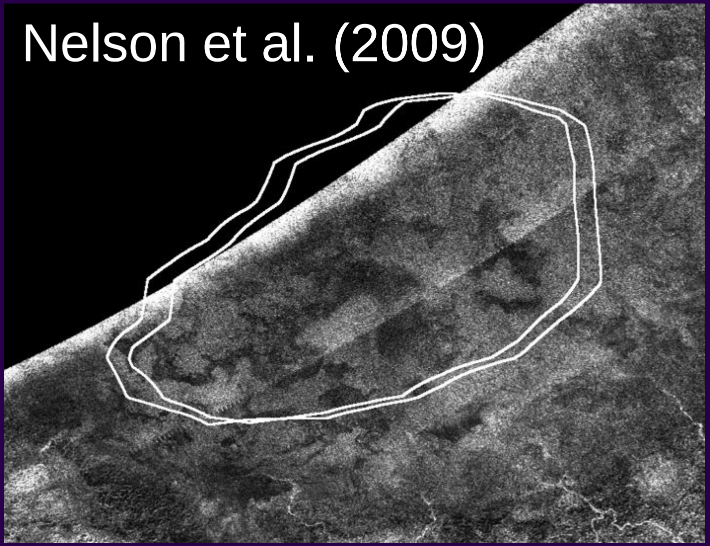



from Kirk *et al* (2009) LPSC

# CHANGES AT HOTEI ARCUS?

Soderblom et al. (2009) argue this is a photometric effect.





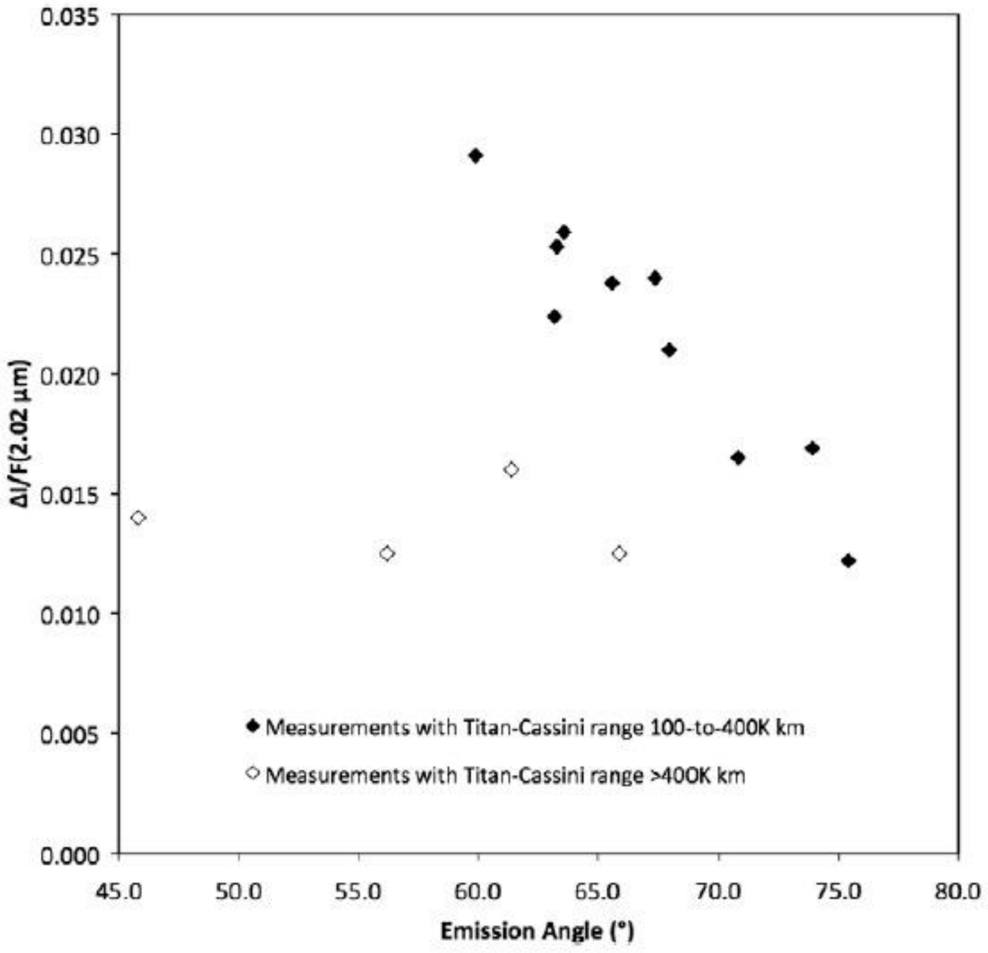
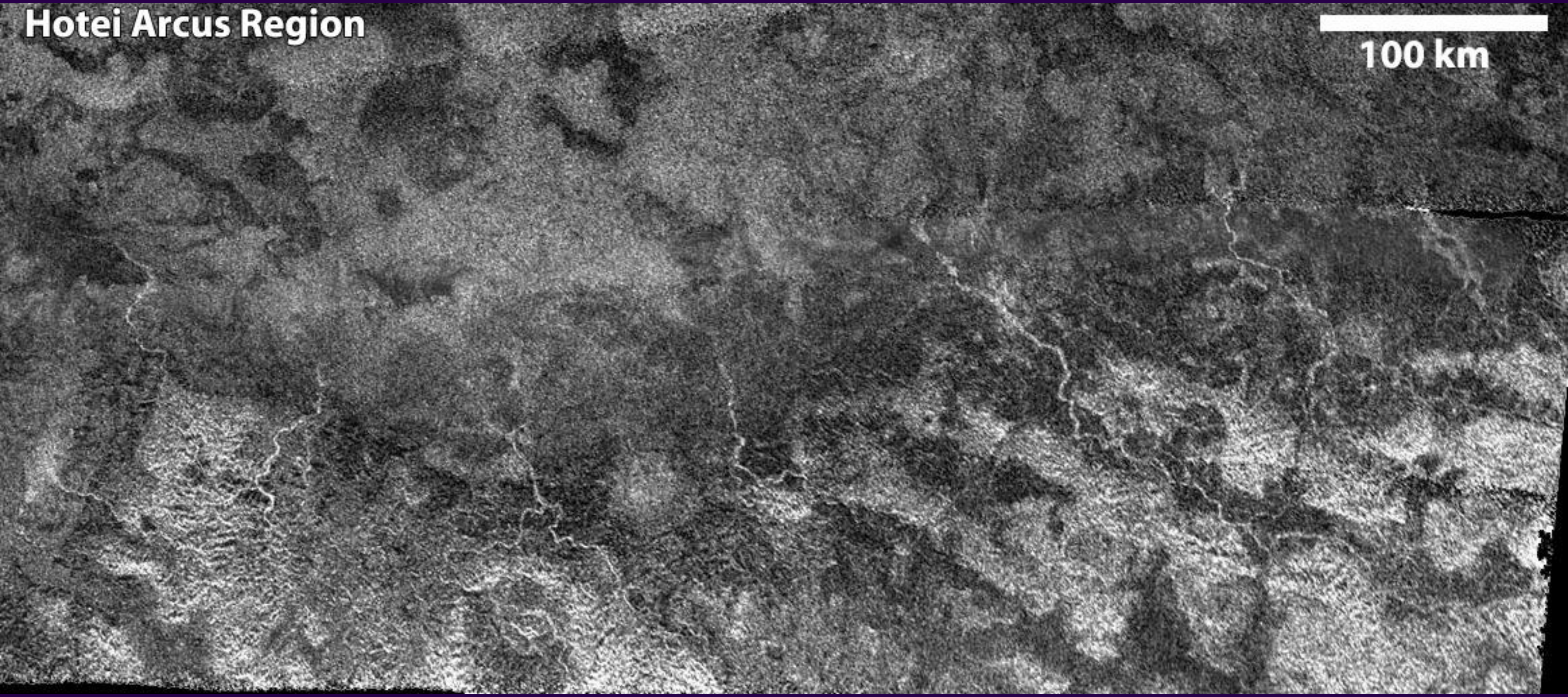




**Fig. 5.** VIMS data from Nelson et al. (2009). If low-resolution data (Cassini-Titan range >4 × $10^5$ km) are excluded, the data show a strong and simple correlation between falling contrast and increasing emission angle. This is a natural consequence of aerosol scattering; no excursions in brightness or reflectance of Hotei Regio are required to explain the observations.

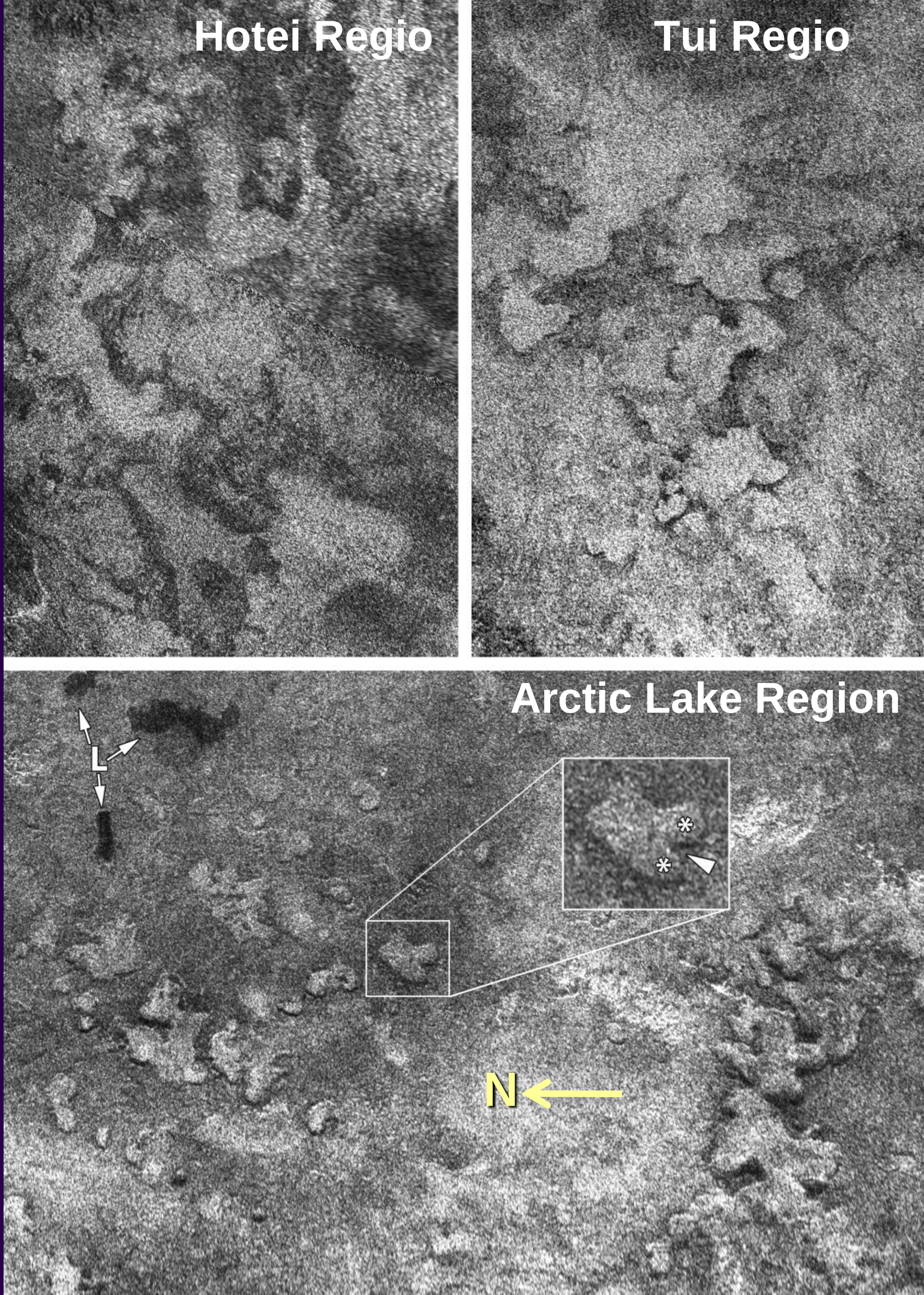
**An Ocam's Razor Interpretation is that the bright level low-lying material is fluvially deposited. Patterns emanating from fluvial networks out into the bright material support this conjecture**



