Gale as a preferred site for snowmelt-limited induration of atmospherically transported sediment: *A testable hypothesis for MSL, with global implications.*

Edwin Kite, Michael Manga, Itay Halevy, Melinda Kahre

MSL final landing site workshop, 17 May 2011

Snowmelt hypothesis for sedimentary rock water source

- Mars sedimentary rock record is a **wet-pass filter**
  Induration of atmospherically-transported sediments probably requires liquid water [*Lewis et al*., 2008]

- **Source of water? -** Top-down or bottom-up?
  Groundwater requires T_{avg}>273K [*Andrews-Hanna & Lewis,* 2011]. Snowmelt requires T_{max}>273K.
  Mineralogy favors marginally wet conditions. Stratigraphy can accumulate in *O*(10) Ma.
  (Jarosite & hematite stopwatches; geochemical modeling; soil profiles; layer-counting.)

- Importance of **orbital diversity**

- **Snowmelt** under rare orbital conditions?
  O(10) x PAL CO2. [*Jakosky & Carr*, 1985; *Niles & Michalski*, 2009; *Cadiuex & Kah*, 2011]
  High obliquity, moderate eccentricity, perihelion at equinox [*Kite et al*., in press]

Global model, identifying Gale as a focus of snowmelt activity

Hypothesis: Early Mars encountered orbital conditions that were favorable for snowmelt *at observed sedimentary rock locations* [*Malin et al.*, Mars, 2010]

Global test:

1) For all possible Early Mars orbital conditions:

2) Use 1D model to calculate potential snow temperature for all seasons and latitudes.

3) Find locations of inter-annually persistent snow, by minimizing annual-average sublimation.

4) Weight results using Early Mars orbital pdf [*Laskar et al.*, 2004]. Compare to data.

1D thermal model: Deep snowpack with material properties from *Carr & Head, GRL, 2003*

$$\left(\frac{1}{\rho c_p \Delta z}\right)\frac{\partial T}{\partial t} = -k\frac{\partial T}{\partial z} - \underbrace{\epsilon\sigma T^4 + LW\downarrow + (1-RCF)(1-\alpha)L_*}_{\text{radiative}} - \underbrace{SH_{free} - SH_{forced}}_{\text{sensible}} - \underbrace{LH_{free} - LH_{forced}}_{\text{latent}}$$

Age = 3.5 Gyr (~0.76 x L_0); albedo = 0.28. Wind-speed and air-surface ΔT fit to Ames GCM output. Longwave forcing (*LW*) & Rayleigh scattering correction factor (*RCF*) from 1D atm. column model

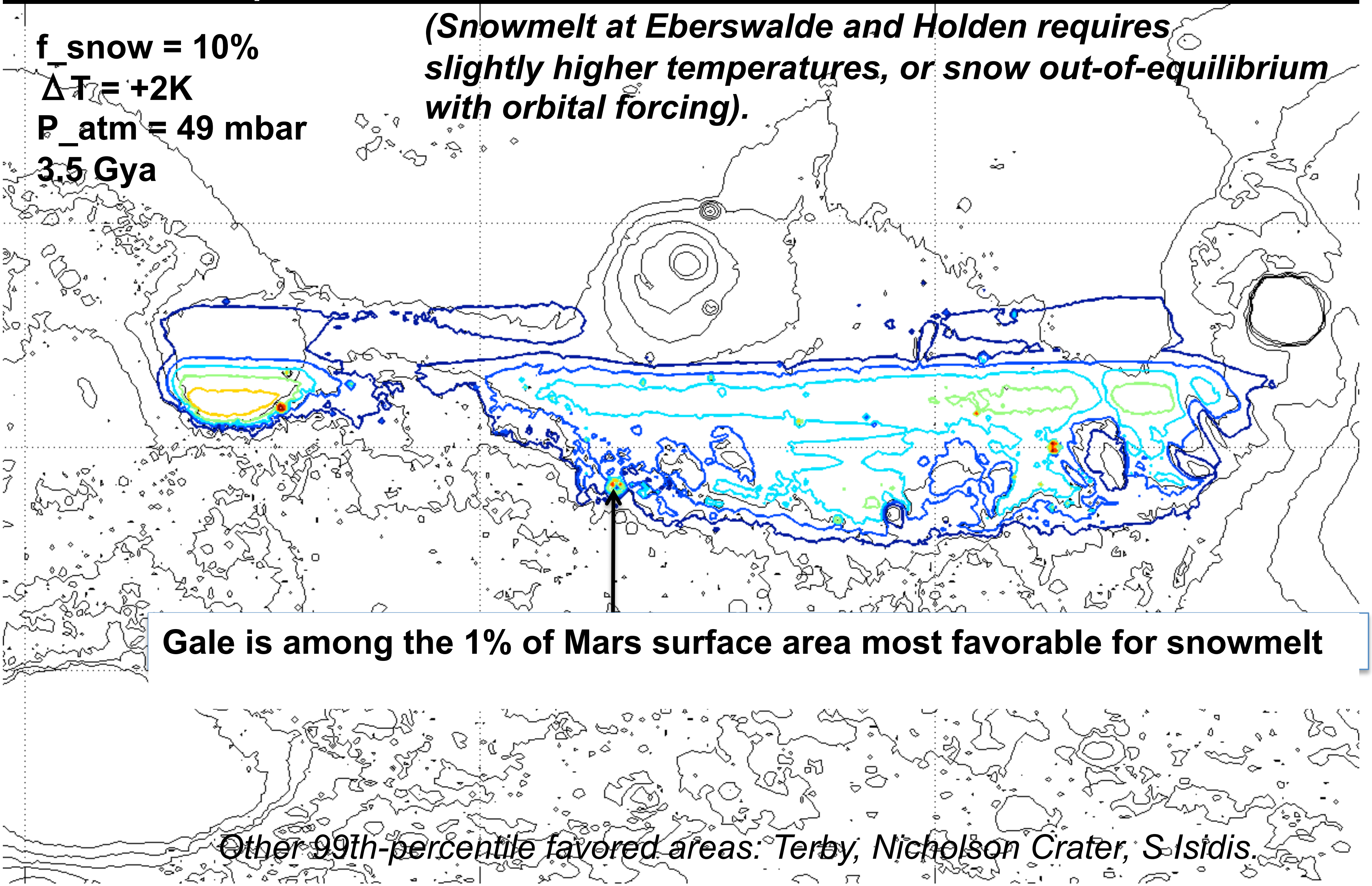
Where will interannually-persistent snow accumulate?

$$m_{free} = 0.14\Delta\eta\rho_{ave}D\left(\left(\frac{\Delta\rho}{\rho}\right)\left(\frac{g}{\nu^2}\right)\left(\frac{\nu}{D}\right)\right)^{\frac{1}{3}}$$

Dundas & Byrne, 2010

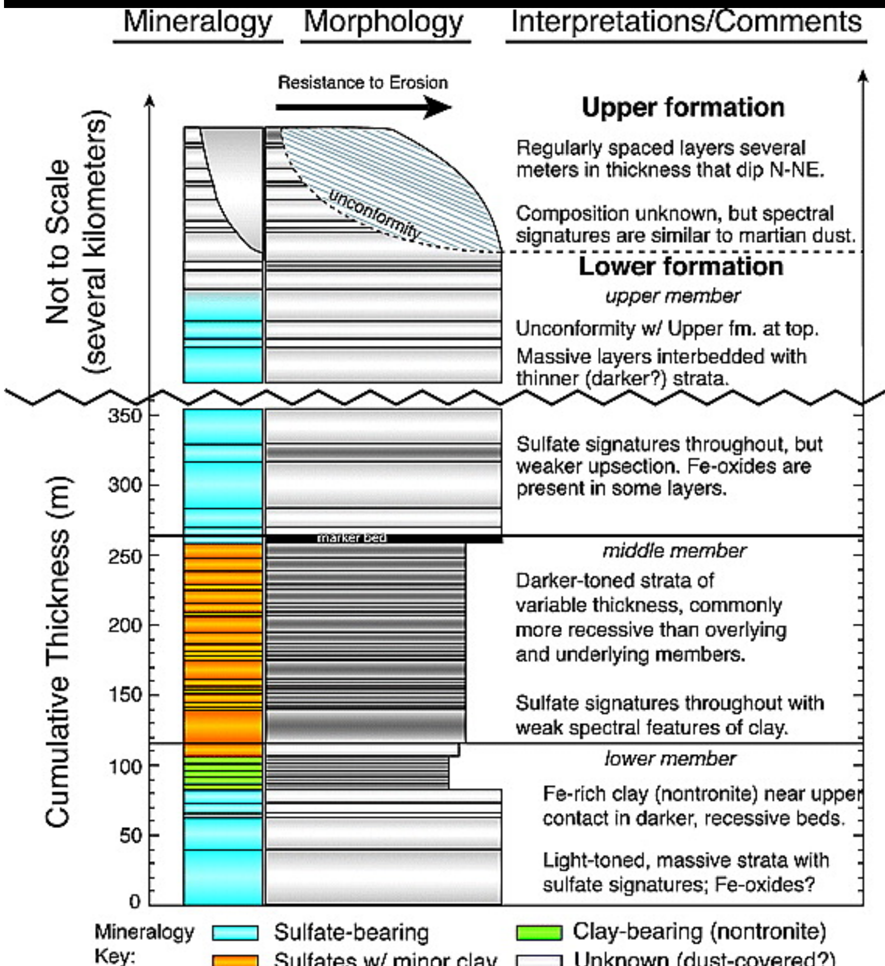
Assumption: Snowpack is only found at the locations of minimum annual-average potential **total** sublimation. (Snow can migrate to track orbital changes.)

