Water in the Hyperarid, Hypothermal Antarctic Dry Valleys: Influence on Geological Processes and Implications for Mars

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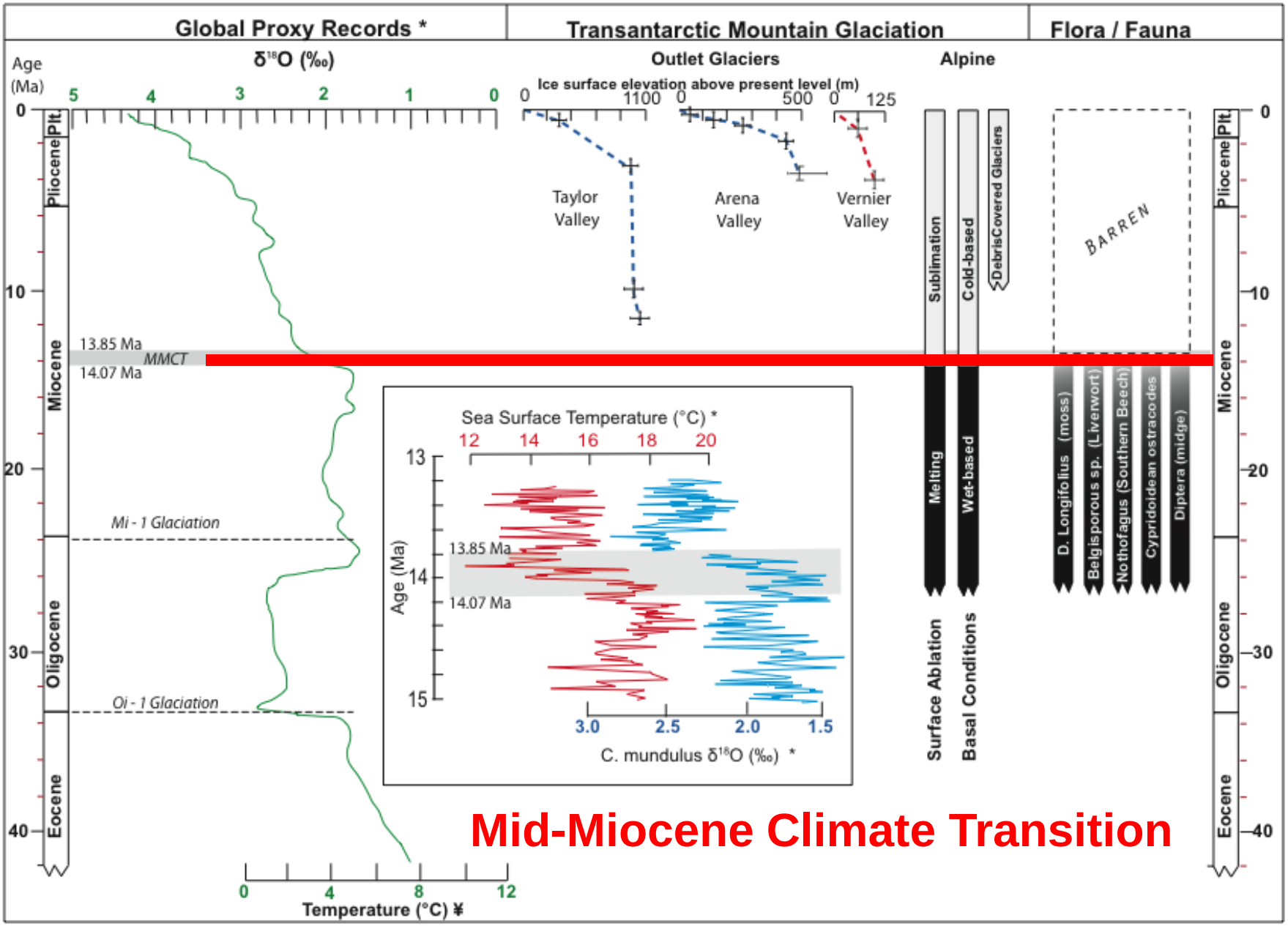
Four Goals:

1. Introduce a Mars-like Environment on Earth.
2. Distinguish Between Temperate and Polar Climates.
3. Distinguish Between Arctic and Antarctic Climates.
4. Share the Trials and Rewards of Polar Exploration.

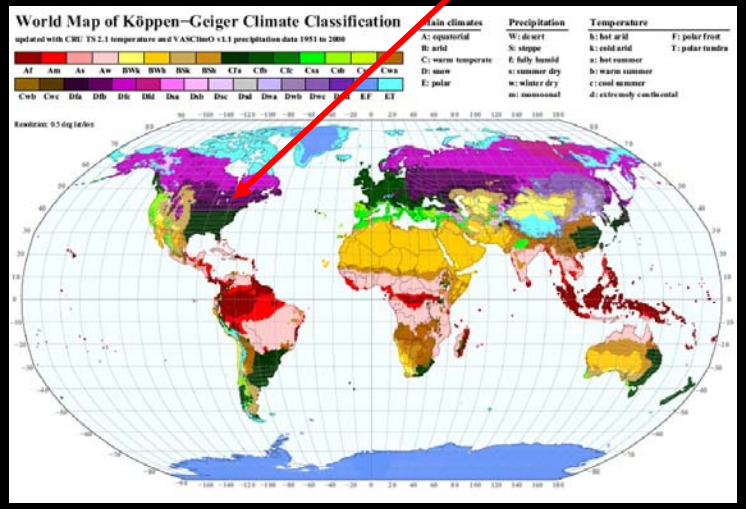
With Contributions From Members of the Brown University-Boston University Antarctic Team:
David Marchant, Adam Lewis, Doug Kowalewski, Kate Swanger, Shawn Mackay, Jen Lamp;
Joe Levy, Jay Dickson, Gareth Morgan, Laura Kerber, Brandon Boldt, David Shean,
Rebecca Parsons, Mike Wyatt, Mark Salvatore.