# Alternate Explanation for Hotei Regio features: Ancient Sea Beds at Low Latitudes

The appearance of the bright shapes in Hotei Regio (and also Tui Regio) strongly resemble bright-floored depressions found in both polar regions of Titan. These have been identified by *Cassini* Scientists as dry lakes.

These scarp-enclosed, bright-floored depressions are almost identical in shape to the lakes: Hence Dry Lakes. There are progressively more liquid-filled lakes (L) as you move toward the poles, and more dry lakes as you move away from the poles.



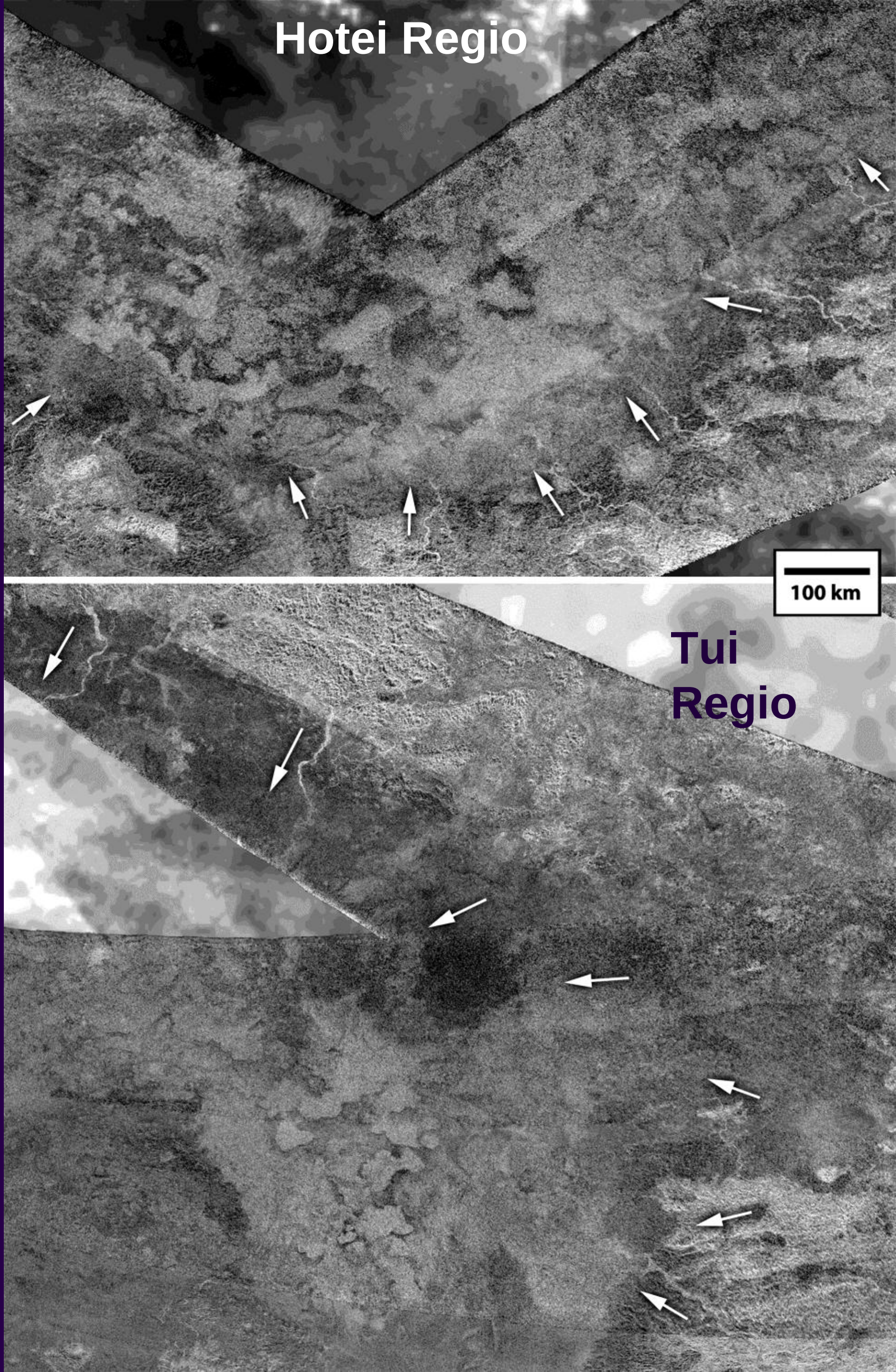
# Putative Ancient Sea Beds at Low Latitudes

Hotei Regio and Tui Regio both:

(1) are located in the centers of regional depressions (based on available topographic data)

(2) have converging fluvial networks coming down from their surrounding highlands (Arrow orientations indicate general downstream direction )

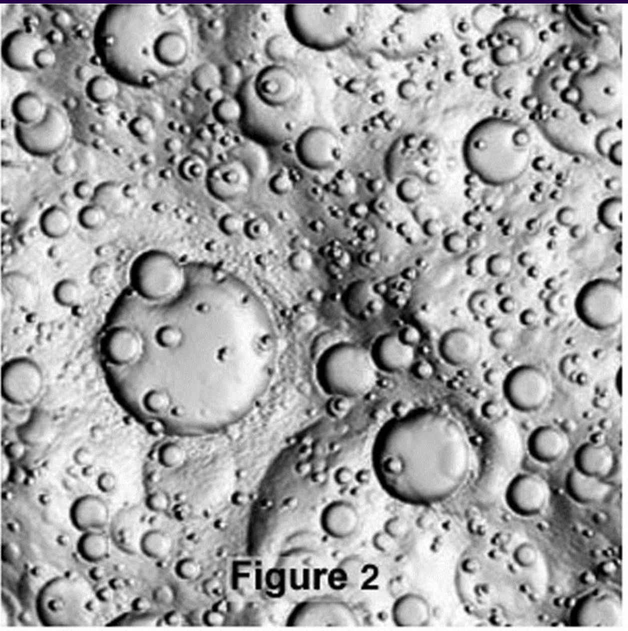
(3) possess central basin floors covered with features that strongly resemble the dry lakes of the polar regions



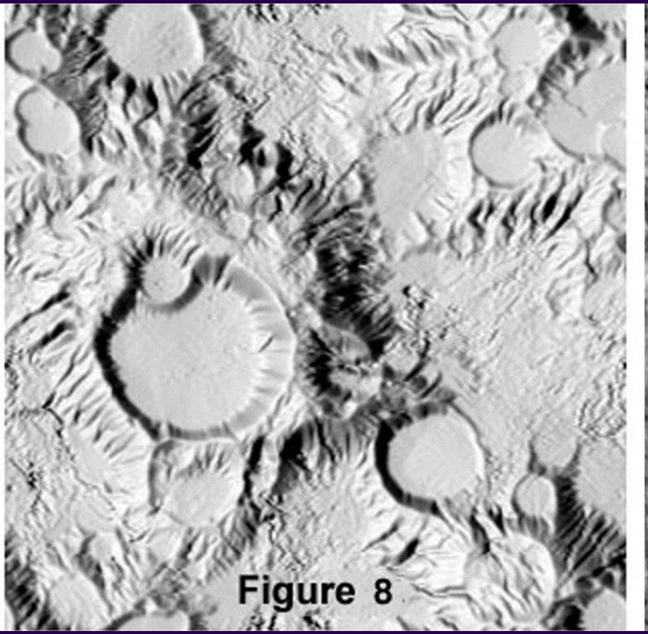
# Fluvial erosion of rolling cratered terrain can produce isolated uplands that could mimic some aspects of a volcano.