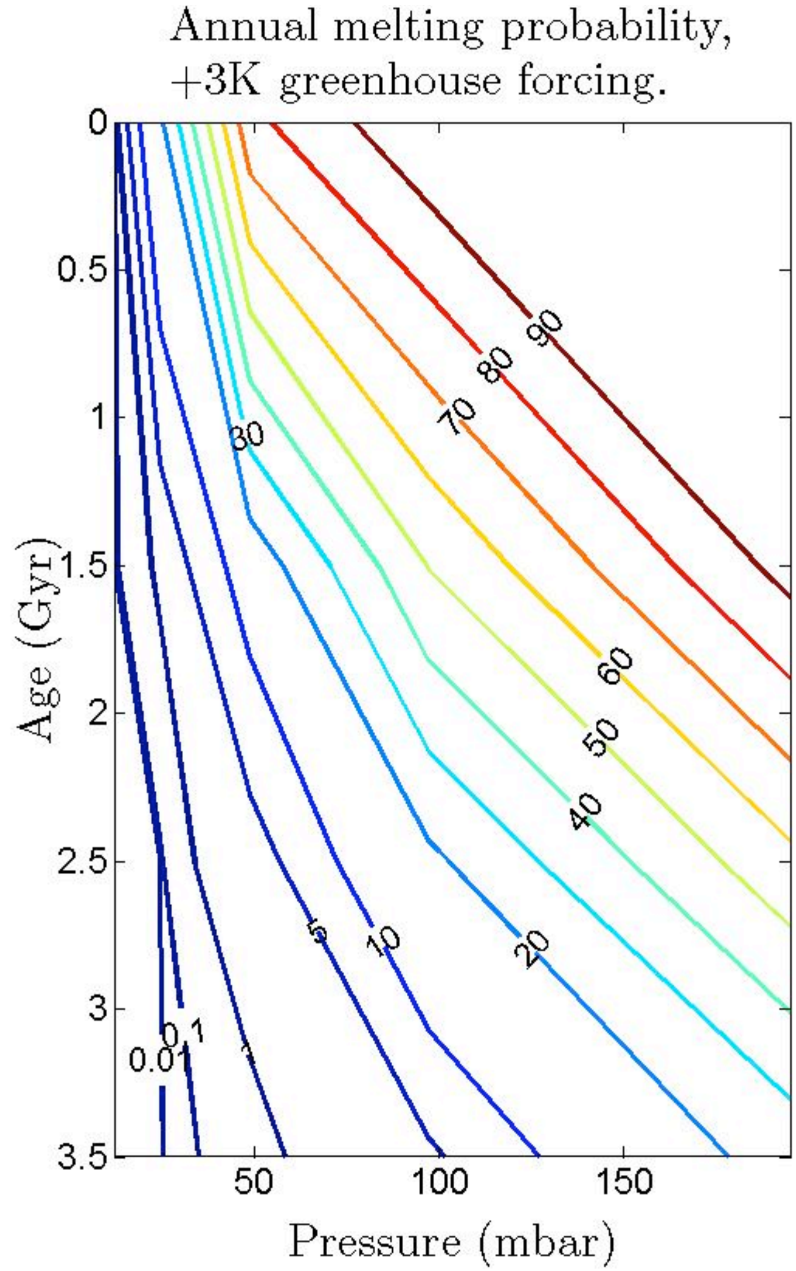
Model output: High obliquity, moderate eccentricity, and perihelion at equinox are optimal for snowmelt. **Melting occurs *O*(1%) of the time. Optimal snowmelt zones are at equatorial latitude and low elevation – and include the floor of Gale.**



Water input: Competition between solar brightening and atmospheric loss recorded by snowmelt at the lower Gale mound.

Lithic input: “Globally averaged” sample?





0^4

[*Milliken et al.*, GRL, 2010]

EXAMPLE *marginalized over orbital pdf*

New model | Why is Gale special? | Predictions for Gale | Tests with MSL at Gale

Problems with my model

→ **3.5 Gya, 49 mbar temperatures at Gale are only just above freezing.**
- Not clear that runoff and channel formation is possible.
- Higher pressures would drive snow to high ground.
- Non-CO_2 greenhouse forcing? 3D effects? Transients form channels? Some sedimentary rocks younger than 3.5 Ga?

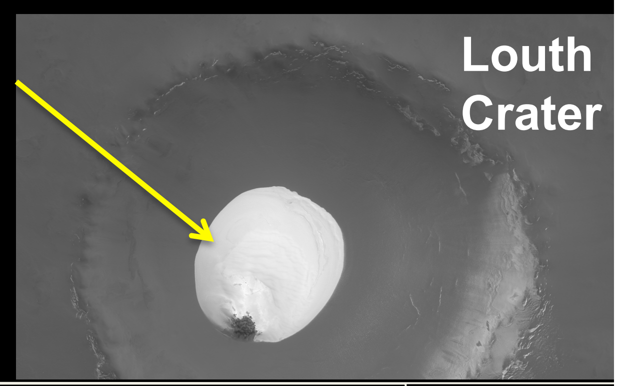
→ **Median number of "years with some snowmelt" is less than mean number of "years with some snowmelt"**
- However, the probability of exeeding *e* = 0.15 is ~80%.

→ **No precipitation in snow location parameterization – but we know this is important in the late Amazonian (e.g., flanks of Tharsis Montes)**

owever, craters do act as cold traps.

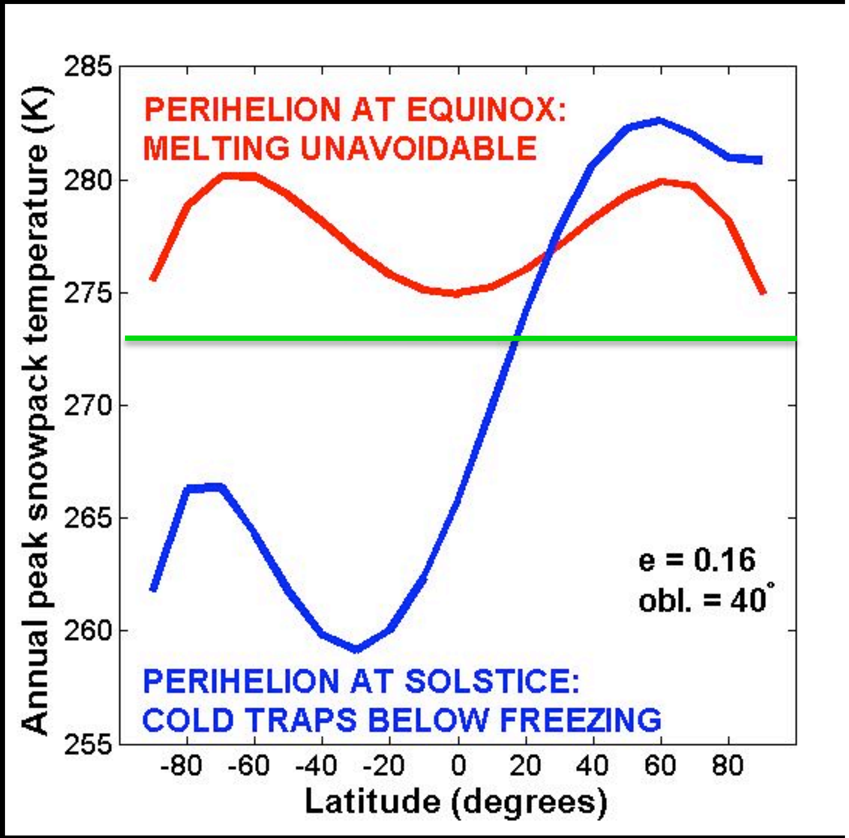
Low latitude
(Shean, GRL, 2010)

High latitude
(e.g. Conway et al., LPSC, 2011)



Predictions for MSL: trends, rhythms and aberrations

Hypothesis: The lower Gale mound is an accumulation of atmospherically-transported sediments that were indurated by snowmelt-limited processes.



PRELIMINARY

Testable by MSL:

1) Large-scale **geochemical and textural homogeneity**, and extremely limited primary depositional variations in a given layer.

2) **Wet-dry cycles on orbital timescales.** *We can relate the fraction of stratigraphic section that must have formed under wet conditions to the warmth of the the background climate.*

3) **Clay→sulfate corresponds to changes in clastic input**, not changing water activity.

4) Secular decrease in sulfate correlates with decrease in volcanic input (tephra).

5) **No evidence for lakes filling Gale Crater** (local lakes are possible, as in the Dry Valleys).