ICDS Drillers: Jim Green, Tanner Kuhl.

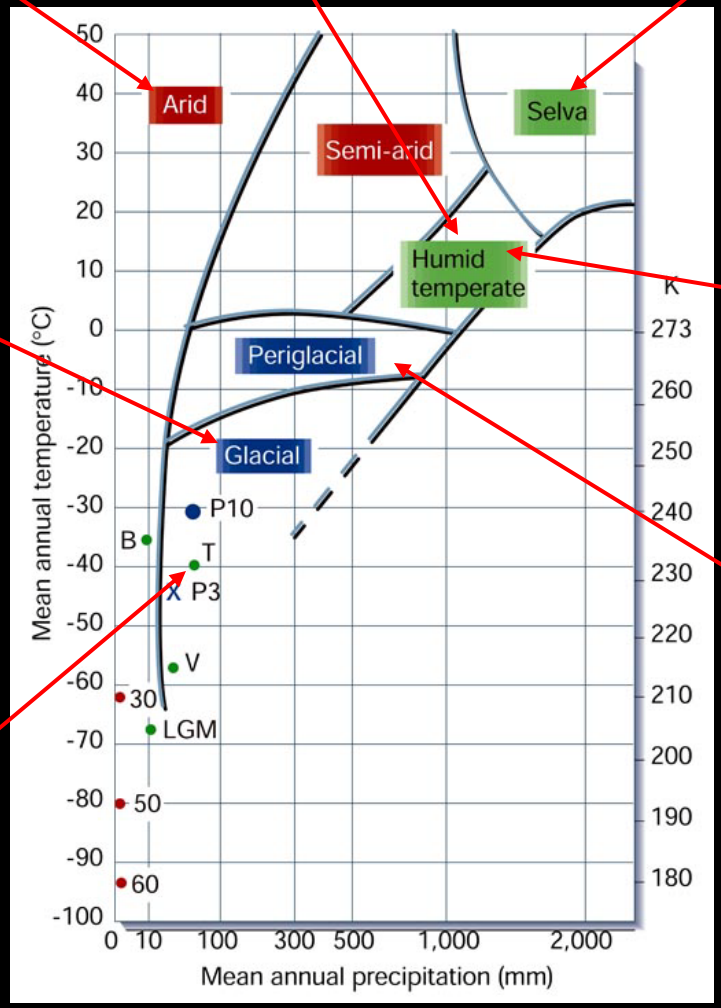

Global Proxy Records *
Transantarctic Mountain Glaciation
Flora / Fauna
Age (Ma)
δ18O (‰)
Outlet Glaciers
Alpine
Ice surface elevation above present level (m)
Taylor Valley
Arena Valley
Vernier Valley
Sublimation
Cold-based
Debris Covered Glaciers
BARREN
Pliocene
Plt.
Miocene
Oligocene
Eocene
13.85 Ma
MMCT
14.07 Ma
Mi - 1 Glaciation
Oi - 1 Glaciation
Sea Surface Temperature (°C) *
Age (Ma)
C. mundulus δ18O (‰) *
Melting
Wet-based
Surface Ablation
Basal Conditions
D. Longifolius (moss)
Belgisporous sp. (Liverwort)
Nothofagus (Southern Beech)
Cyprideidean ostracodes
Diptera (midge)
Temperature (°C) ¥
Mid-Miocene Climate Transition

Distinguishing Between Temperate and Polar Climates

- We live in temperate regions of planet Earth:
  - -Dominated by water in its liquid state.
  - -An extremely active, vertically integrated hydrological cycle.
  - -High rates of erosion and sediment transport.
  - -A huge, diverse and pervasive biota.
- In the ice-free regions of Antarctica:
  - -Mean annual temperatures way below freezing.
  - -The hydrological cycle is completely different.
  - -Rates of erosion are the lowest on Earth.
  - -The biota is small, simple and not pervasive.
  - -Antarctic landscapes are “fossilized” and preserve the record of conditions millions of years ago.
  - -Changes are so slow that “palimpsest” landscapes can be recognized and studied.
  - -Temperatures are so low that ice millions of years old can be preserved.
  - -Conditions are also very Mars like in the realm of temperature, precipitation, and rates of change.