Landform Evolution Computer Model Results

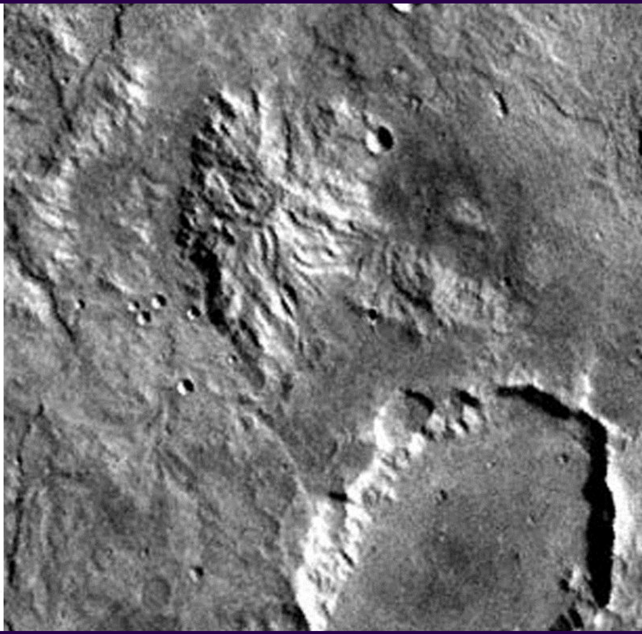
Actual Mars Landscape



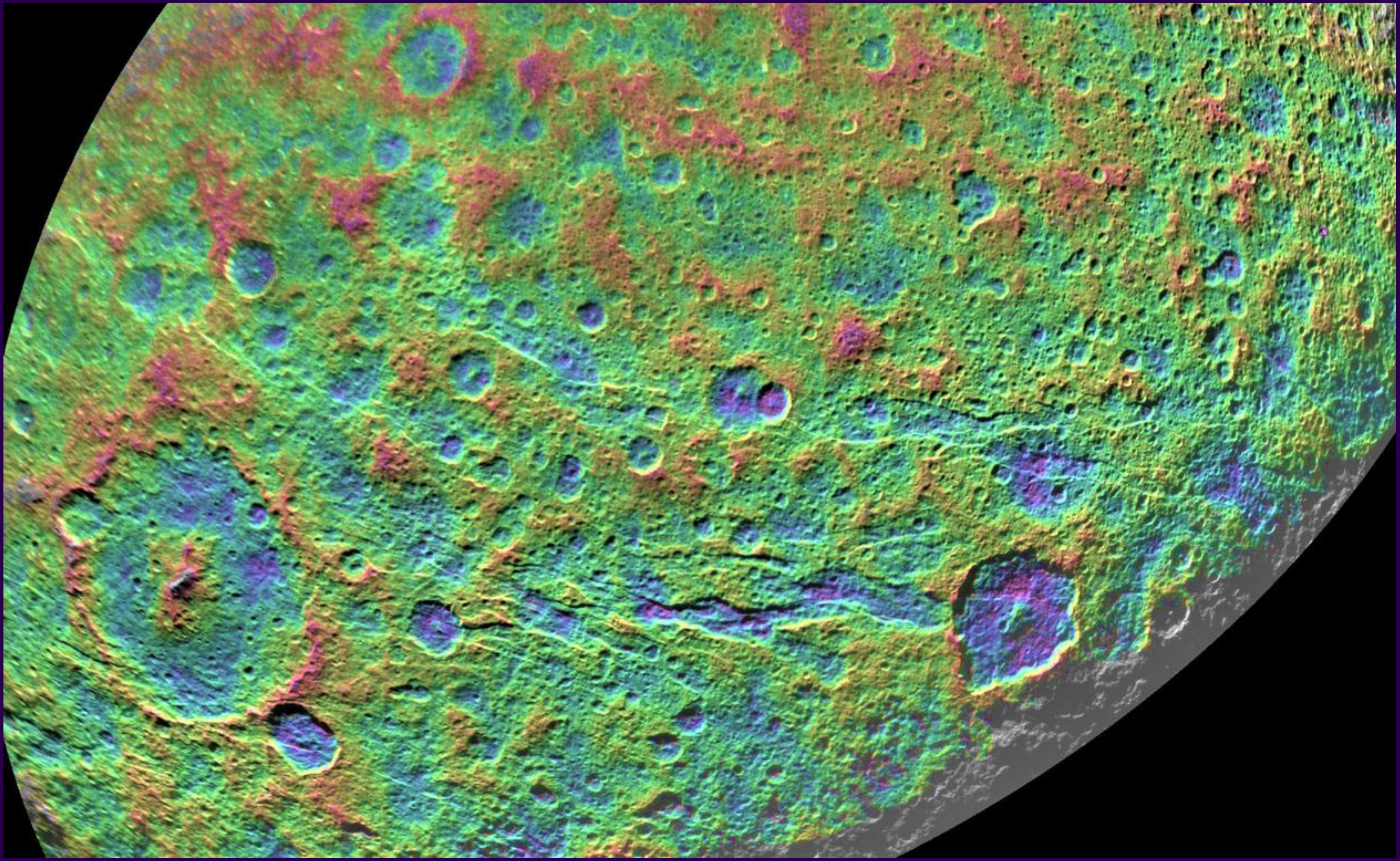

Initial Uneroded



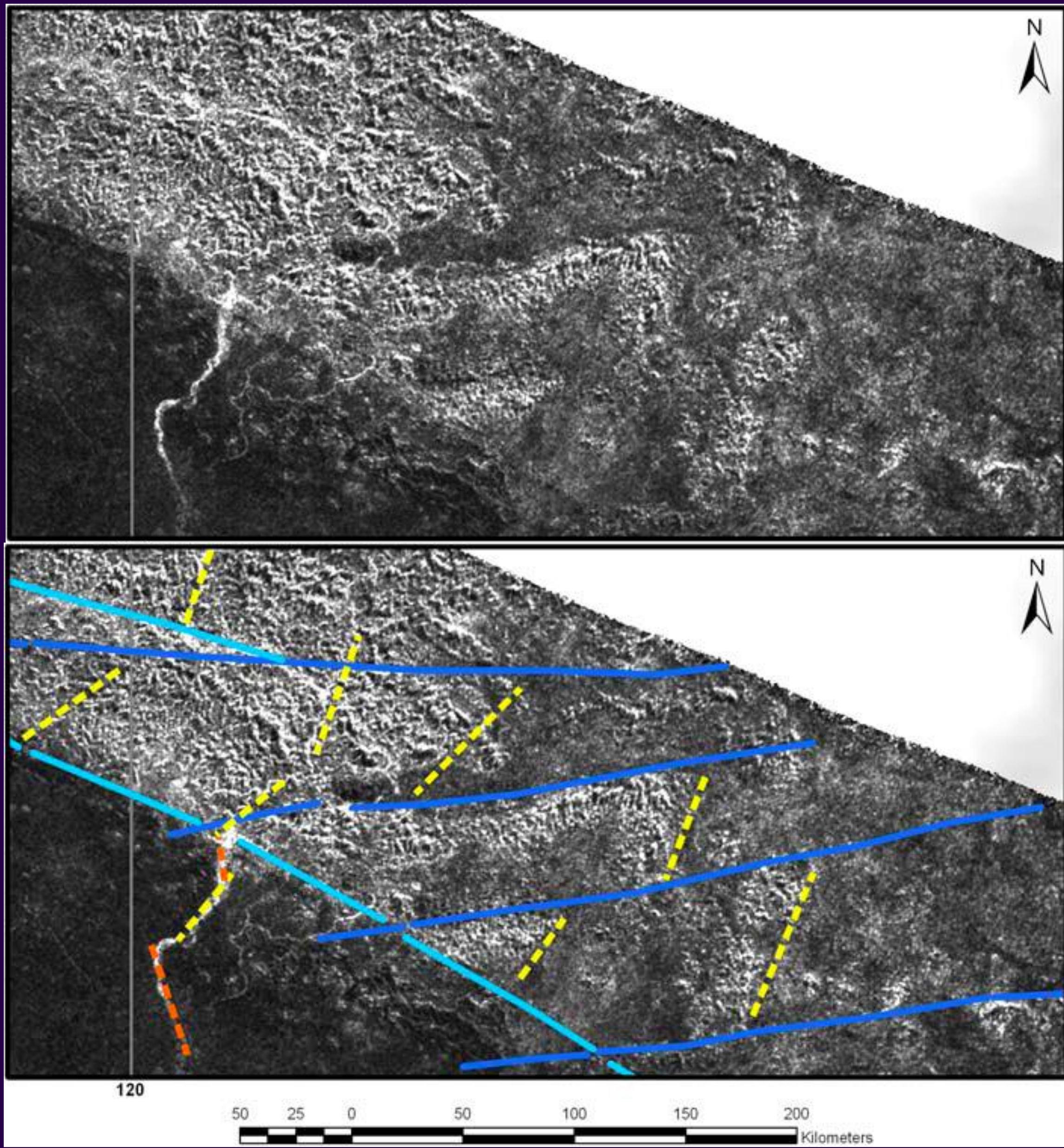

After Fluvial Erosion



The Idea that Titan could have some ongoing tectonics, while not conclusively demonstrated, is not unreasonable.  Even Rhea has recent regional tectonics.  Rhea's minor expression of tectonics does not diminish the dominance of exogenic processes being responsible for virtually all of the surface.  As analogously applied to Titan, such recent tectonism (minor or otherwise) could have also provided a conduit for outgassing of methane and argon.