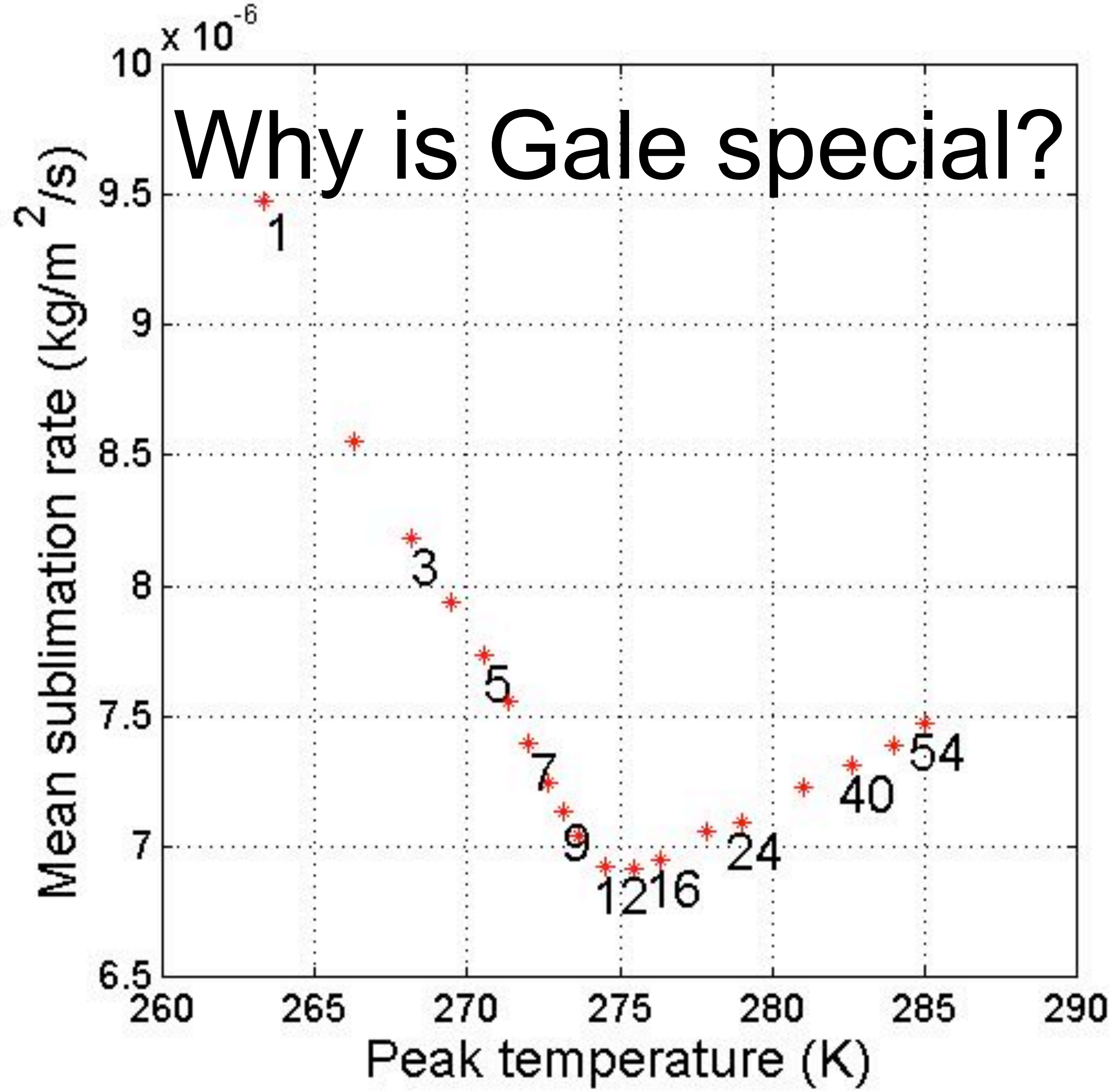
Backup

Hypothesis test at Gale

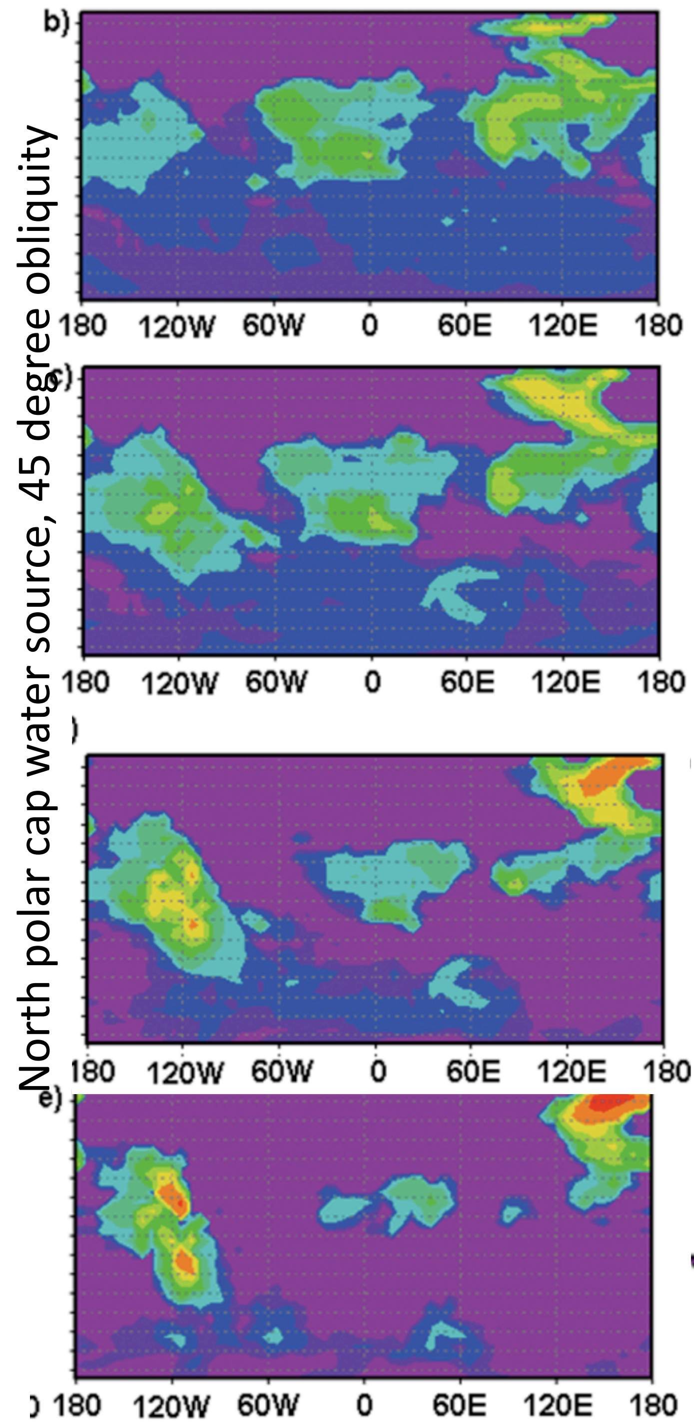
Hypothesis: The lower Gale mound is an accumulation of atmospherically-transported sediment that was indurated by snowmelt-limited processes

Prediction	Measurement objective	Measurement requirement	Instrument requirement	Traverse requirement
Geochemical and textural homogeneity			MastCam+MAHLI +APXS+ChemCam +SAM+CheMin	
Orbital wet-dry cycles			MastCam+MAHLI+ +DAN	At least 10m stratigraphic
Clay→sulfate due to changes in clastic input	Mineralogy + APXS + MAHLI through the clay→ sulfate transition		APXS+MAHLI +ChemCam+SAM+ CheMin	
Secular decrease in sulfate				Reach 260m stratigraphic (upper part of lower member
No Gale-filling lakes		Sedimentary textures	MastCam+MAHLI	

Why is Gale special?



Precipitation versus sublimation - model-dependent in GCMs



Favoring broad precipitation:

high pressure

high dust column abundance

low water column abundance

(lag formation on sources)

Mischna & Richardson, 2nd Mars Atm. Workshop, 2006

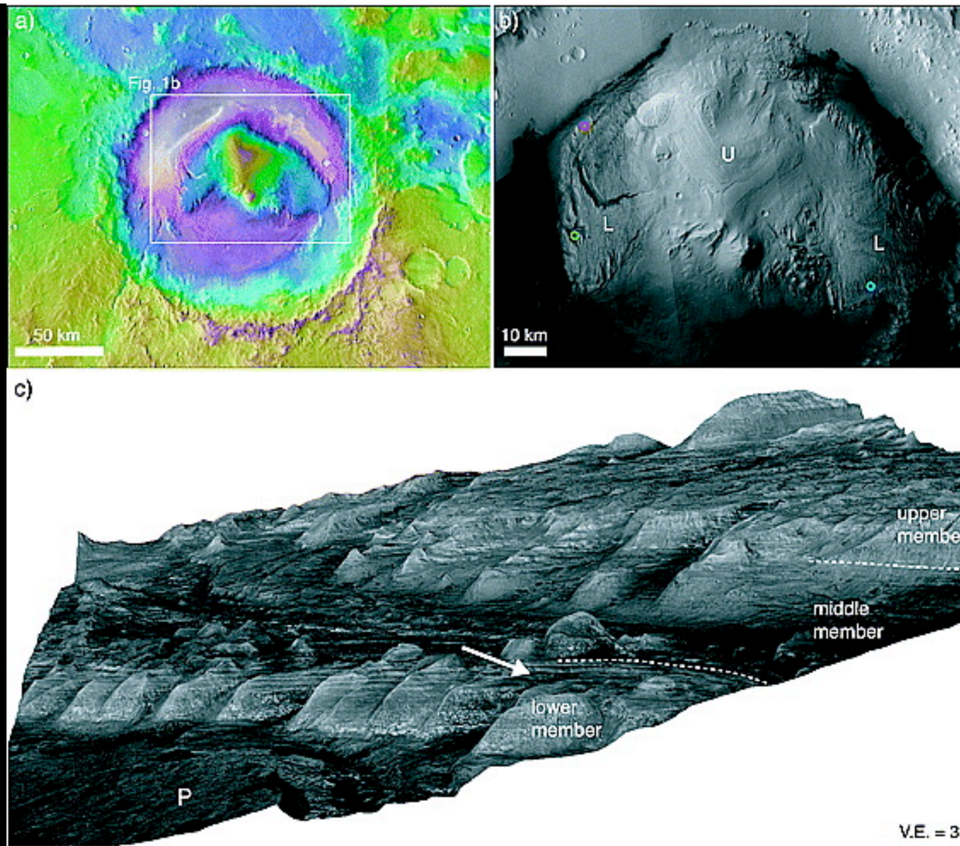
Albedo: The probability of melting depends on snow albedo, which is high for pure snow but much lower for realistic, dust-contaminated snow. *Warren & Wiscombe* [1980] show that 1000 ppmw of Saharan dust can reduce ice albedo from >0.9 to 0.3. In the words of *Langevin et al.* [2005], "Water ice is very bright in the visible spectrum when clean, but even a small amount of dust contamination can reduce the albedo to values close to that of the dust itself if the dust grains are embedded in ice grains." *Clow* [1987] shows that 1000 ppmw dust reduces snow albedo to 0.45-0.6 for ice grain sizes 400μm - 100μm, respectively. This is for precipitation grain sizes in our model; metamorphism will increase grain size and decrease albedo. The mean bolometric albedo of bright regions in Mars' North Polar Residual Cap is inferred to be 0.41 from energy balance [*Kieffer et al.*, 1976]. Near-infrared spectroscopy has identified seasonal water ice layers up to 0.2 mm thick on pole-facing slopes in the Mars low latitudes [*Vincendon et al.*, 2010]. Analysis of the spatial and seasonal dependence of these detections indicates that low-latitude surface water ice has albedo 0.3 – 0.4 [*Vincendon et al.*, 2010]. Modelling of OMEGA data indicates that water-rich terrains in the South Polar Layered Deposits have albedo $\sim$ 0.3 – 0.4 (Figure 7 in *Douté et al.* [2007]). Measurements of the gray ring component of Dark Dune Spots in Richardson Crater at 72°S show it to be composed of seasonal water ice deposits with an albedo of 0.25 – 0.30 [*Kereszturi et al.*, 2011]. When melting starts, the albedo of dust-contaminated ice remains low because "when snow melts, the impurities often tend to collect at the surface rather than washing away with the meltwater" [*Warren*, 1984], forming a lag. Water has a low albedo, so stream and melt pond albedo is lower than unmelted surface albedo. *Gardner