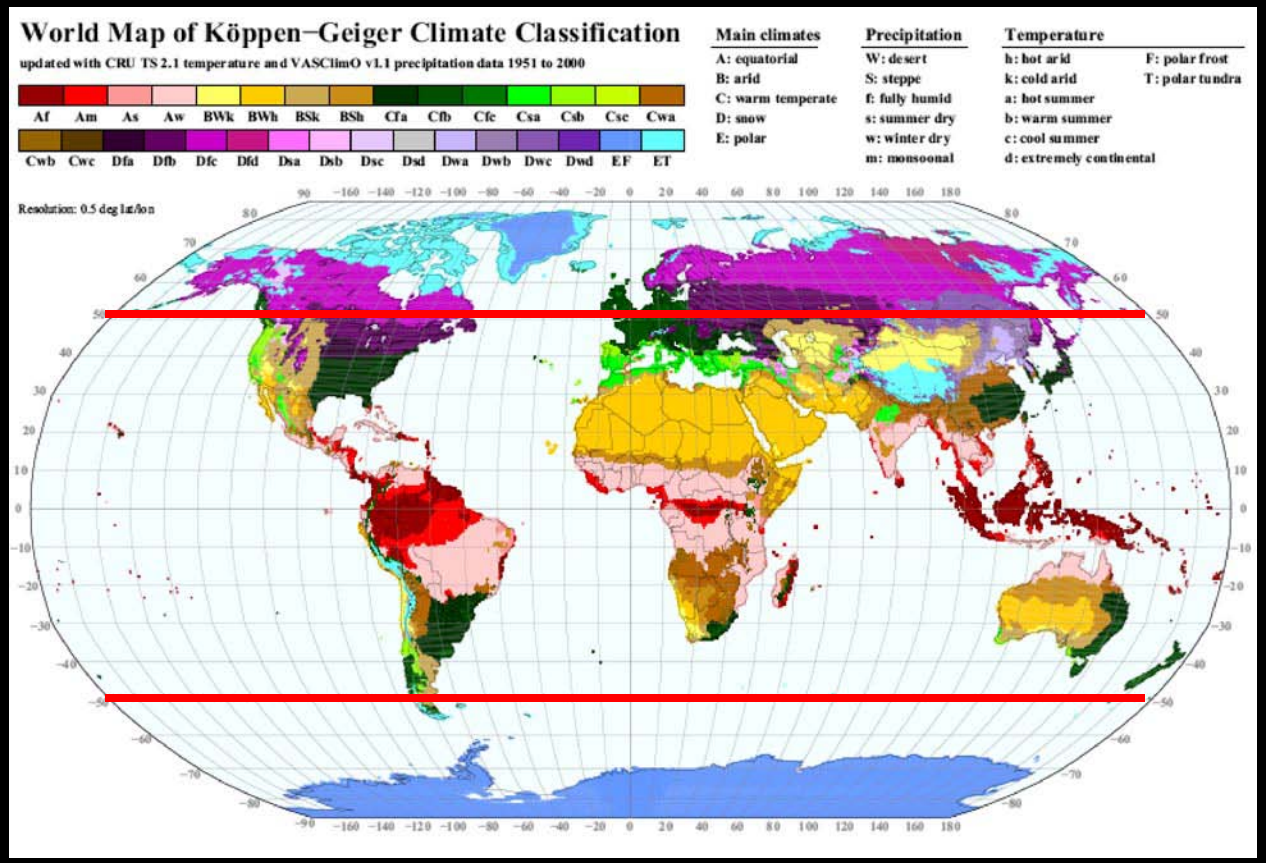


(Marchant and Head, 2007; Head and Marchant, 2011; http://www.planetary.brown.edu/html_pages/publications.htm)

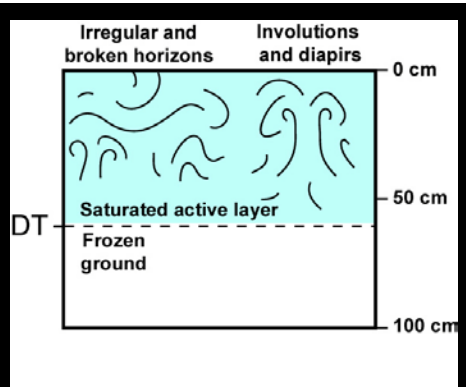

Arid
Semi-arid
Selva
Humid temperate
Periglacial
Glacial
P10
B
T
P3
V
30
LGM
50
60
Mean annual temperature (°C)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
K
273
260
250
240
230
220
210
200
190
180
0
10
100
300
500
1,000
2,000
Mean annual precipitation (mm)

Arctic Climates: Alaska, Canada, Svalbard, Russia, etc.

-Saturated Active Layer: Significant seasonal melting, freeze-thaw cycling.