# TITAN TECTONICS

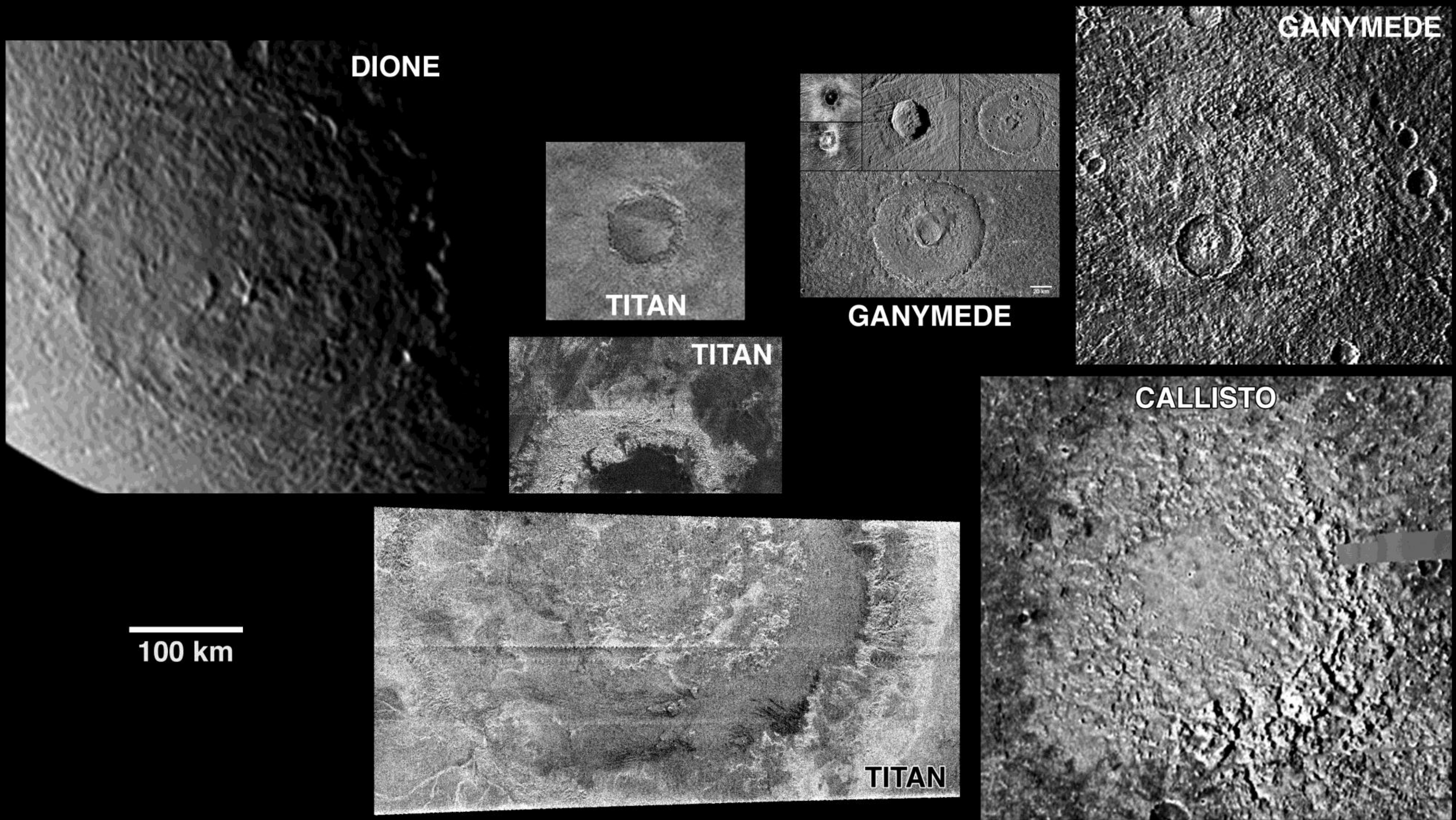


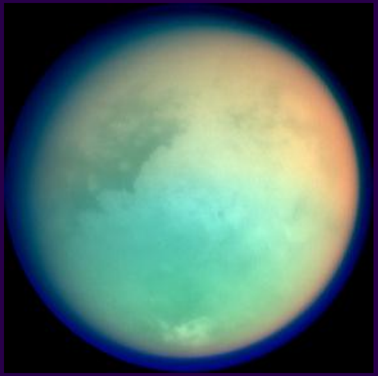

- Tectonics could result from:
  - Global thermal evolution and contraction (Mitri et al., 2010)
  - Externally driven forcing, from tidal interactions and/or atmosphere (decreasing eccentricity, non-synchronous rotation, polar flattening)
  - Large impacts

Paganelli et al. (2010)

# IMPACT CRATER MORPHOLOGIES

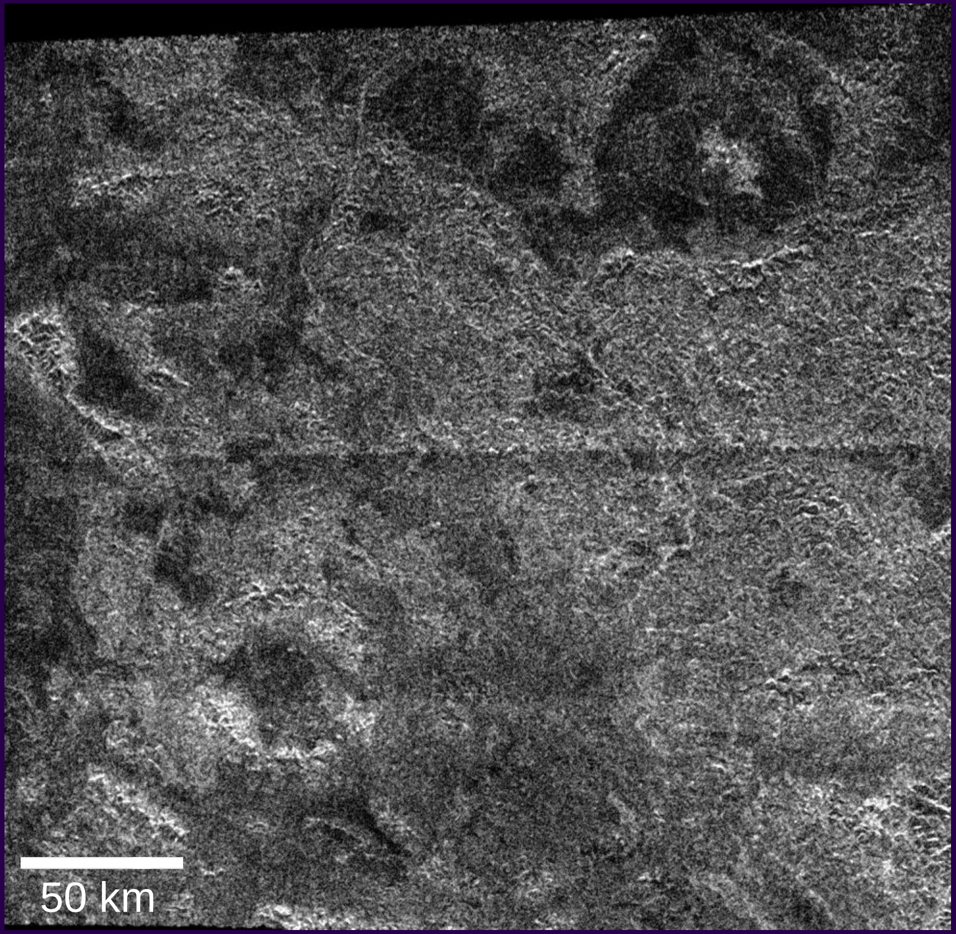
- Implies Titan's lithosphere is stiffer than those of the icy Galilean satellites.



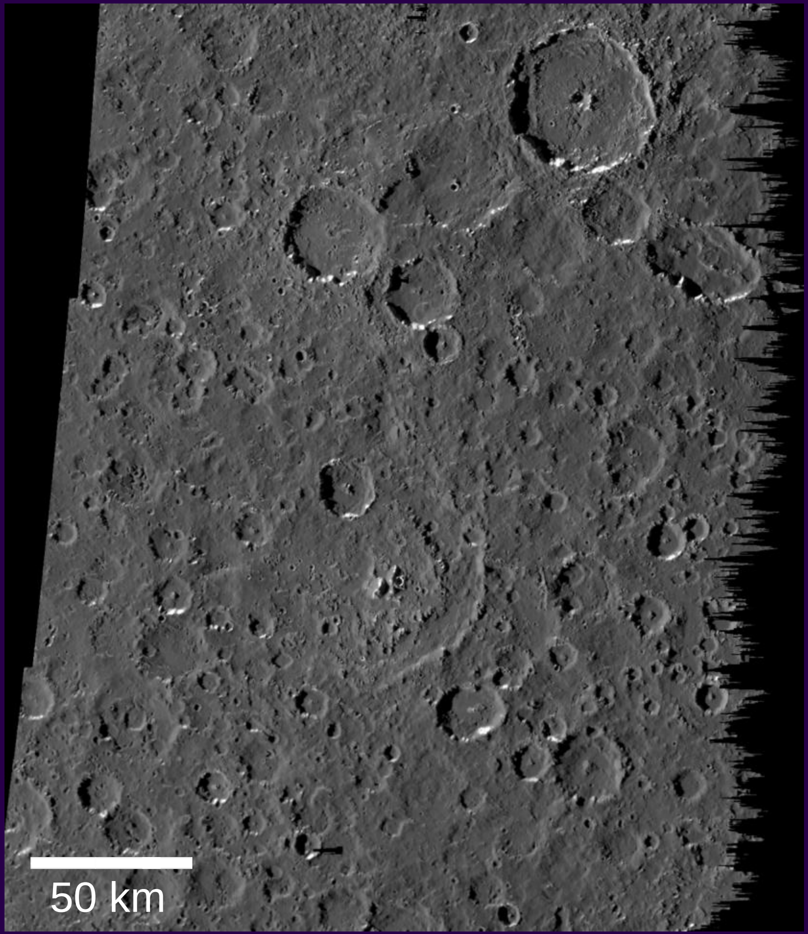


# TITAN: CALLISTO WITH WEATHER?

Xanadu: Eroded cratered craton?




Xanadu, Titan




Cratered terrain, Callisto

# Can Fluvial Erosion Patterns Tell Us Anything about Initial Landscape Types?

**We ask the questions:**

(1) To what degree can the formative processes and morphology of an initial endogenic or cratered landscape be inferred after sufficient modification by fluvial erosion as to resemble Titan's surface?

(2) How much erosion would have had to occur to make inferences about the nature of the initial landscape impossible?

**Our goals are to:**

(1) determine the existence and recognizability of endogenic processes on Titan

(2) the relative dominance and nature of fluvial activity over the landscape

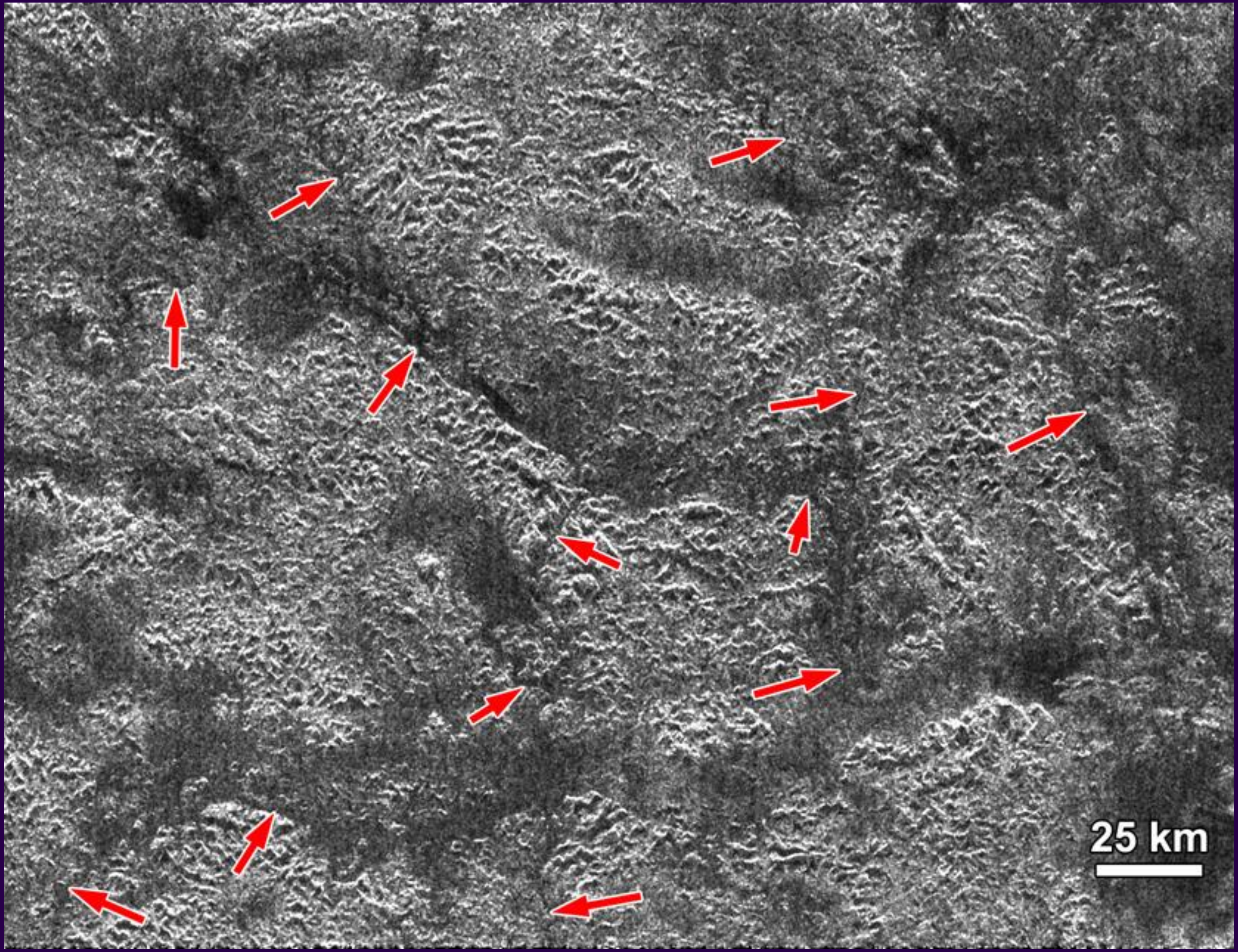
(3) the expression and rates of landform erosion and sediment redistribution, and