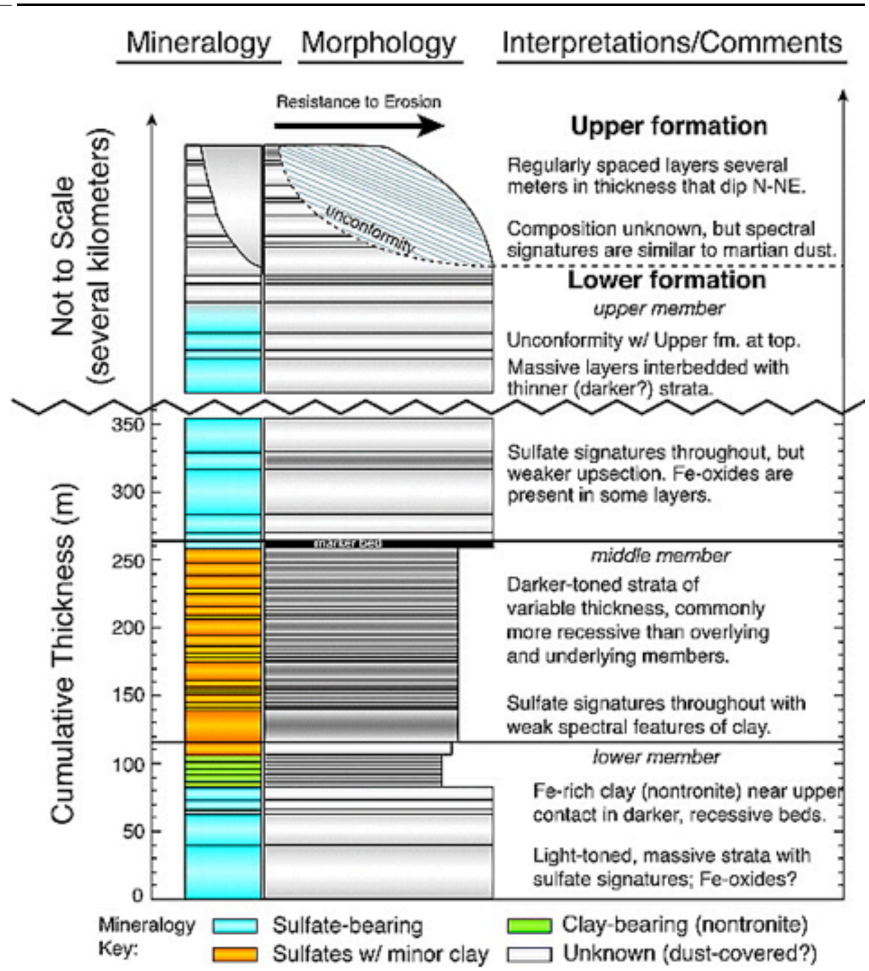
ties often tend to collect at the surface rather than washing away with the meltwater" [*Warren*, 1984], forming a lag. Water has a low albedo, so stream and melt pond albedo is lower than unmelted surface albedo. *Gardner

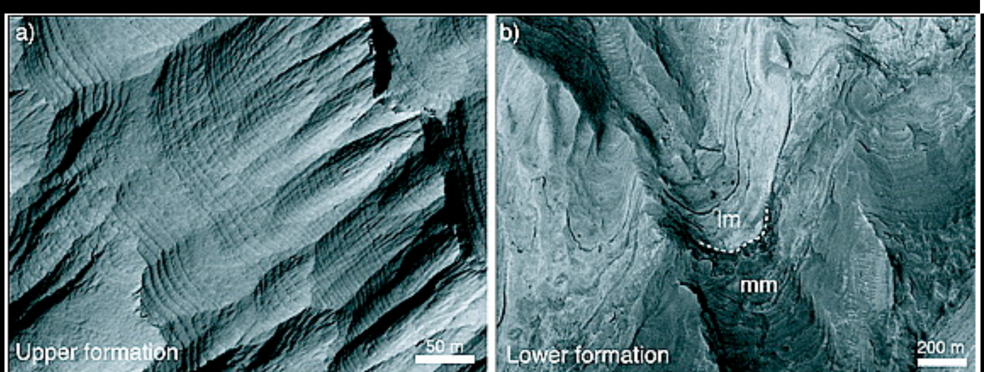
& Sharp* [2010] show that 2 ppmw soot can greatly reduce snow albedo. Soot is 200$\times$ more optically effective than Earth crustal dust, and presumably more effective than Mars dust. We use an albedo of 0.28 (the albedo of Mars' dust continents; *Mellon et al.* [2000]). This corresponds to very dirty snow. Higher albedos will lead to lower melting probabilities (Paper 1).

Talk from LPSC 2011

Gale Crater





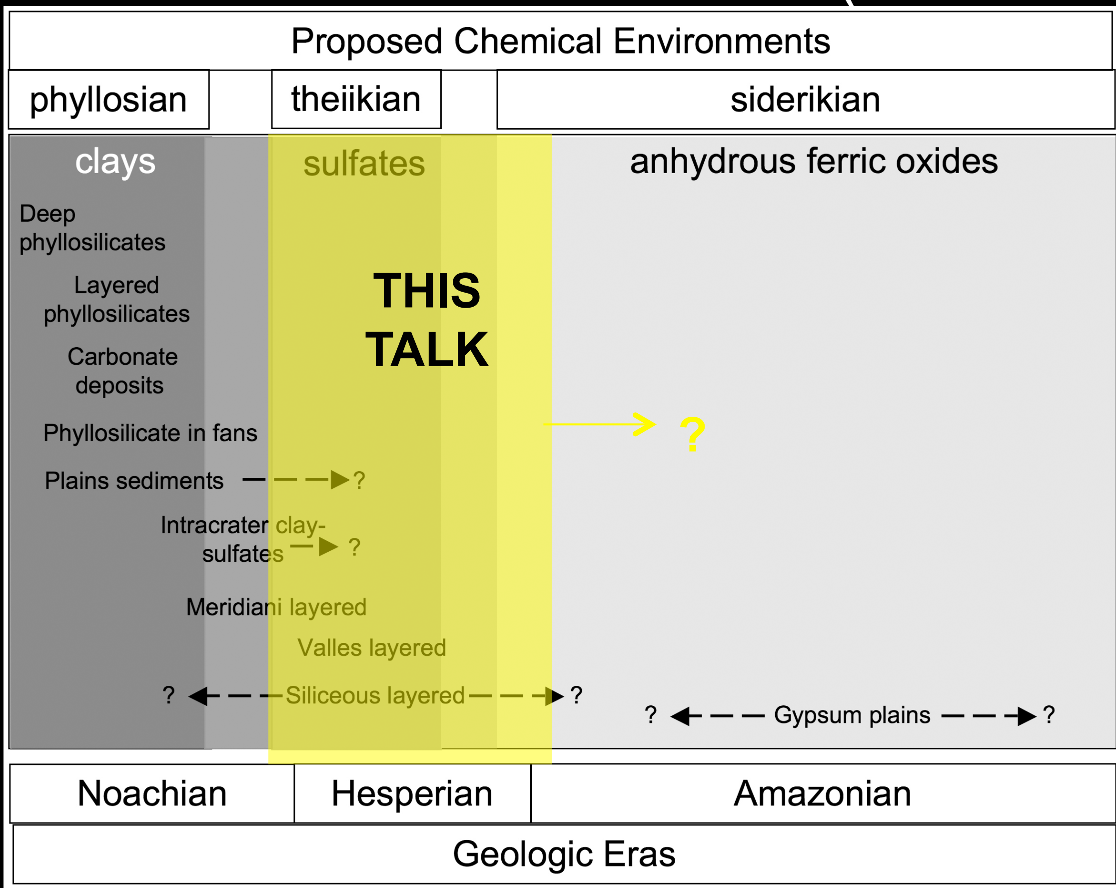


Crater is ~3.5 Gya

Milliken, Grotzinger and Thompson, GRL, 2010

Snowmelt model for formation and distribution of sedimentary rocks on Mars: Multibar atmosphere not required?

Edwin Kite (UC Berkeley),
Michael Manga (UC Berkeley), Itay Halevy (Caltech),
Melinda Kahre (NASA Ames/BAERI)



Murchie et al., JGR 2009

Solar luminosity for 3.5 Gya assumed throughout

What was the water source for the (often sulfate-bearing) sedimentary rocks? Under what environmental conditions (*P*,*T*) did they accumulate?

New global model for sedimentary rock water source

We search for orbital and atmospheric parameters that generate seasonal snowmelt on flat surfaces with $T_{av} << 273$ K. We combine a 1D snowpack surface energy balance model with a simple snow stability parameterisation, run for all orbital conditions, map onto topography, and weight by the corresponding orbital probabilities.

First results

Snow melting occurs even for the Faint Young Sun - for high obliquity, moderate eccentricity, perihelion at equinox, low latitude, at equinox, and $P \sim O(10^2)$ mbar.