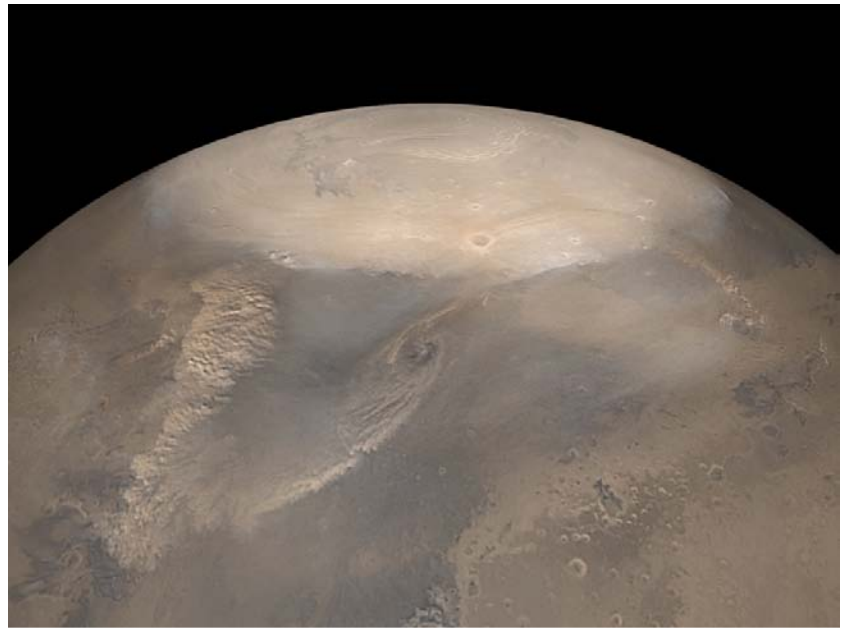


Pingos

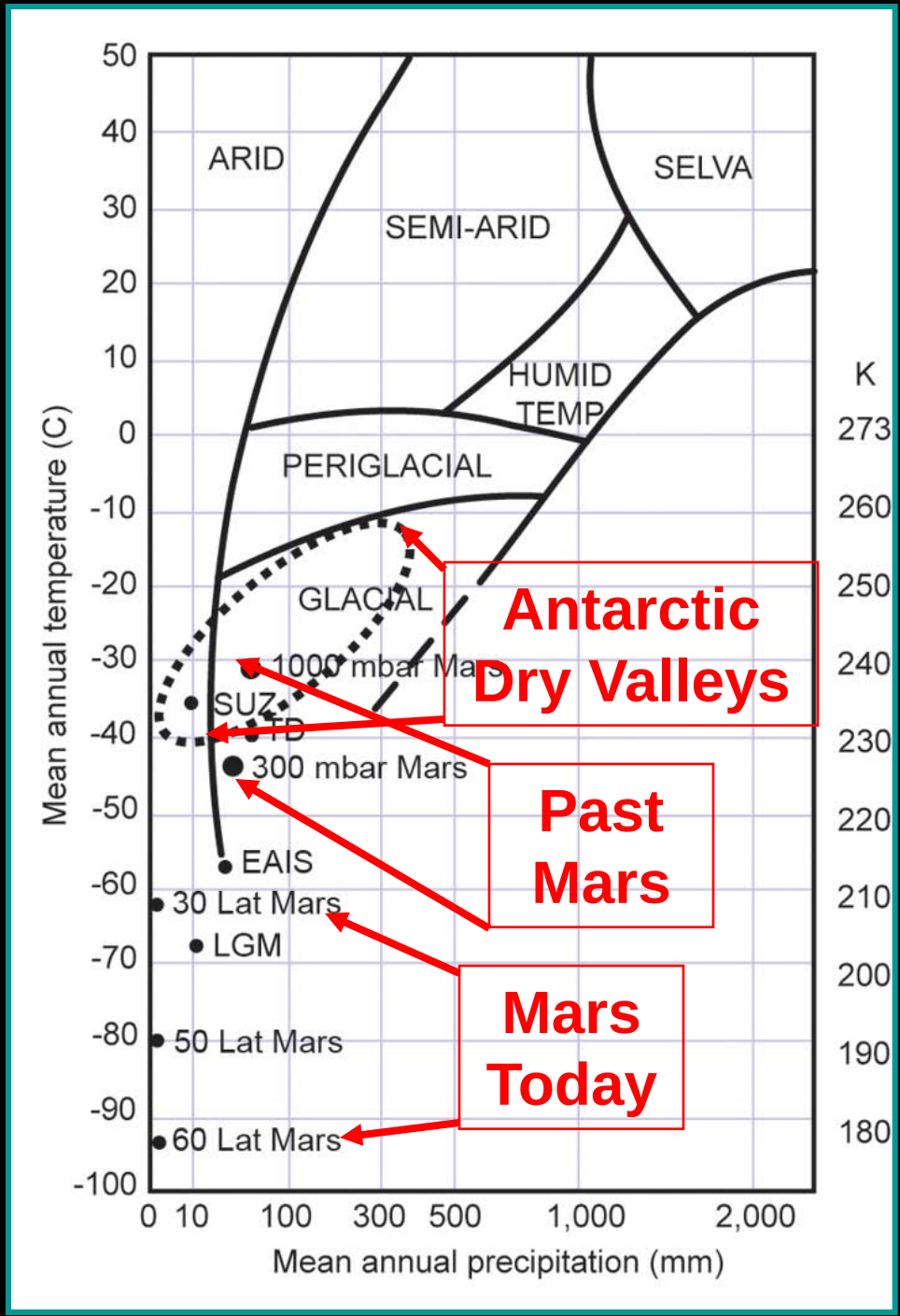


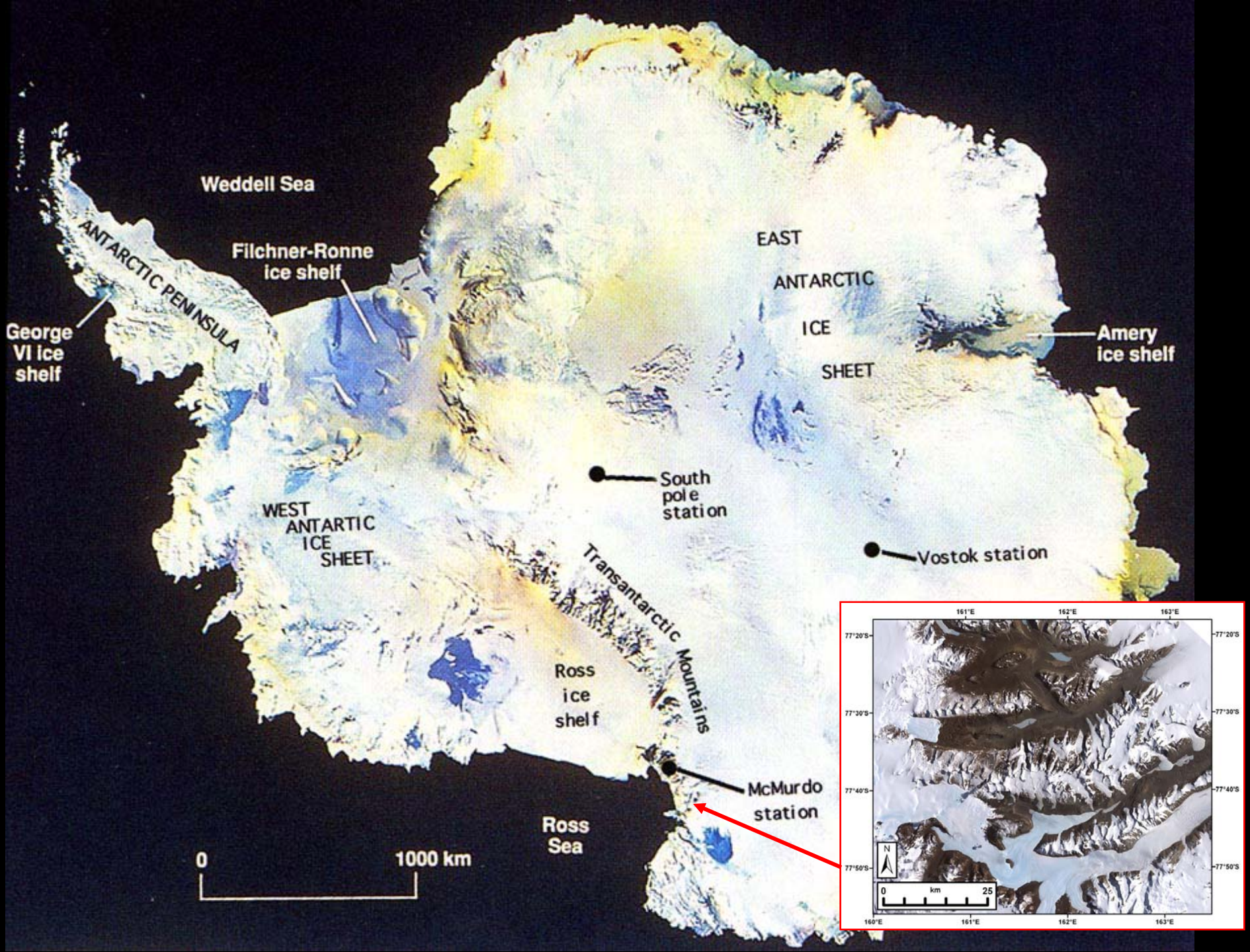