(4) the specific morphological expressions of modified endogenic landforms

# Here we give preliminary results our model

We use a landform evolution model to simulate fluvial and lacustrine modification of icy satellite landscapes to evaluate whether fluvial erosion of these landscapes can begin to replicate the present Titan landscape. We performed modeling work on several initial landscape types:

1. A mixture of endogenic belts and zones with blocks of older cratered terrain but little regional relief (Ganymede)
2. A thoroughly tectontized surface with little regional relief (Europa)
3. A regionally cratered and mantled landscape with some regional relief due to impact basin ring tectonics (Callisto)




Uplands region on Titan with pronounced “banding” or “crinkling” interpreted to be ridge and valley patterns of fluvially-dissected topography. Red arrows point to trunk fluvial valleys. Smooth, dark areas are interpreted to be sedimentary basins.

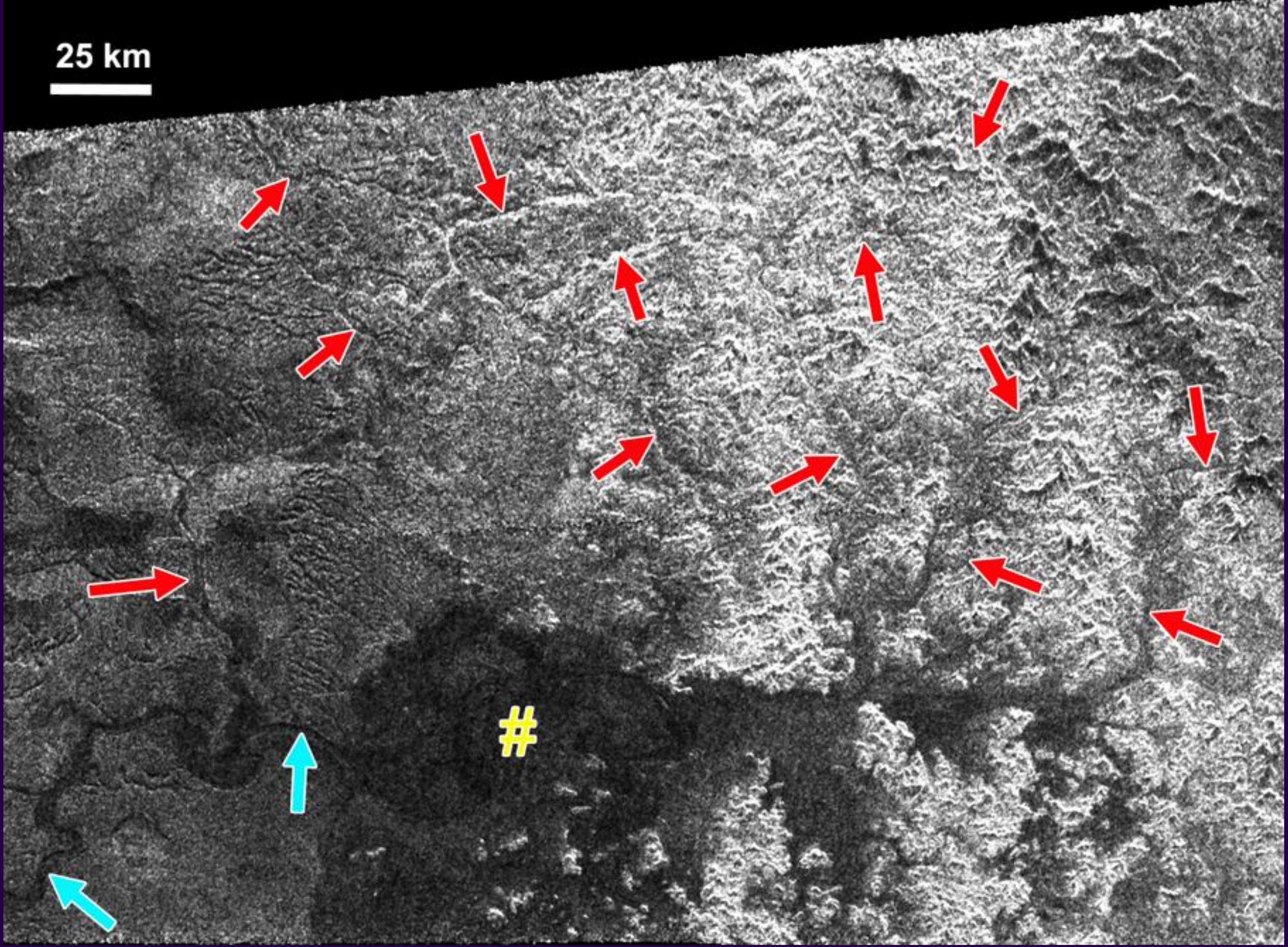


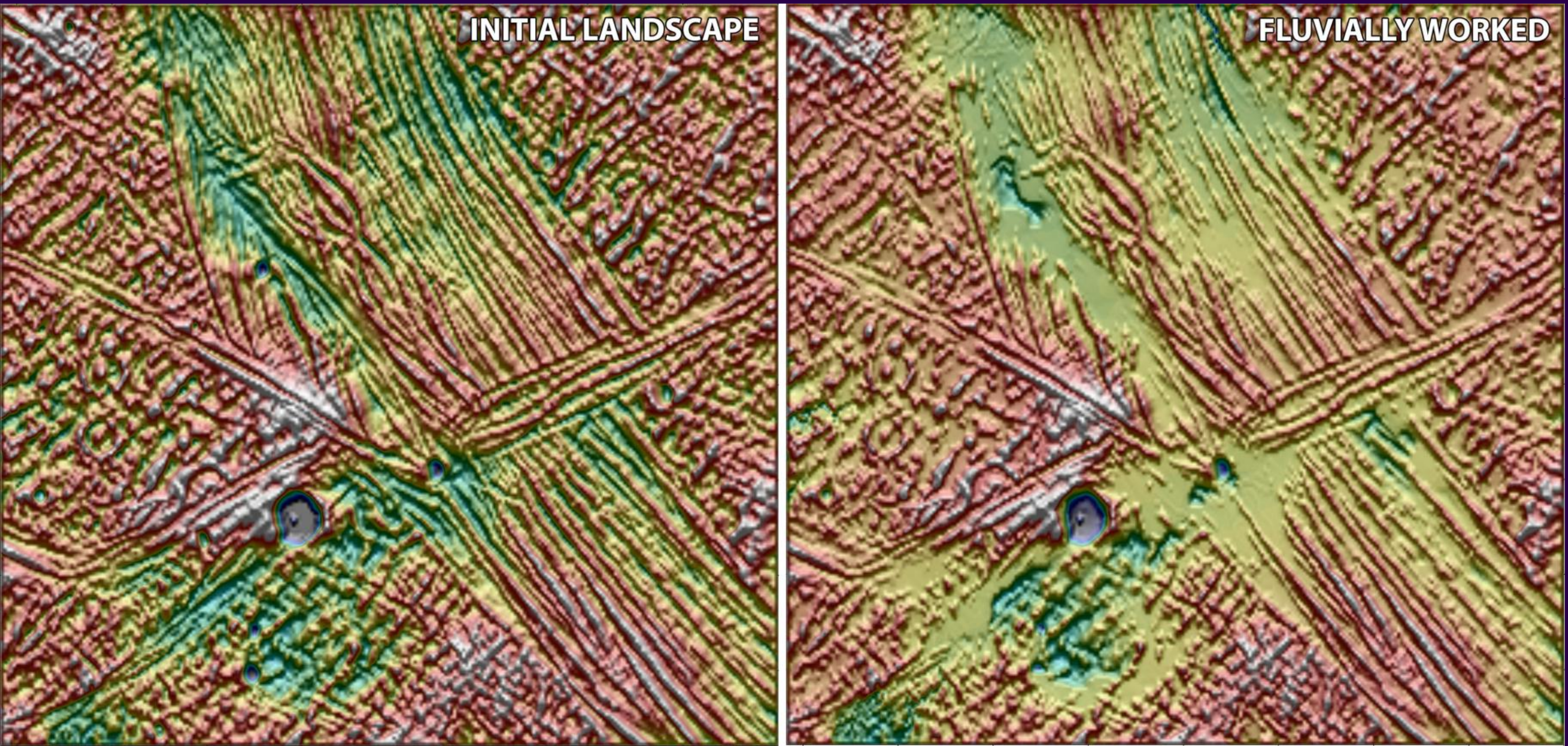
Image of dissected uplands in high southern latitudes of Titan. Blue arrows point to sinuous channel flowing into smooth dark area at “#” which we interpret to be a sedimentary basin possibly shallowly covered by a methane lake.  Red arrows point to trunk drainages in dissected uplands.

# Initial Model Assumptions:

- Complete runoff, so that depressions become lakes, and drainage exits somewhere along edges of simulation domain
- Edges of simulation domain are fixed (non-erodible)
- Flow rates scaled to Titan gravity
- Rate of channel incision proportional to shear stress on bed (parameterized as a power function of discharge and gradient)
- Weathering produces transportable debris
- Sediment is deposited in low-lying areas, producing alluvial fans and infilling depressions from the edges inwards in deltaic deposits
- There is little fine suspended sediment deposited in lakes
- The spatial pattern shouldn't vary much with different parameters *but* the rate of erosion would be very affected.