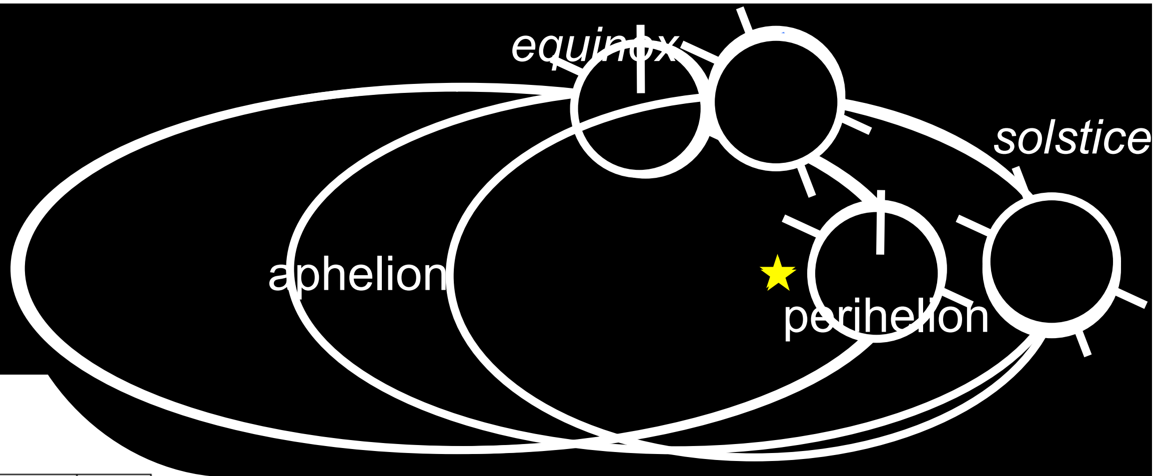
Comparison with data

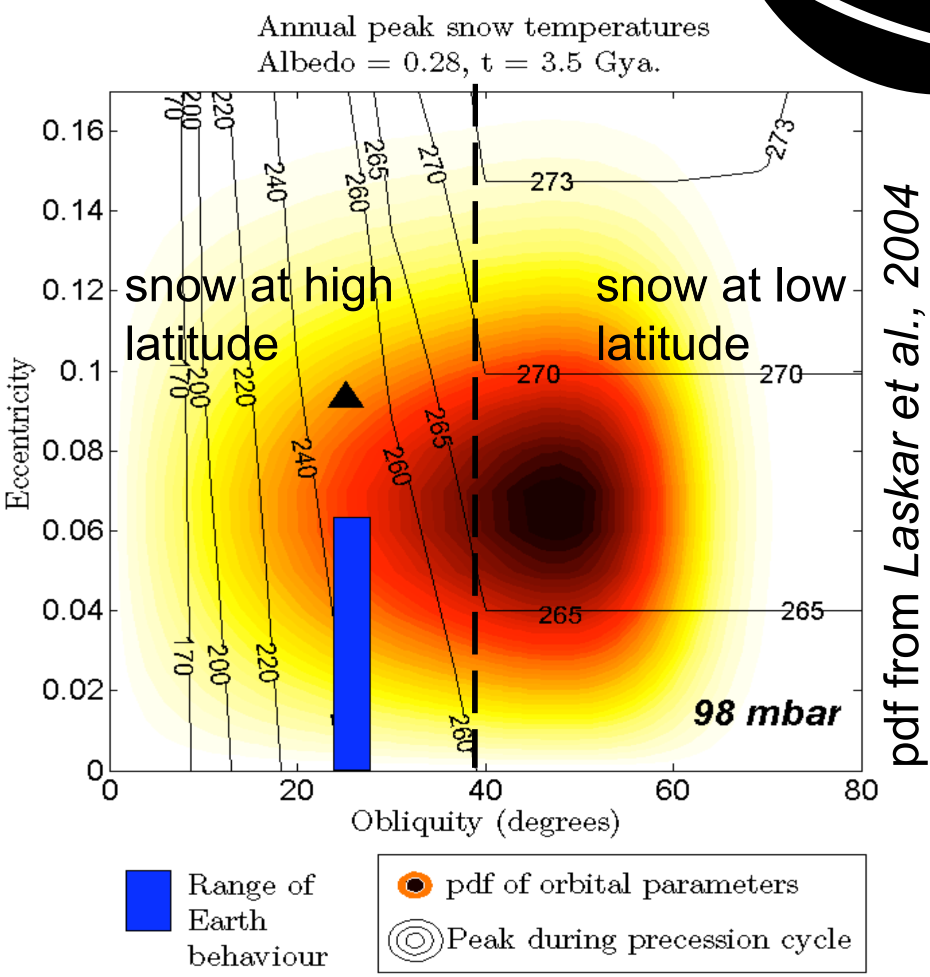
Two-thirds of sedimentary rocks on Mars formed at <10° latitude, most at <-1500m elevation. Modeled snowmelt locations show good correspondence with sedimentary rock locations.

Context and tests

Comparison of bottom-up (groundwater) and top-down (snowmelt) water source models.

First general result: High obliquity, moderate eccentricity, and perihelion at equinox are optimal for snowmelt





1) Increase obliquity.

2) Increase eccentricity.

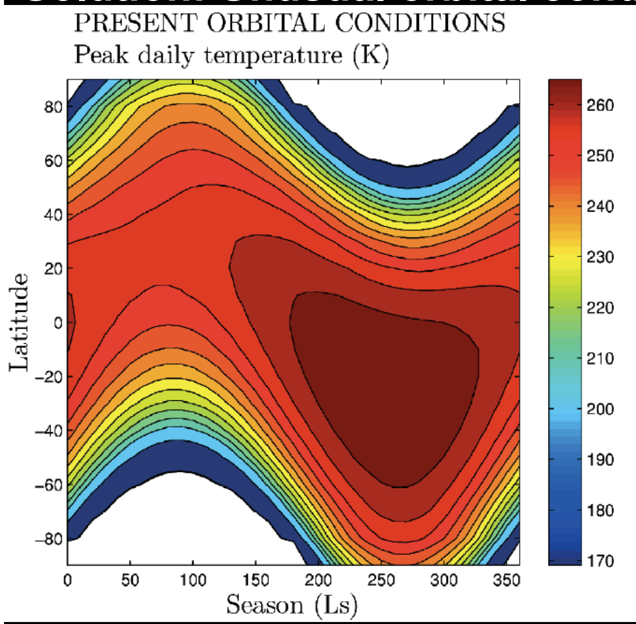
3) Align equinox with perihelion

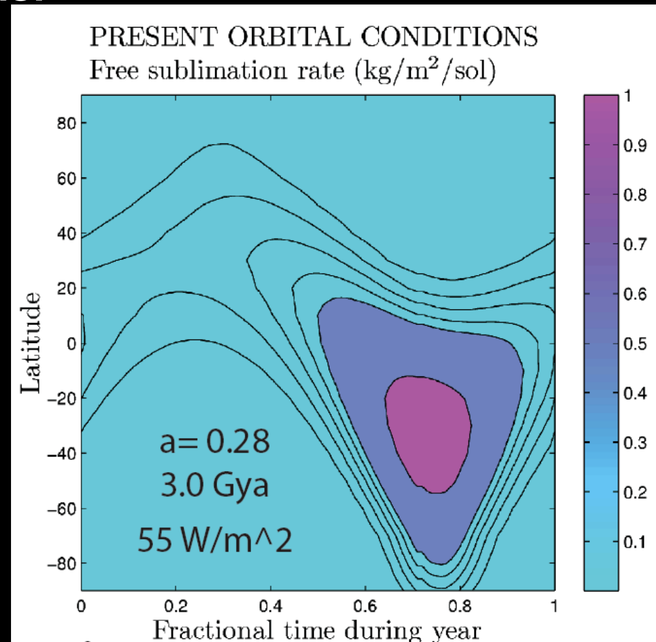
→ Latitudinal cold traps are eliminated.

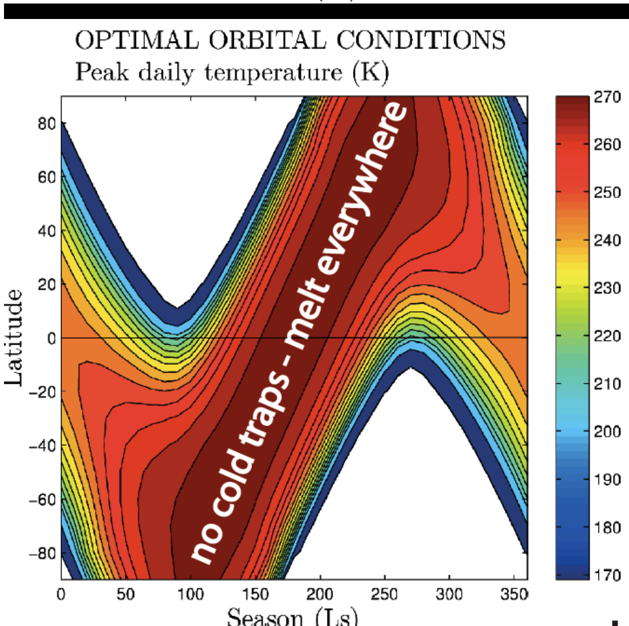
→ Sun is at zenith above snow noon at perihelion.

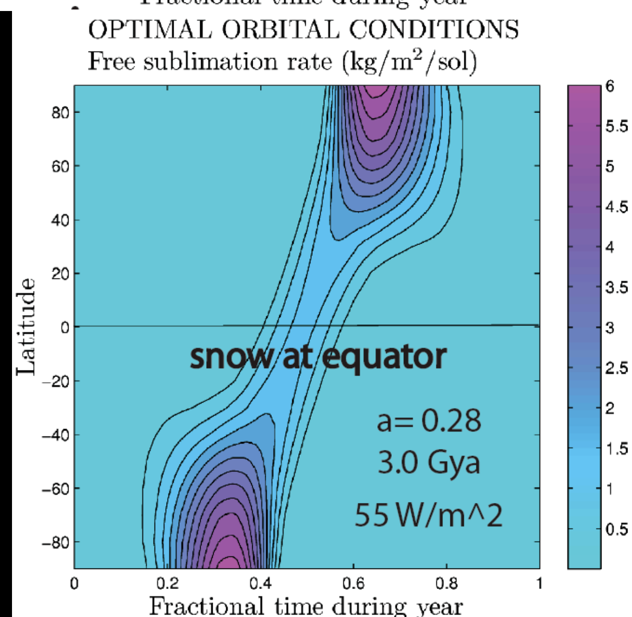
Previous work going back to (e.g.):
Jakosky & Carr, Nature, 1985
Jakosky et al., JGR, 1995

Problem for snowmelt model: Snow accumulates in planetary cold traps.
Solution: Unusual orbital conditions.