Frost-Sorted Stone Circles

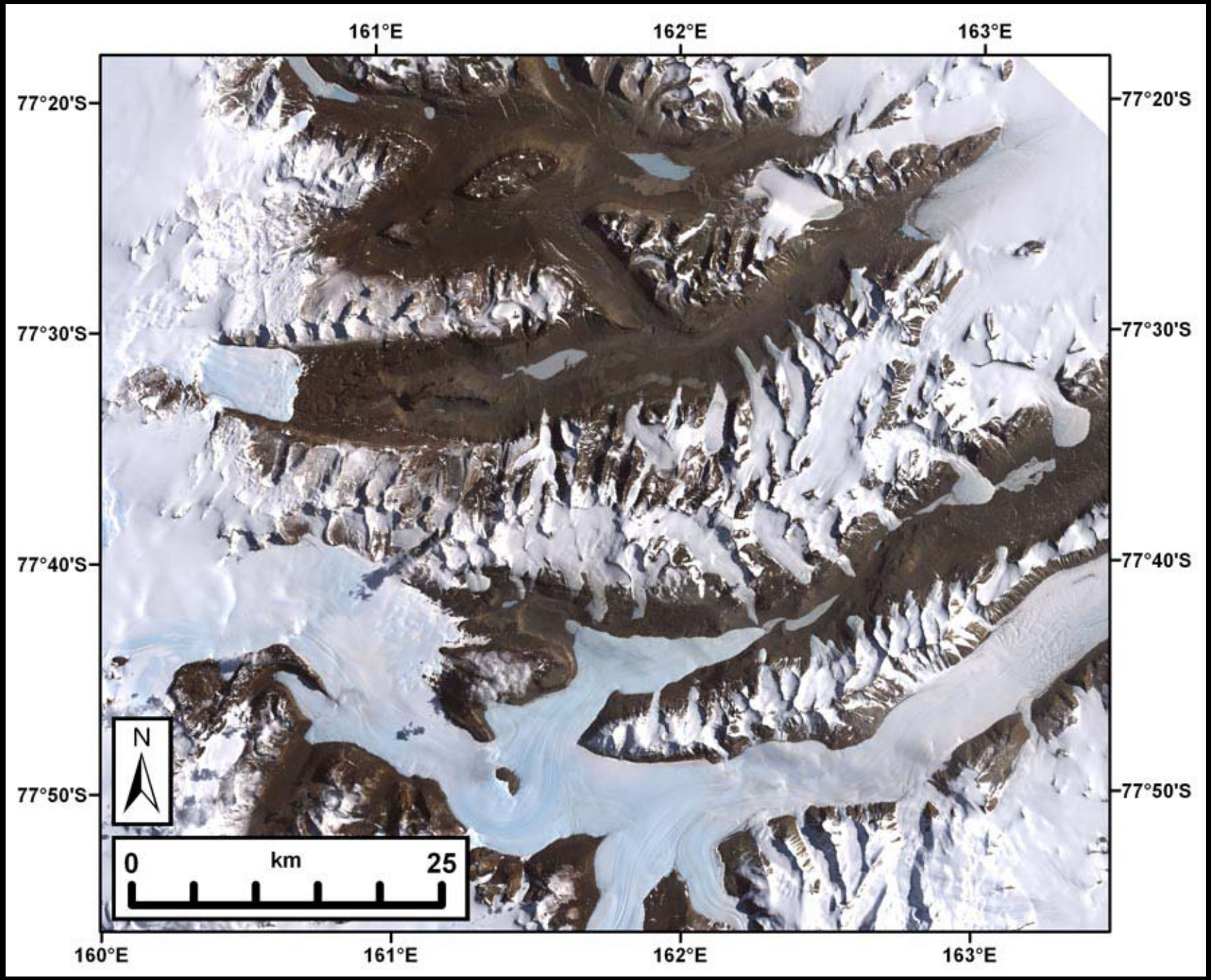
Thaw Lakes in Polygons

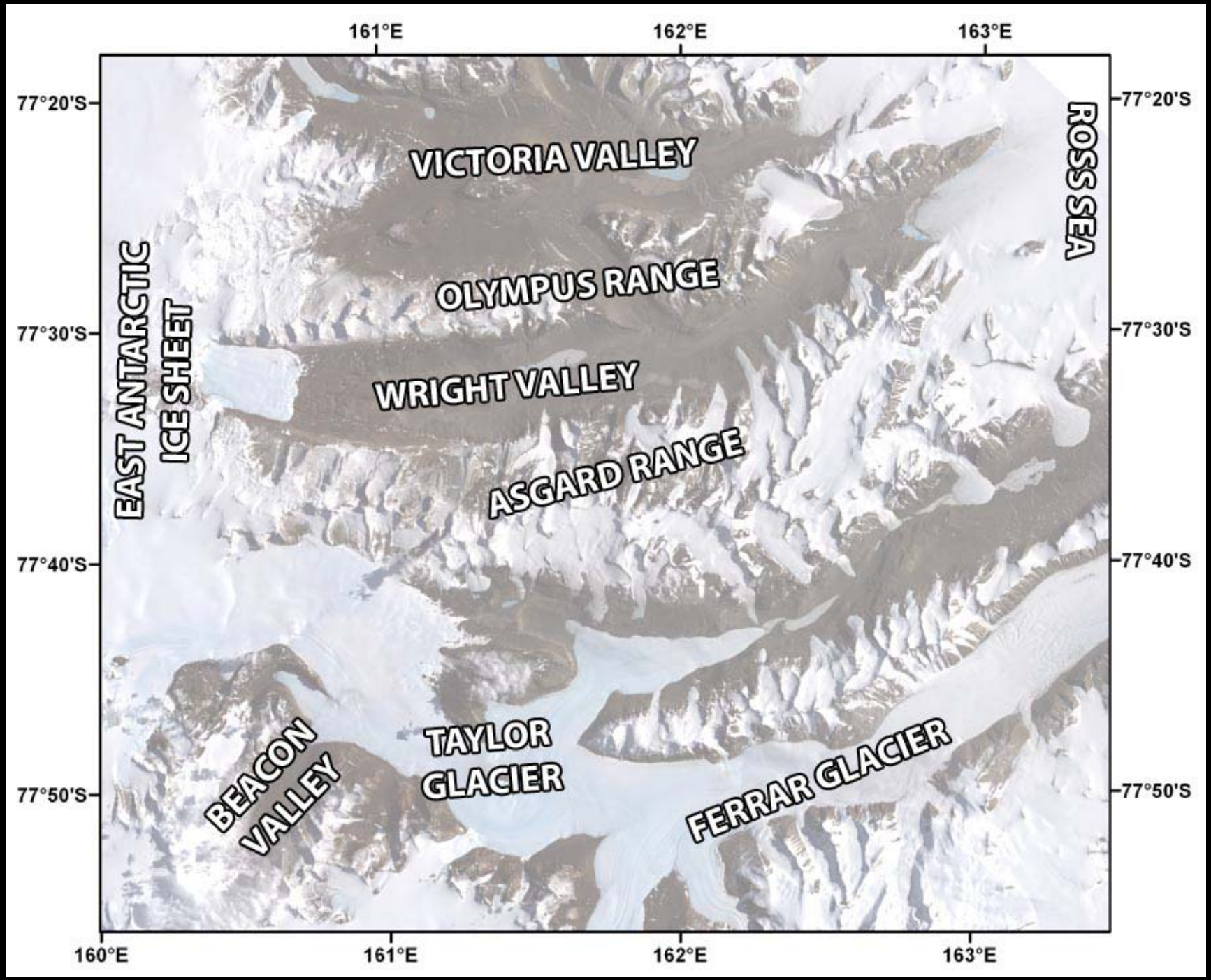


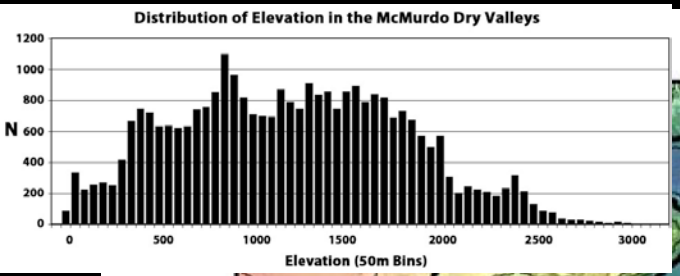
Both Antarctica and Mars are Currently Extremely Cold Hyperarid Deserts.