# Tiamat Region, Ganymede

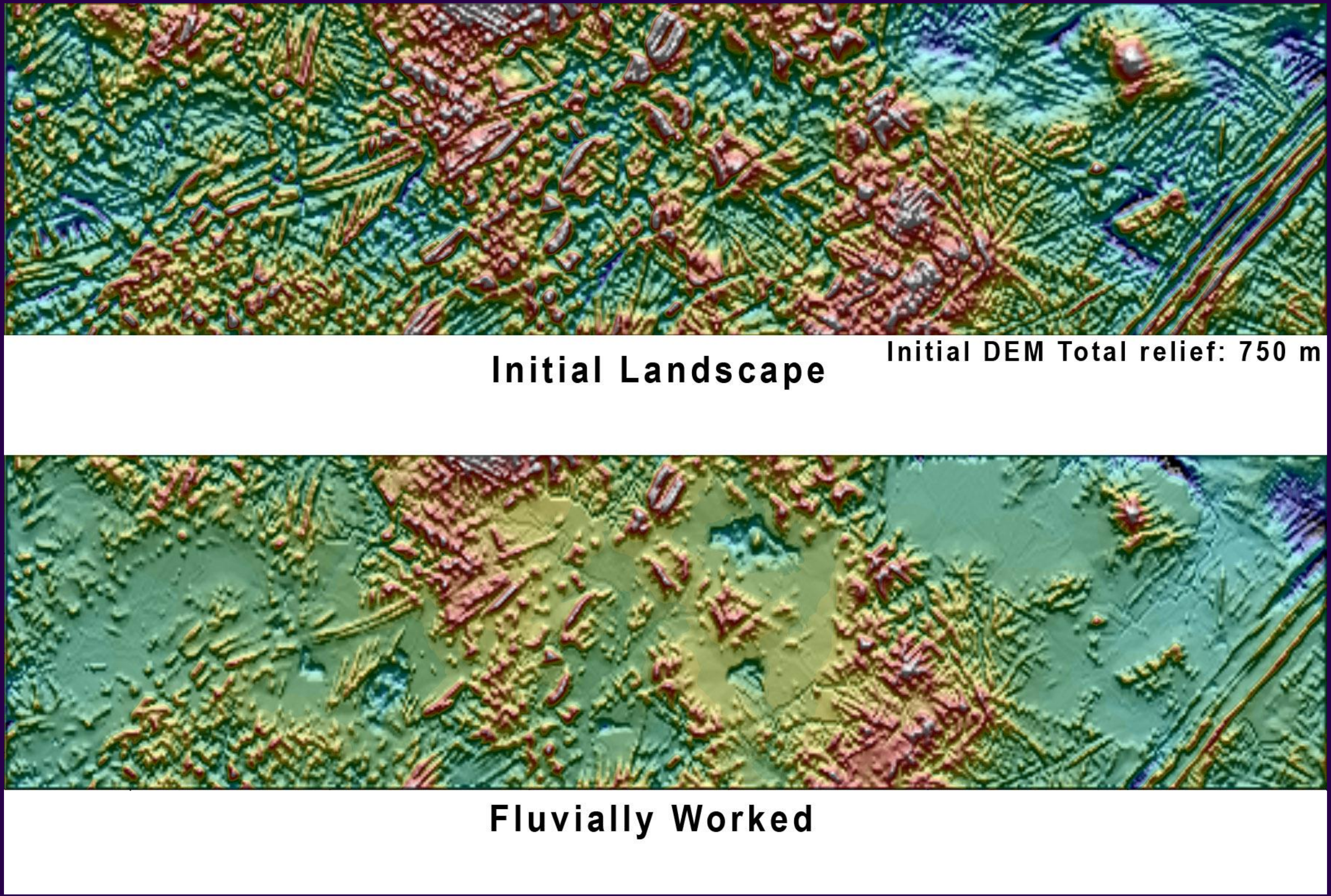
- There are no long, deeply-incised valleys but there are extensive alluvial plains
- Some depressions remain unfilled – hosting lakes
- The remaining depressions (lakes) have well-defined shorelines (encroaching delta fronts) that look similar to some of the depressions (lakes and dry lakes) in the polar regions of Titan
- Even extensive erosion of the landscape does not erase the signature of the original tectonic overprint on the topography



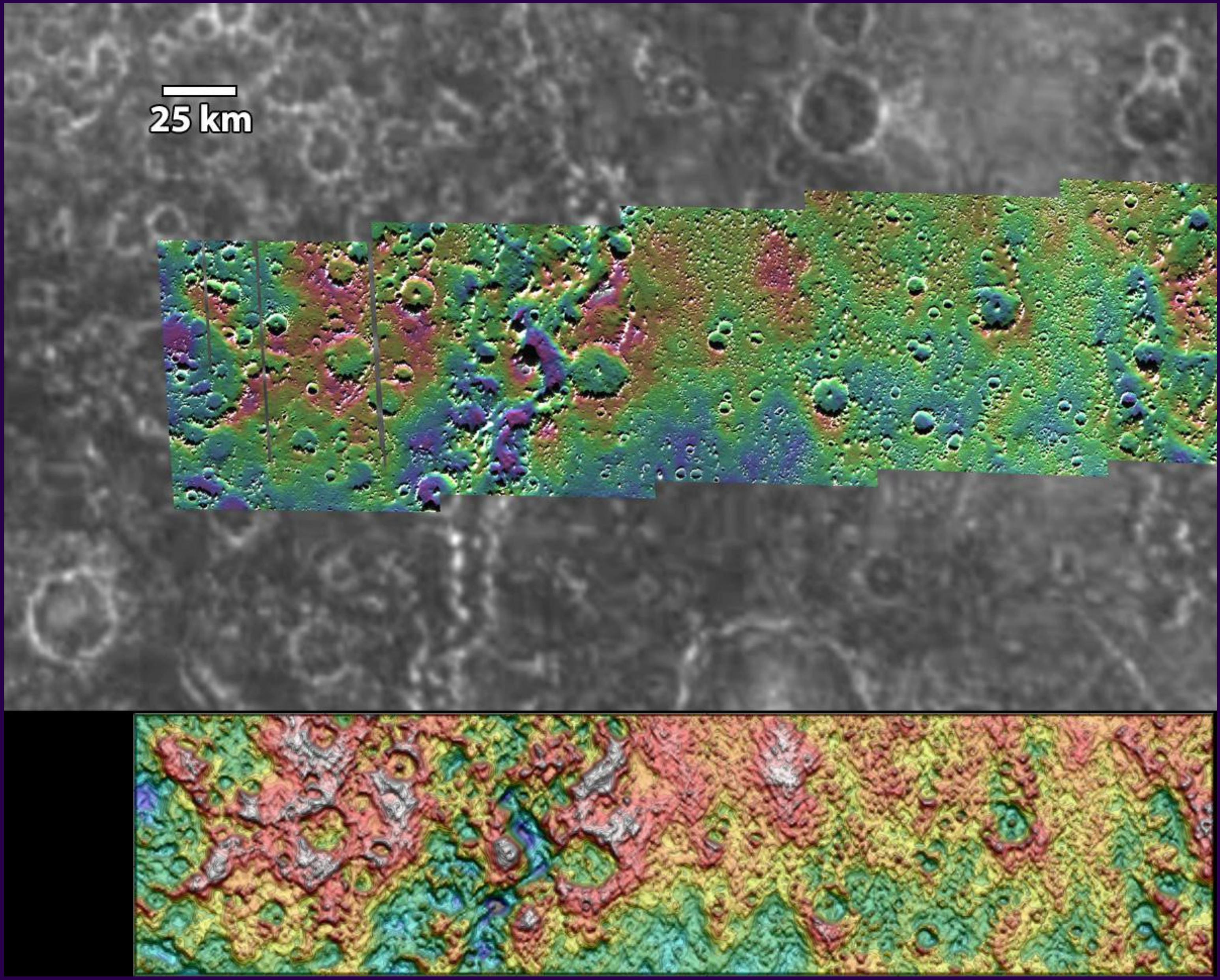

Initial DEM Total Relief: 1 km

# Conamara Chaos, Europa

- Similar situation to Ganymede after fluvial action: no long, deeply-incised valleys & the persistence of the signature of the original tectonic overprint on the topography