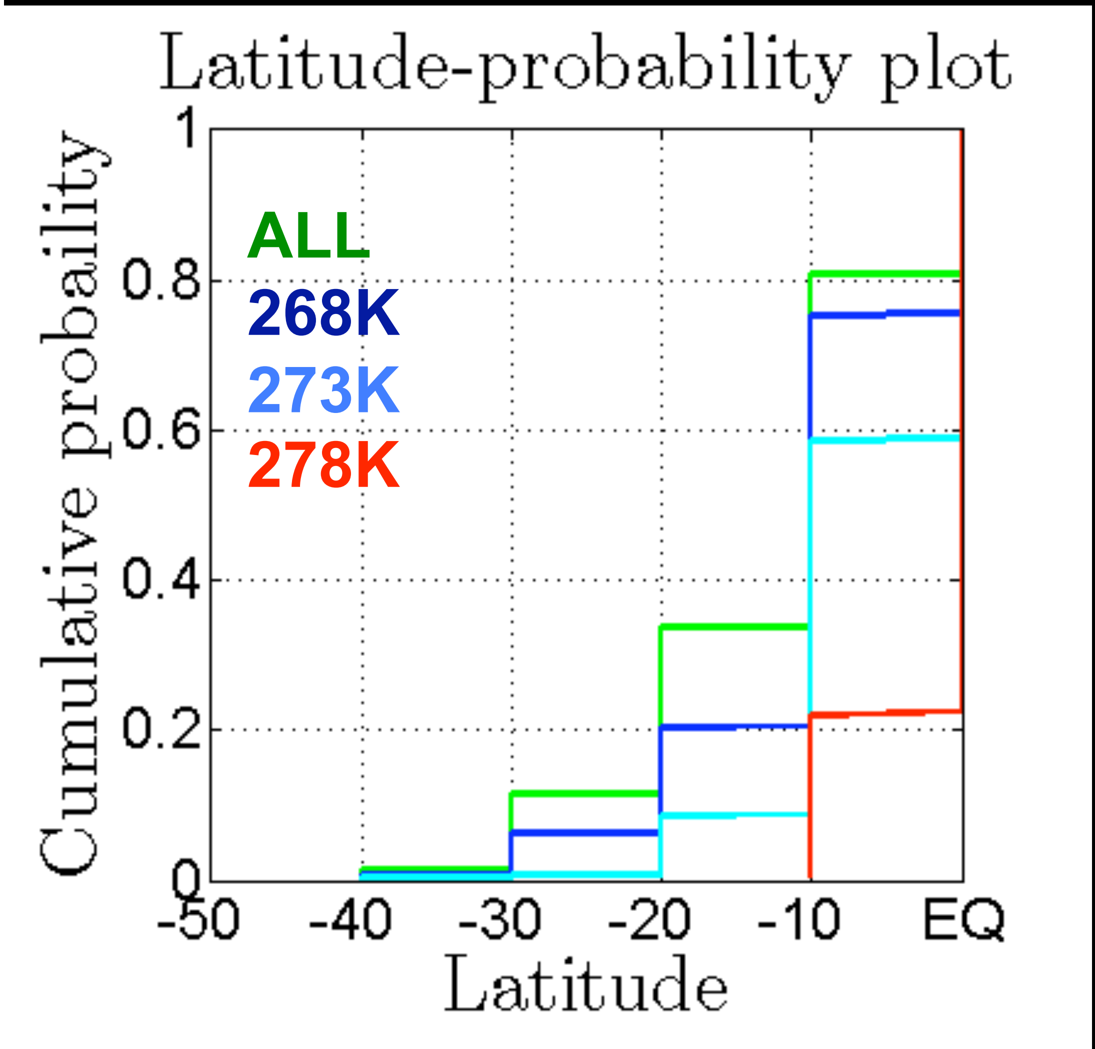


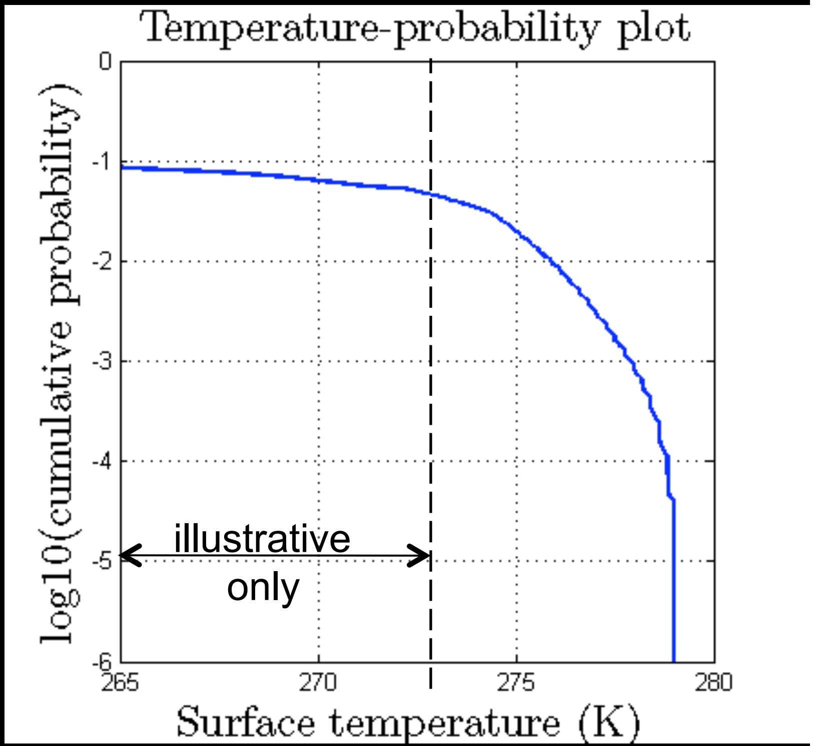


Assume that snow is in equilibrium with orbital forcing, but can be out of equil. with seasonal forcing.

→-->
→**Eccentricity is**
→**fundamental.**

Second general result: Snow is near the equator when it melts. Melting is rare.





assuming flat "cueball" Mars

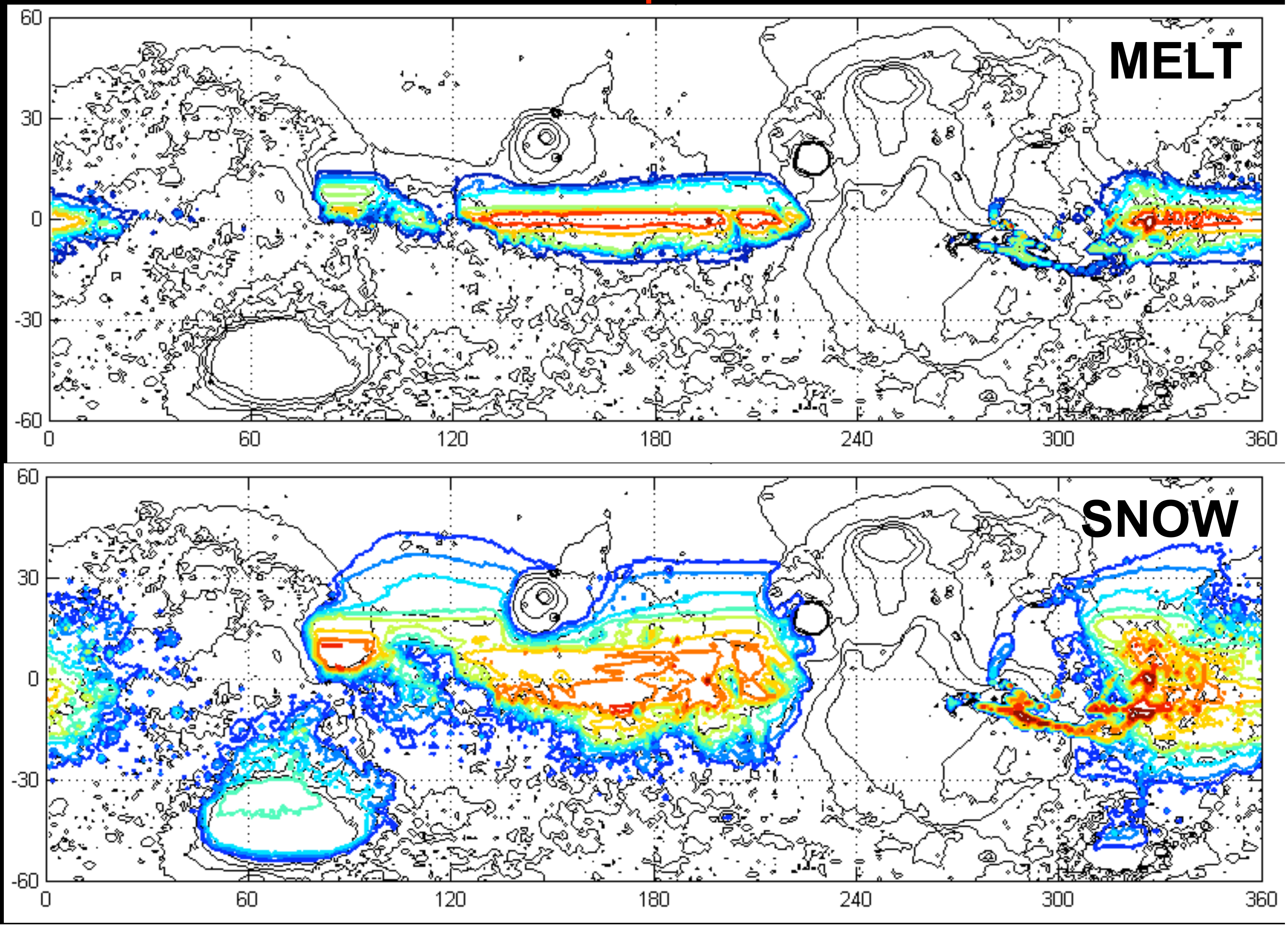
Third result (preliminary): Snowmelt zones are at low elevation as well as low latitude. - Discussed previously by *Fastook et al., Icarus 2008*

f_snow = 10%

PRELIMINARY: Sensitive to pressure.