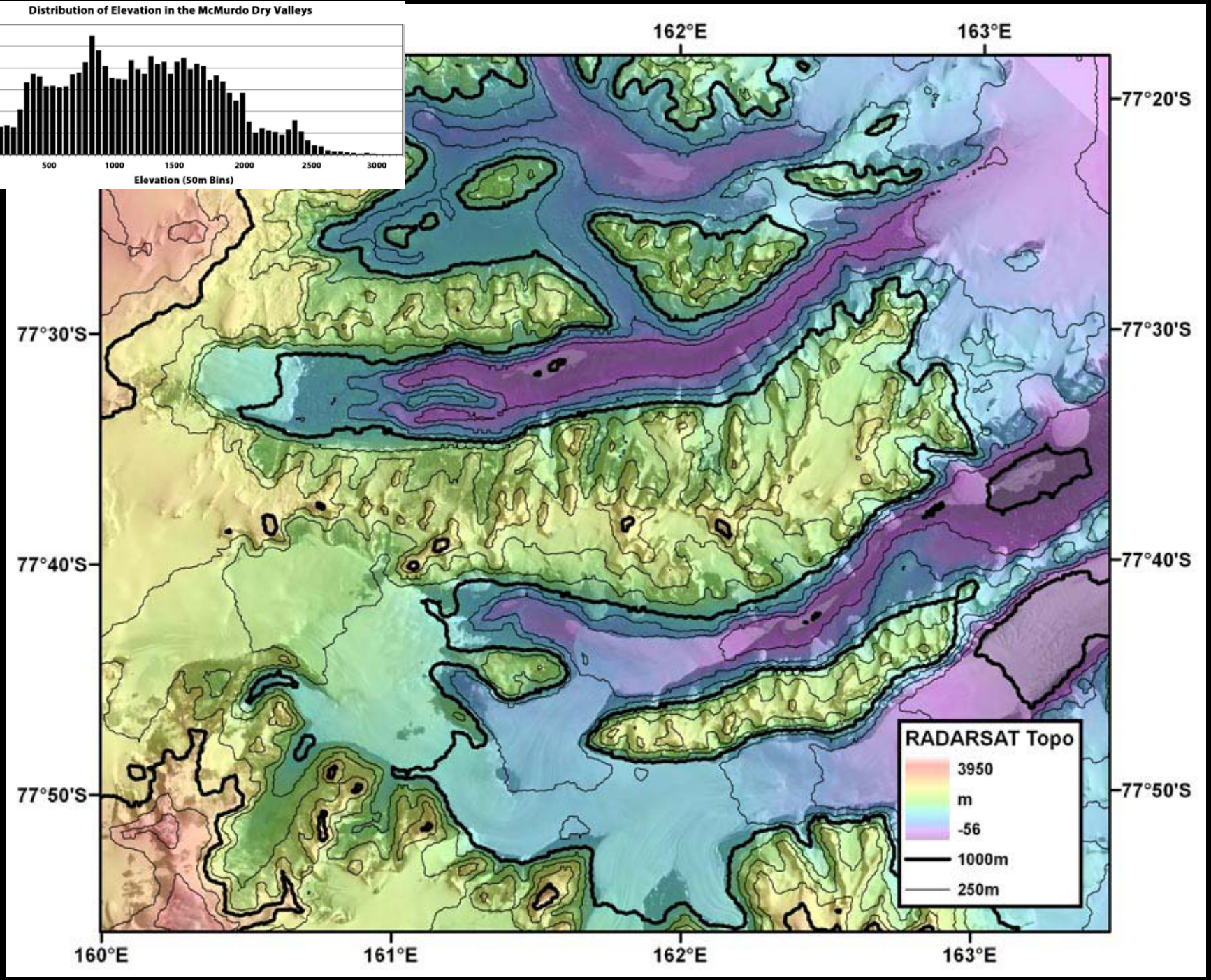



Weddell Sea
ANTARCTIC PENINSULA
Filchner-Ronne ice shelf
George VI ice shelf
EAST ANTARCTIC ICE SHEET
Amery ice shelf
South pole station
WEST ANTARTIC ICE SHEET
Vostok station
Transantarctic Mountains
Ross ice shelf
McMurdo station
Ross Sea
0
1000 km
161°E
162°E
163°E
77°20'S
77°30'S
77°40'S
77°50'S
N
0
km
25
160°E