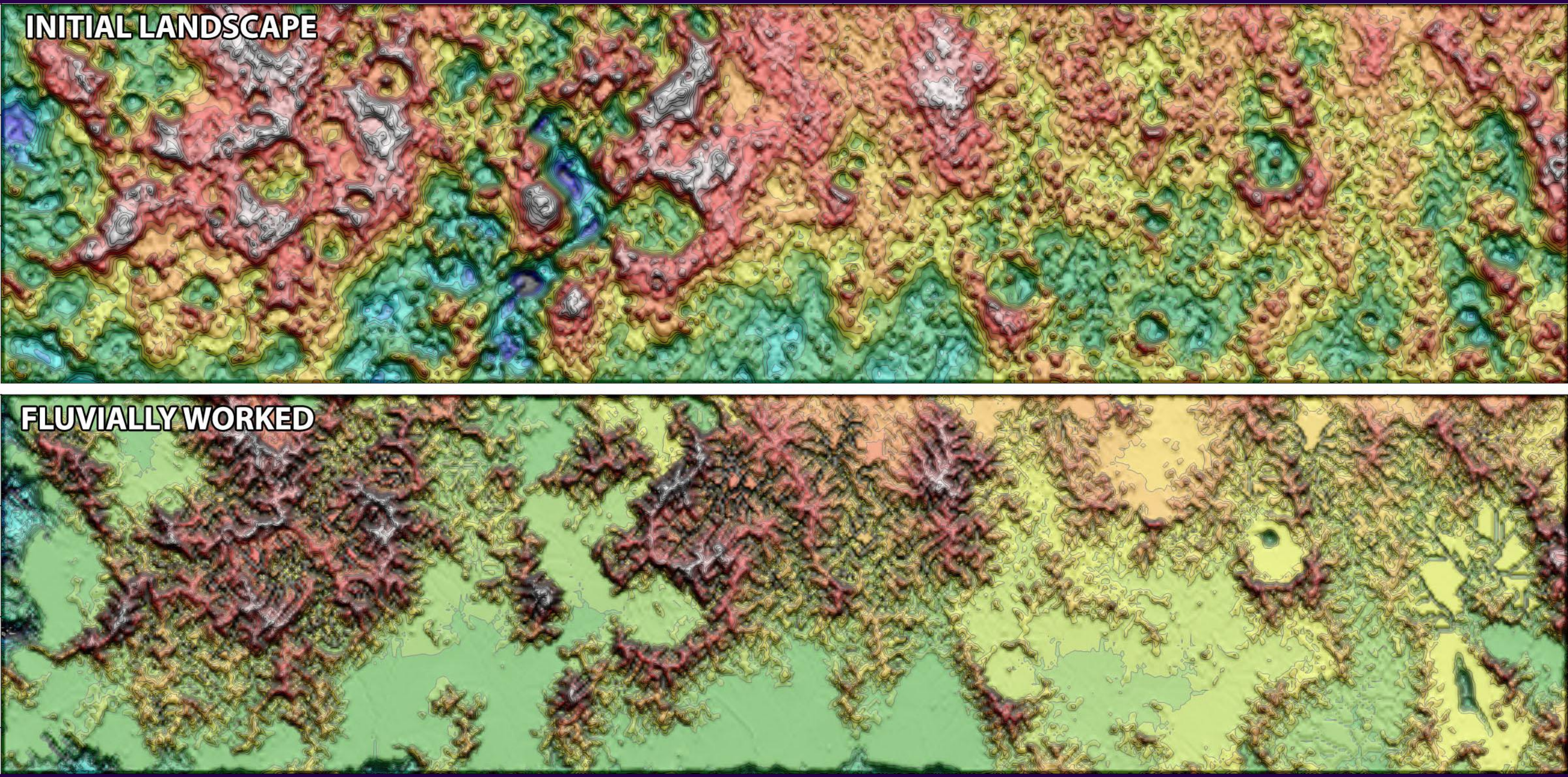


# ASGARD RING-GRABEN SYSTEM, CALLISTO

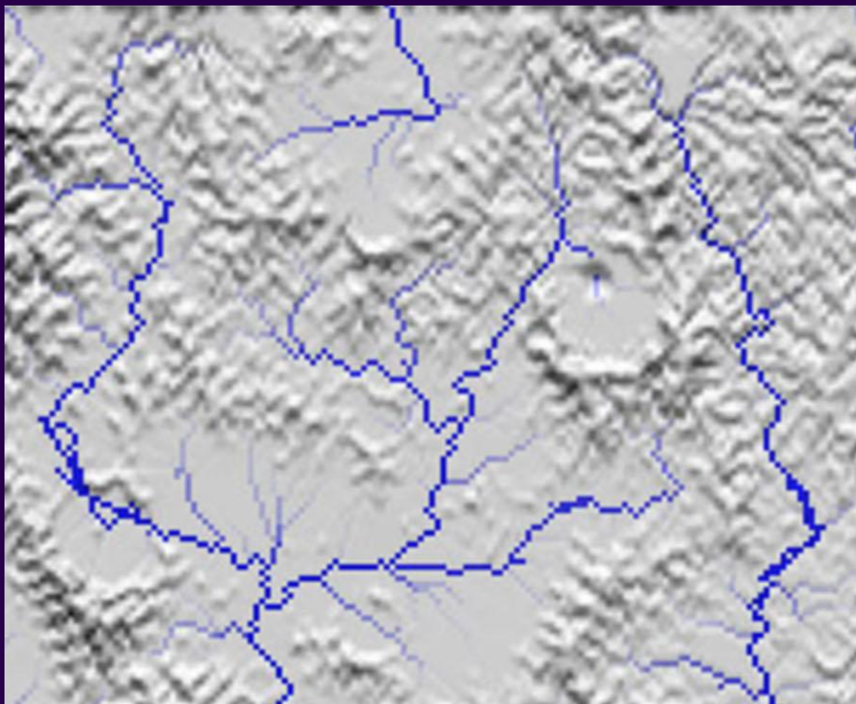


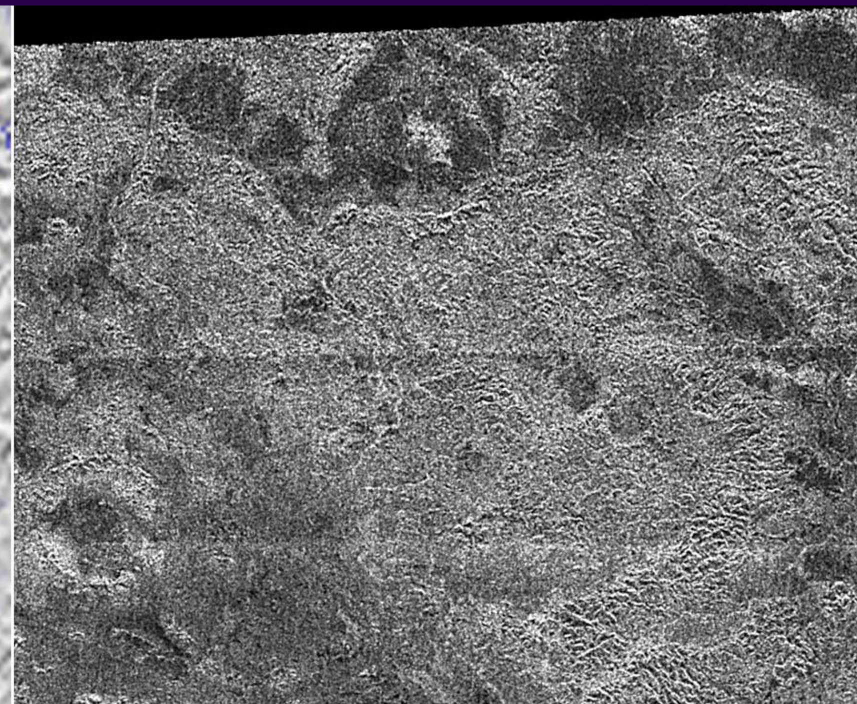

Initial DEM Total Relief: 2.5 km

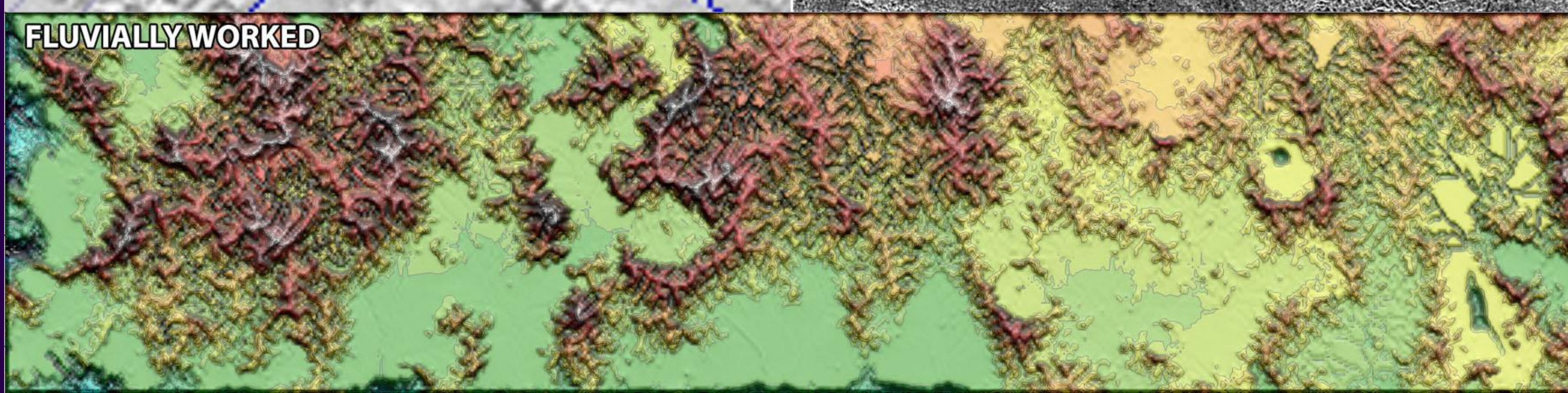
# ASGARD REGION, CALLISTO
# AFTER FLUVIAL WORK



Callisto's cratered surface, which is mantled (but so is Titan's by atmospherically derived solids) and only weakly tectonized (i.e., basin ring graben) when rained upon produces a surface where the highlands are fluvially dissected and the lowlands are broadly filled with sediment. This resembles much of the highlands of Titan much more than Ganymede or Europa with rain.





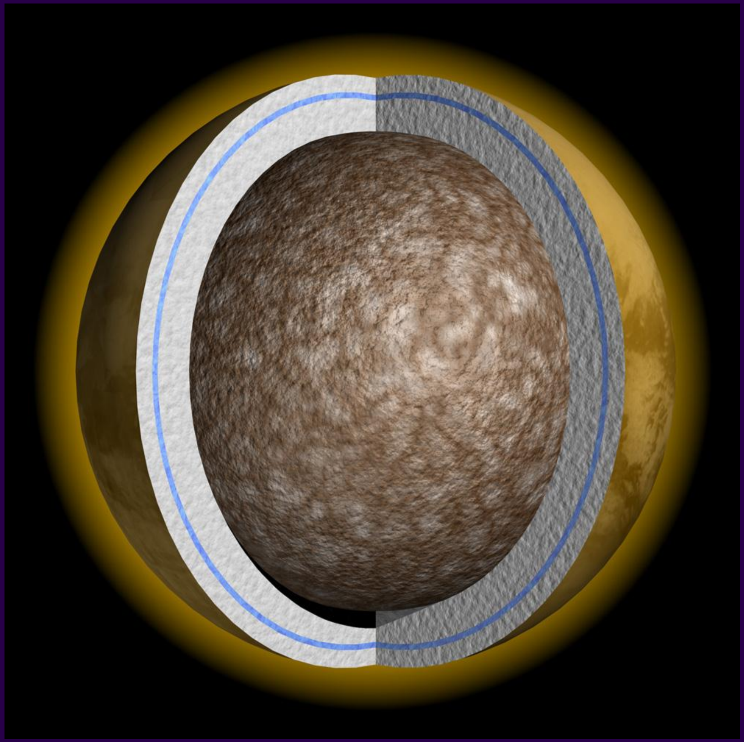


# Preliminary Conclusions form Landform Modeling

- Combination of convoluted short wavelength topography (as exemplified by the intensely tectonized landscapes of Ganymede and Europa) and little overall regional topography (~ 1 km) results in little erasure of tectonic texture and poorly expressed (though well integrated) fluvial networks when rained upon.
- This same modeling suggests that initial landscapes like that of Callisto with larger regional relief (on order 2-3 km) and weakly tectonized *is* susceptible to large-scale fluvial dissection, valley network formation, and alluvial infilling of low regions, and produces a landscape that reasonably resembles Xanadu.
- SOME ISSUES: The importance of fluvially transportable sediment
- What might the the consequences of compensative uplift of highlands undergoing fluvial denudation?
- How much erosion can an uplands landscape endure before the original texture (craters or otherwise) become unrecognizable?