ΔT = +2K

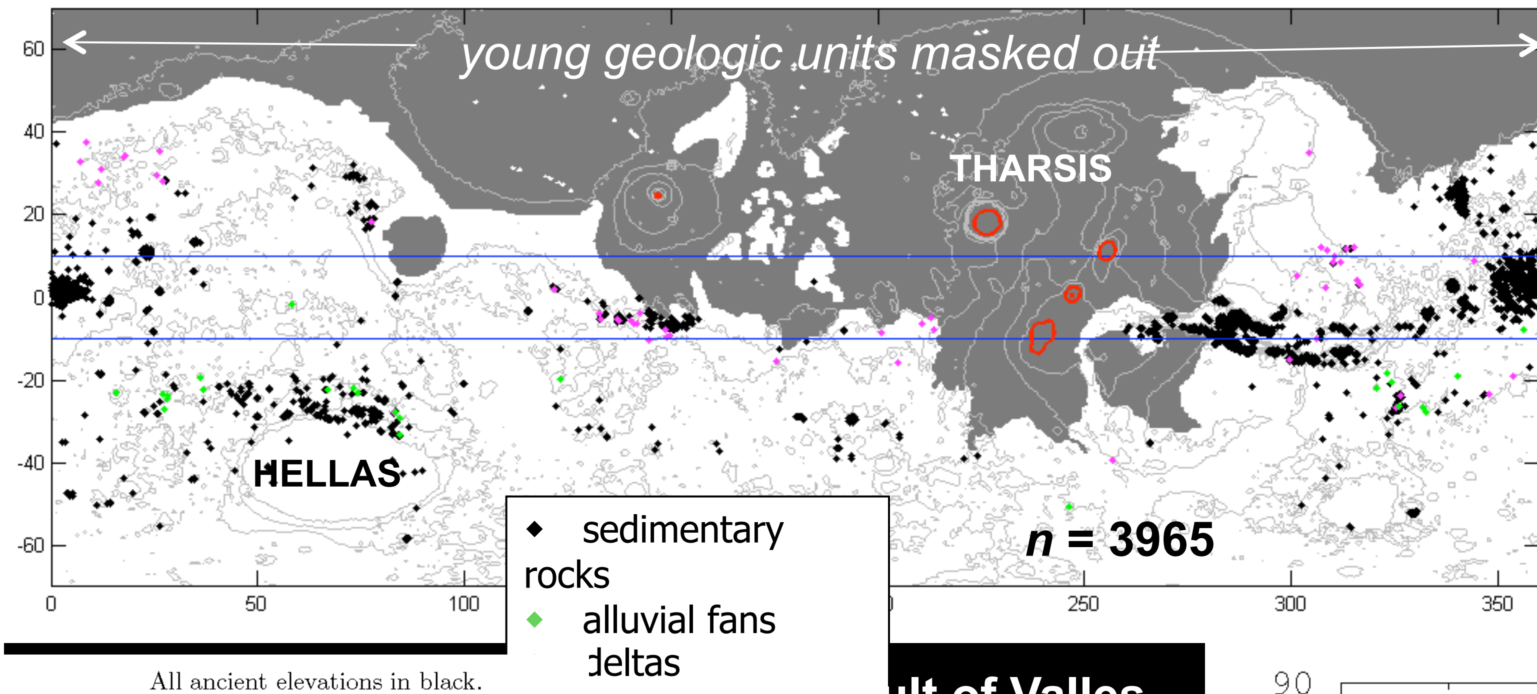
integrated over all orbital conditions



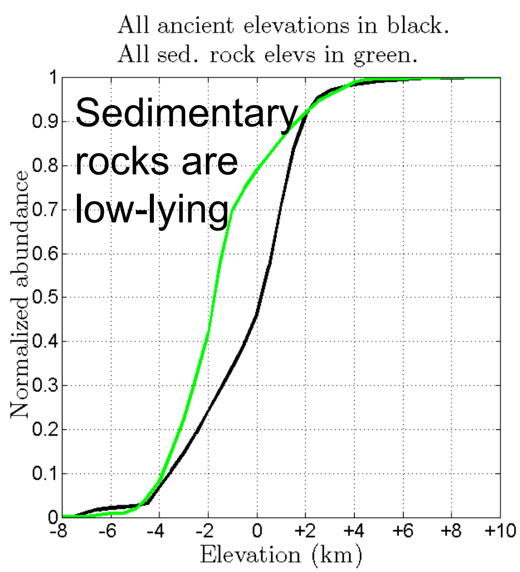
How does this compare to data?

What must a good model explain?

Sedimentary rocks are found at low latitude and low elevation (MOC-NA database,

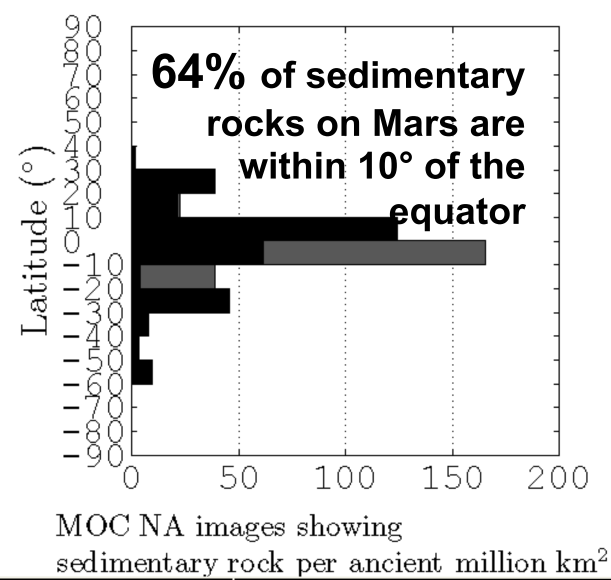


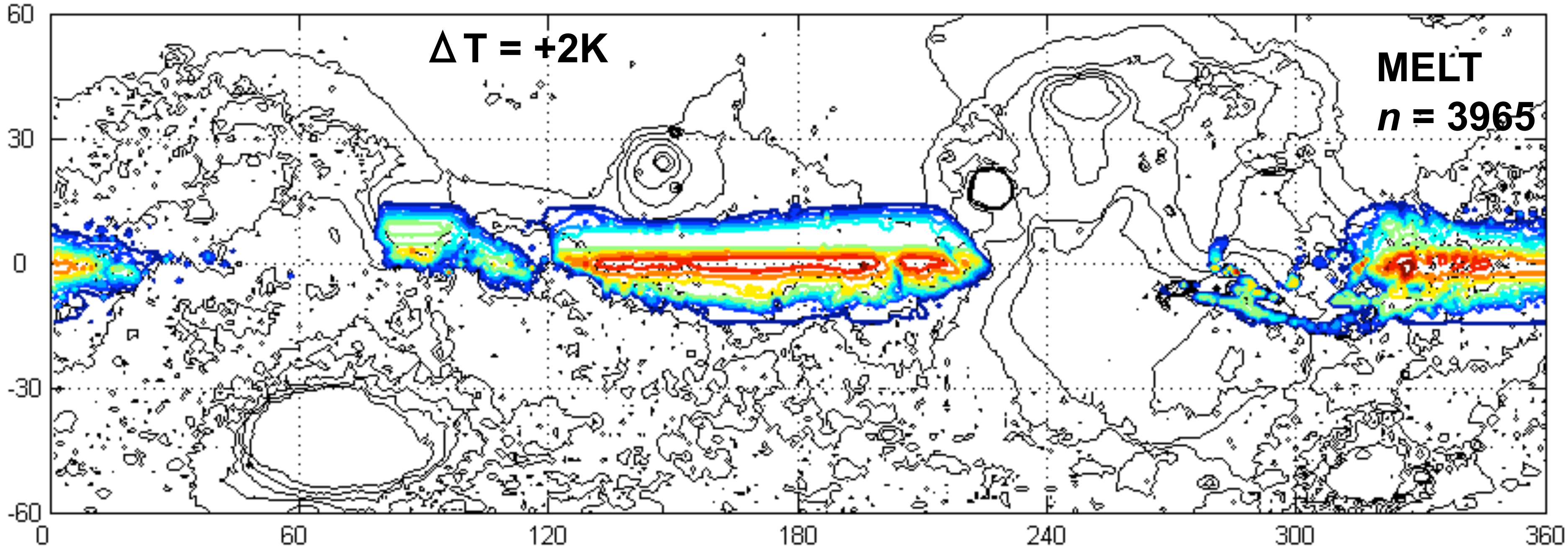
alin et al., Mars Journal, 201
i Achille et al., Nat. Geo 2010
raal et al., Icarus 2008
immo & Tanaka, AREPS, 200



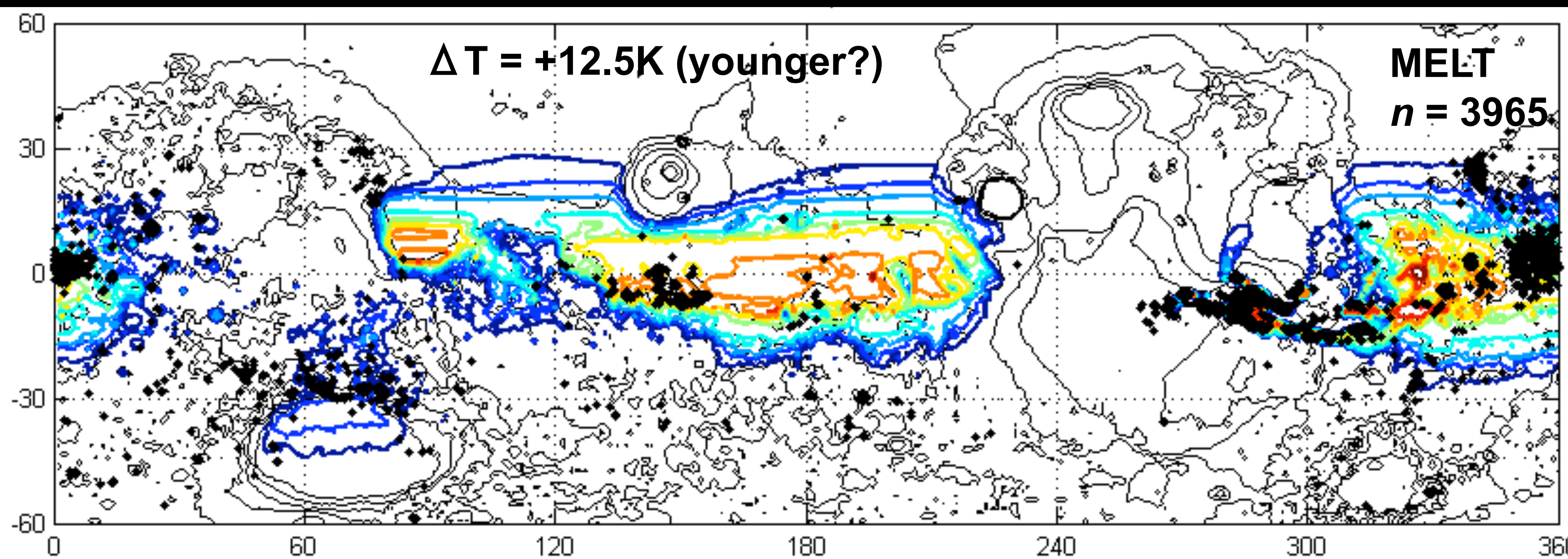
Not the result of Valles Marineris

Sedimentary rock elevations are biased low by ~2km. This trend is robust to exclusion of equatorial rocks





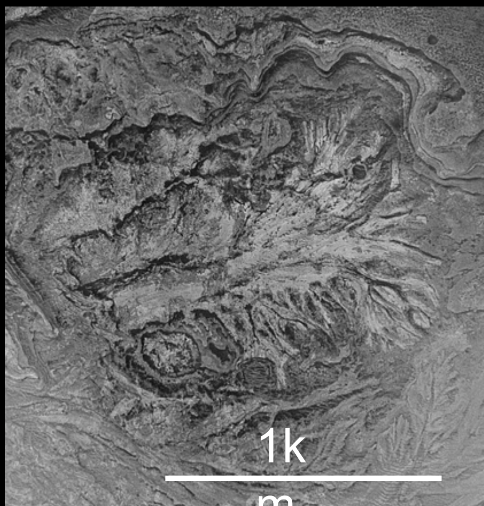
Δ T = +2K
MELT
n = 3965
60
30
0
-30
-60
0
60
120
180
240
300
360

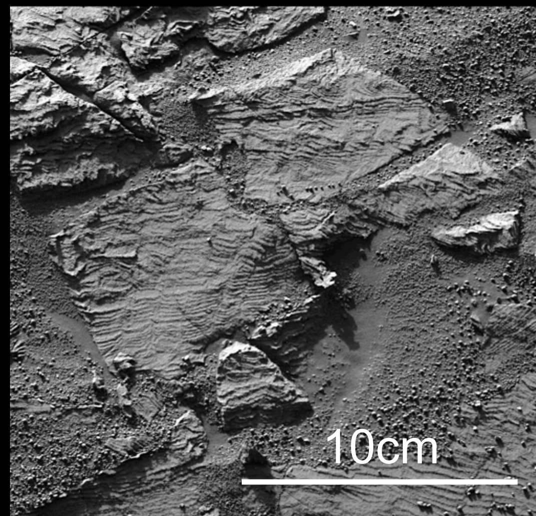


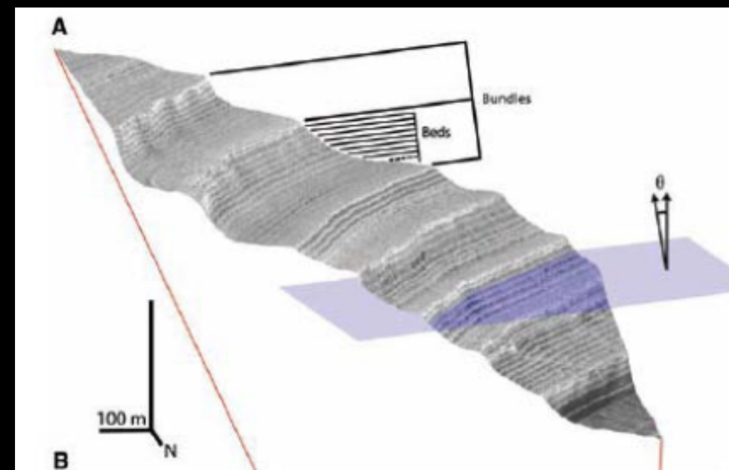
Δ T = +12.5K (younger?)
MELT
n = 3965
60
30
0
-30
-60
0
60
120
180
240
300
360

What must a good model explain?

Orbitally-paced, water-limited, interbedded with fluvially transported sediment.







Lewis et al., Science, 2008

quasi-periodic layers + bundles
→ suggestive of strong orbital
→pacing of sediment accumulatio

- **Limited timescale of water-rock interaction**
  - ***•- Jarosite and hematite stopwatches (e.g. Elwood-Madden et al, 2004, 2009)***
- **Low water:rock ratios (e.g. *Hurowitz & McLennan, EPSL, 2007*)**
- **Only 1-10 Myr (cumulative) wet conditions may be necessary**
  - ***-Bed thickness, total thickness + orbital assumption (Lewis et al., LPSC, 2010)***
- **Inference: sulfate grains grew in shallow lakes.**
- **Top-down mobilization of soluble ions?**
  - ***•- Burns formation element profiles (e.g. Amundson et al., GCA, 2008)***

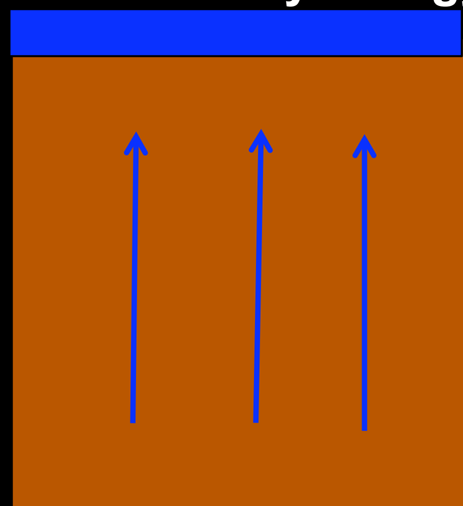
Metz et al., J. Sedimentary Res., 200
Metz et al., JGR, 2009

What is the water source for sedimentary rock (and sulfates) on Mars?

→ What were the environmental conditions that allowed sedimentary rocks to fo

"bottom-up"

coupled surface and subsurface hydrology



Andrews-Hanna et al., Nature, 2007;
Andrews-Hanna et al., JGR, 2010;
Andrews-Hanna et al & Lewis, JGR, 2011.

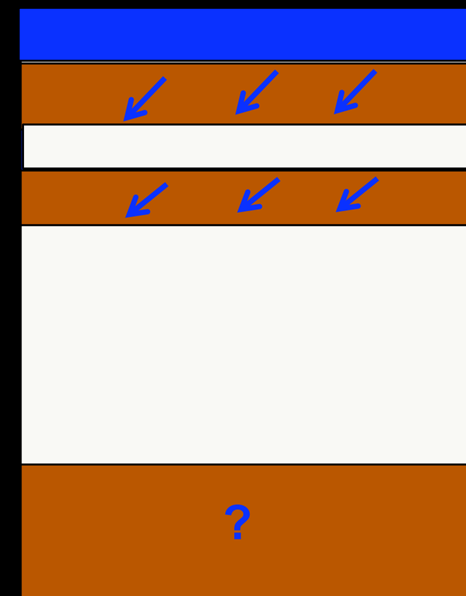
Requires T_{avg} > 273K

T_{avg} > 273K requires a multibar atmosphere (Tian, Wordsworth).

Problems: 1. Photochemically unstable (Zahnle).
2. Polar collapse (Soto & Richardson).
3. Reflective CO2 clouds (Colaprete).
4. Insufficient degassing (reduced mantle;Hirschmann & Withers).
5. Insufficient warming. 6. How to get rid of bars of CO2 post-LHB?

"top-down"

decoupled surface and subsurface hydrology



Amundson et al., GCA, 2008,* & especially *Niles* *2009

subfreezing lakes?, seasonal runoff, evaporites

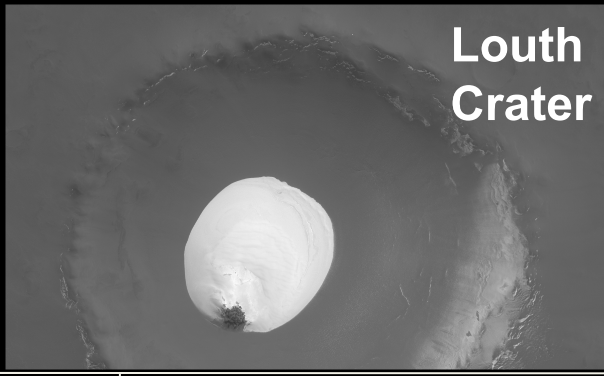
Problems with my model

→ As of now I do not have a self-consistent solution for Early Mars.
- At ~200 mbar : snow melts, but accumulates on high ground
- at lower pressures: snow fills valleys, but evaporative cooling prevents melt.
- Non-CO_2 greenhouse forcing? Bad extrapolation of GCM output? Some sedimentary rocks younger than 3.5 Ga?

→ Orbital probabilities assume Mars explores its orbital parameter space in much less than the age of the solar system, but this is not true.
- However the probability of exeeding e = 0.15 is ~80%.

→ No precipitation in snow location parameterization – but we know this is important today (e.g., flanks of Tharsis
- However craters do act as cold traps.

High latitude (e.g. Conway et al., this conference)
Low latitude (Shean, GRL, 2010)



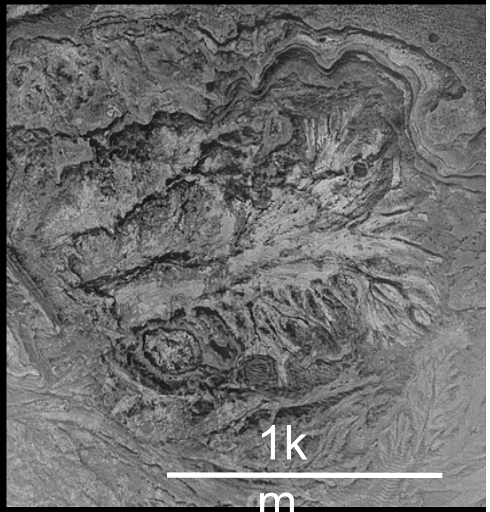
Tests

- Geochemical variability; mineral lifetime
- Layer orientation : draping versus geopotential
- Runoff should be *especially strongly* concentrated at equator (highest temps): sinuous ridge distribution work by Williams?
- Discharge rates, regional extent, latitudes, longitudes, elevation
- Equatorial craters are preferred sites for high-obliquity ice deposition (Shean, GRL, 2010)
- (Lower) Medusae Fossae Formation should have formed the same way as the Meridiani sediments. Sulfates in fresh impact crater ejecta?

Example future test: Hydrological assessment of SW Melas Chasma

Chezy-type discharge constraints from probable sublacustrine fan draining 832 km^2 catchment (supplied by Joannah Metz)

minimum melt rate for bankfull flow > (0.01-0.4) mm/hr
(no hydrology)
→ 1-40W



Potential for a lower bound on Mars T?

Conclusions and implications

overall

Snowmelt hypothesis passes initial tests and is worth investigating further.

Mars sedimentary record acts as a wet-pass filter. **Modeling typical orbital conditions is not sufficient if we want to understand the sedimentary rock reco T_{avg} > 273K is not required, and a multibar atmosphere may not be required, to explain liquid water availability for sedimentary rock formation on Mars.**

for MSL

Gale Crater is among the most favored spots for snowmelt on Mars
- **You cannot keep snow out of Gale ***
- **If snowmelt on Mars occurs anywhere, it occurs in Gale. ***

(*Assuming that our model's neglect of precipitation and horizontal heat transport does not affect the 1^{st}-order patterns in the model output.)

Eberswalde+Holden: agreement that Eberswalde+Holden form in Hesperian (or Early Amazonian), favorable for snowmelt in Uzboi-Ladon-Margaritifer corridoor. May require additional greenhouse forcing for snowmelt. However, impacts could drive fluvial activity.

other sites

Southern Isidis and area of MFF <u>strongly</u> favored for fluvial activity
- **work of Jaumann et al., EPSL, 2010, and especially Burr et al. 2009 & 2010**
- **Inspection of eastern and central MFF should show more (inverted?) chan**

Broader distribution suggested by recent work of Moore & Howard + Grant & W