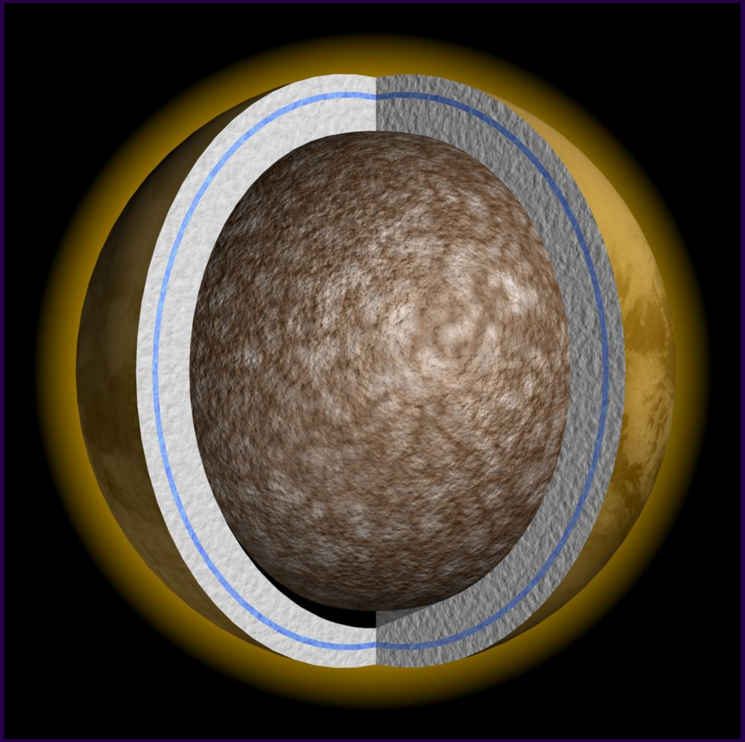
# TITAN: An internally Quiescent World?

- Titan might have accreted relatively cold
- Titan may never have experienced significant tidal heating
- Titan may be incompletely differentiated (that is, the heavy material may not have completely separated out and sunk toward the center)
- No internal magnetic field is expected (or has been detected) at Titan



# CONSISTENCY WITH GEOPHYSICAL ARGUMENTS

- A cool, quiescent interior is consistent with incomplete differentiation (Iess et al., 2010)
- A cool interior is consistent with Titan’s flattened shape which suggests a currently conductive (not convective) ice shell above a cool ammonia-water ocean (Nimmo and Bills, 2010)
- An internal ammonia-water ocean ocean is permitted even if the deep interior is incompletely differentiated
- Titan's orbital eccentricity (0.029) should have damped if its interior is warm; its high eccentricity can be ancient if the interior is cool and relatively non-dissipative.



# TITAN: CALLISTO WITH WEATHER?

- Different from Callisto, Titan has a thick atmosphere:
  - Impacts can generate significant atmosphere at Titan (and Callisto) [Zahnle et al. 1992; Zahnle, 2010]
  - Titan’s atmosphere may have inflated then deflated through time [McKay et al. 1993; Lorenz et al., 1997; McKay, 2010].
  - Titan’s $^{40}Ar$ could be remnant from LHB [McKinnon, 2010 LPSC]

# TITAN: CALLISTO WITH WEATHER? CONCLUSIONS

- The only unambiguously identified landforms on Titan are *exogenic* (fluvial, aeolian, impact).
- There are **no** *unambiguously* identified endogenic landforms on Titan (i.e., cryovolcanism).
- A viable working hypothesis is that Titan is "Callisto with weather," with a cool interior and only exogenic geological processes.
- This idea is being tested through additional Cassini observations, geophysical and thermal modeling, and modeling the evolution of landscapes shaped by exogenic processes alone.

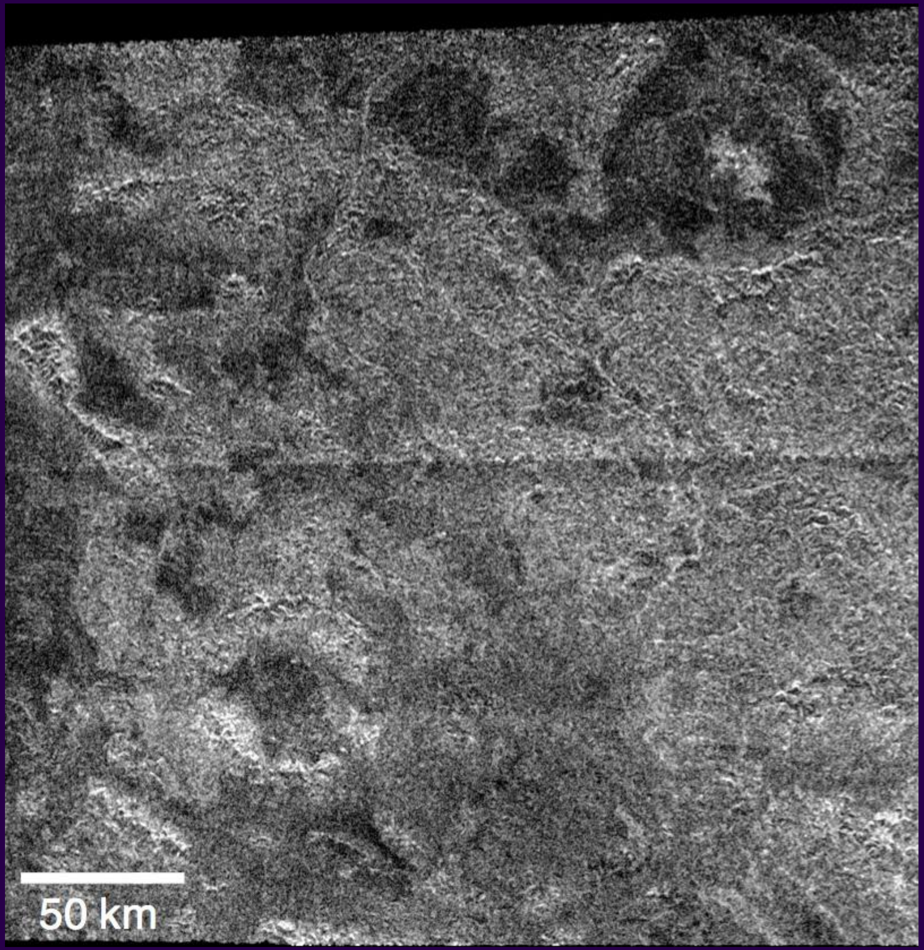
# CLIMATE HISTORY IMPLICATIONS OF ANCIENT CRATERED TERRAIN

If Titan displays regions of degraded ancient cratered terrain, then this would have significant implications for Titan's history. Martian fluvially degraded cratered terrain still exhibits craters because fluvial activity largely ceased soon after the curtailment of heavy bombardment. For Titan to have such terrains *and* ongoing fluvial activity would imply at least three possible explanations:

(1) methane fluvial erosion on Titan is extremely inefficient relative to that by water on the Earth and Mars, or

(2) fluvial erosion very rarely occurs on some regions on Titan; or

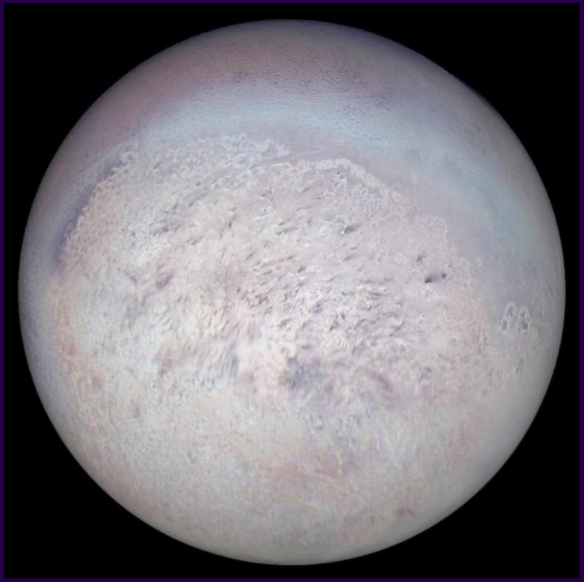
(3) it has started raining on Titan only in geologically recent times.



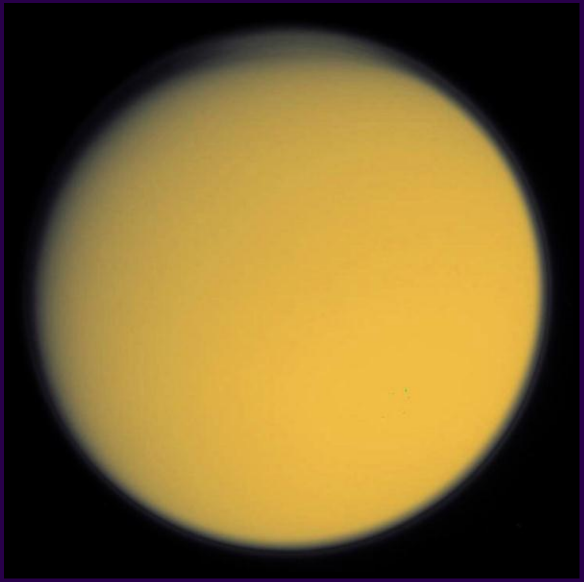
# TITAN: PAST, PRESENT, FUTURE

## The "Triton-Titan-Mars" Hypothesis of McKay, Lorenz, and others

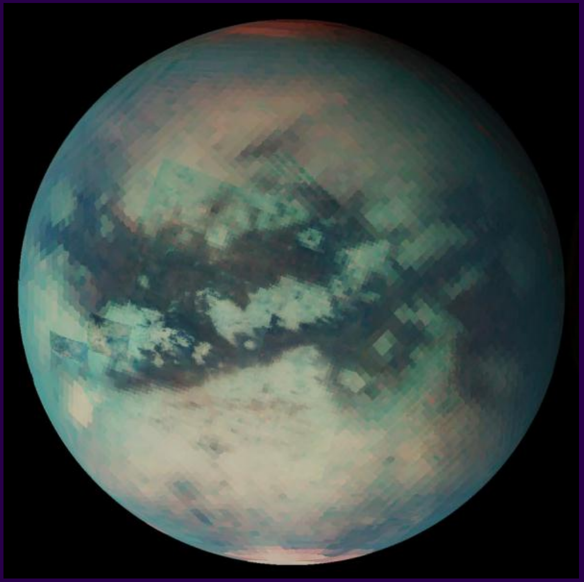
Until a Billion Years Ago?



Present



Billion Years from Now?



For most of Solar System History N and $CH_4$ lie frozen on the surface until Solar brightening (and possibly a large impact event) created the atmosphere, initially with many times the $CH_4$ as present. No new outgassing of $CH_4$. Atmospheric $CH_4$ will be exhausted in less than 1 billion years, forming dark detritus.

Mid 20th Century Artist Chesley Bonestell may have portrayed a realistic Titan after all, but one which will exist in the future