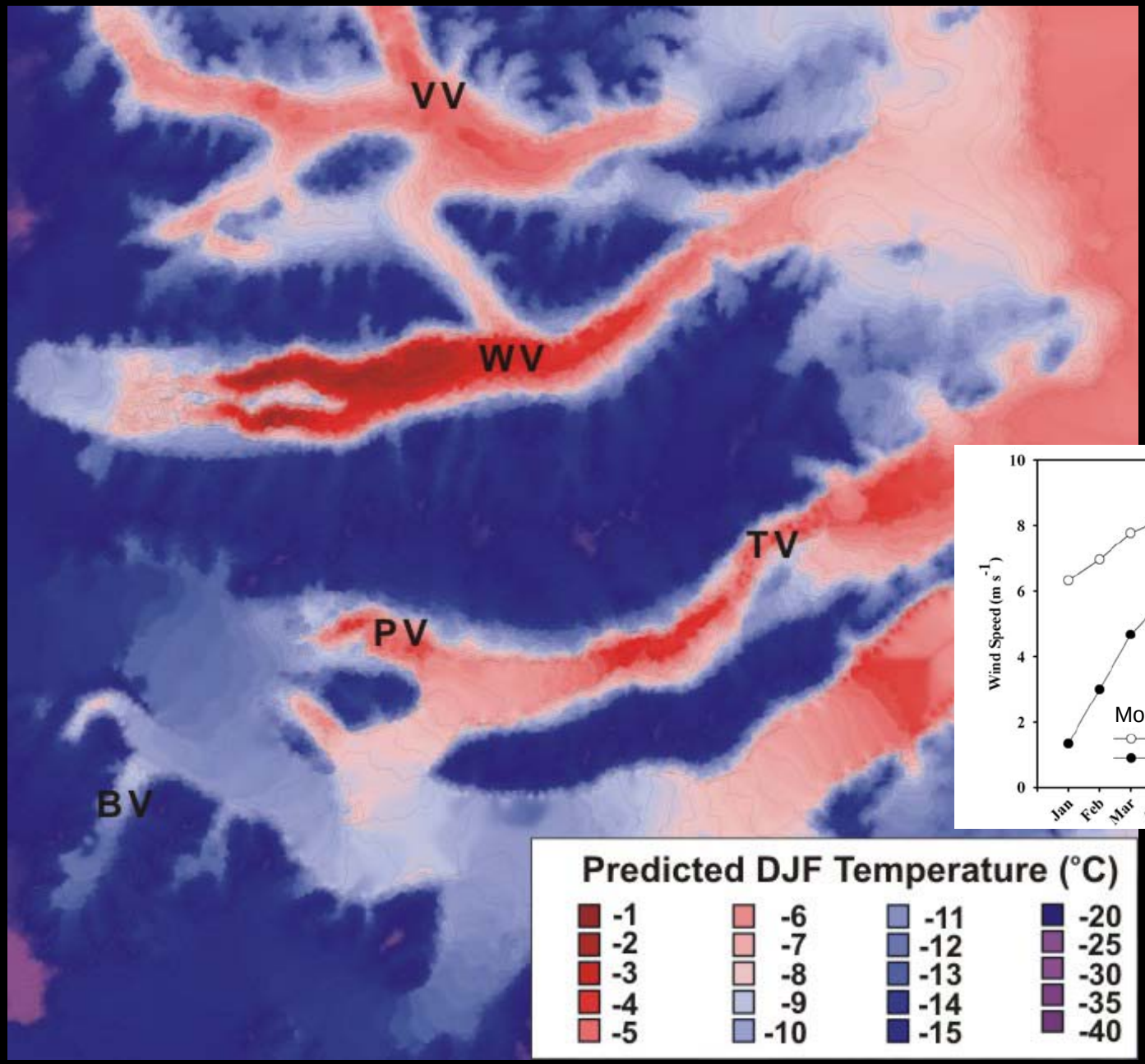

161°E
162°E
163°E
77°20'S
77°30'S
77°40'S
77°50'S
N
0
km
25
160°E
161°E
162°E
163°E

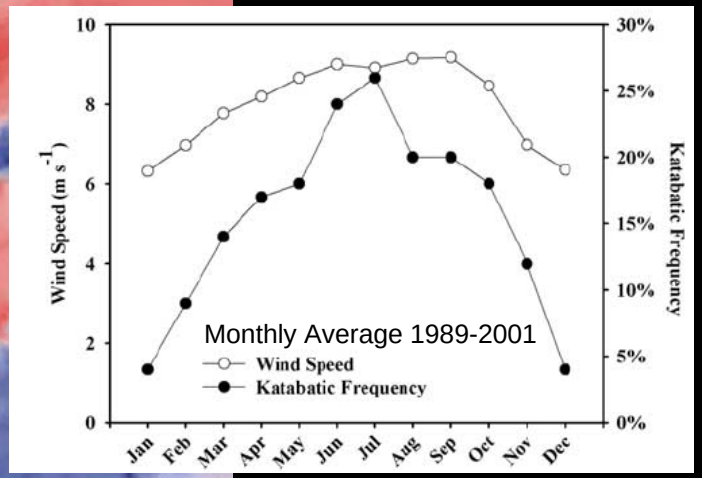

161°E
162°E
163°E
77°20'S
77°30'S
77°40'S
77°50'S
160°E
VICTORIA VALLEY
OLYMPUS RANGE
WRIGHT VALLEY
ASGARD RANGE
EAST ANTARCTIC ICE SHEET
ROSS SEA
TAYLOR GLACIER
BEACON VALLEY
FERRAR GLACIER


Distribution of Elevation in the McMurdo Dry Valleys
N
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
Elevation (50m Bins)


162°E
163°E
77°20'S
77°30'S
77°40'S
77°50'S
160°E
161°E
162°E
163°E
RADARSAT Topo
3950
m
-56
1000m
250m

Topographic Control on Summer and Winter Temperature

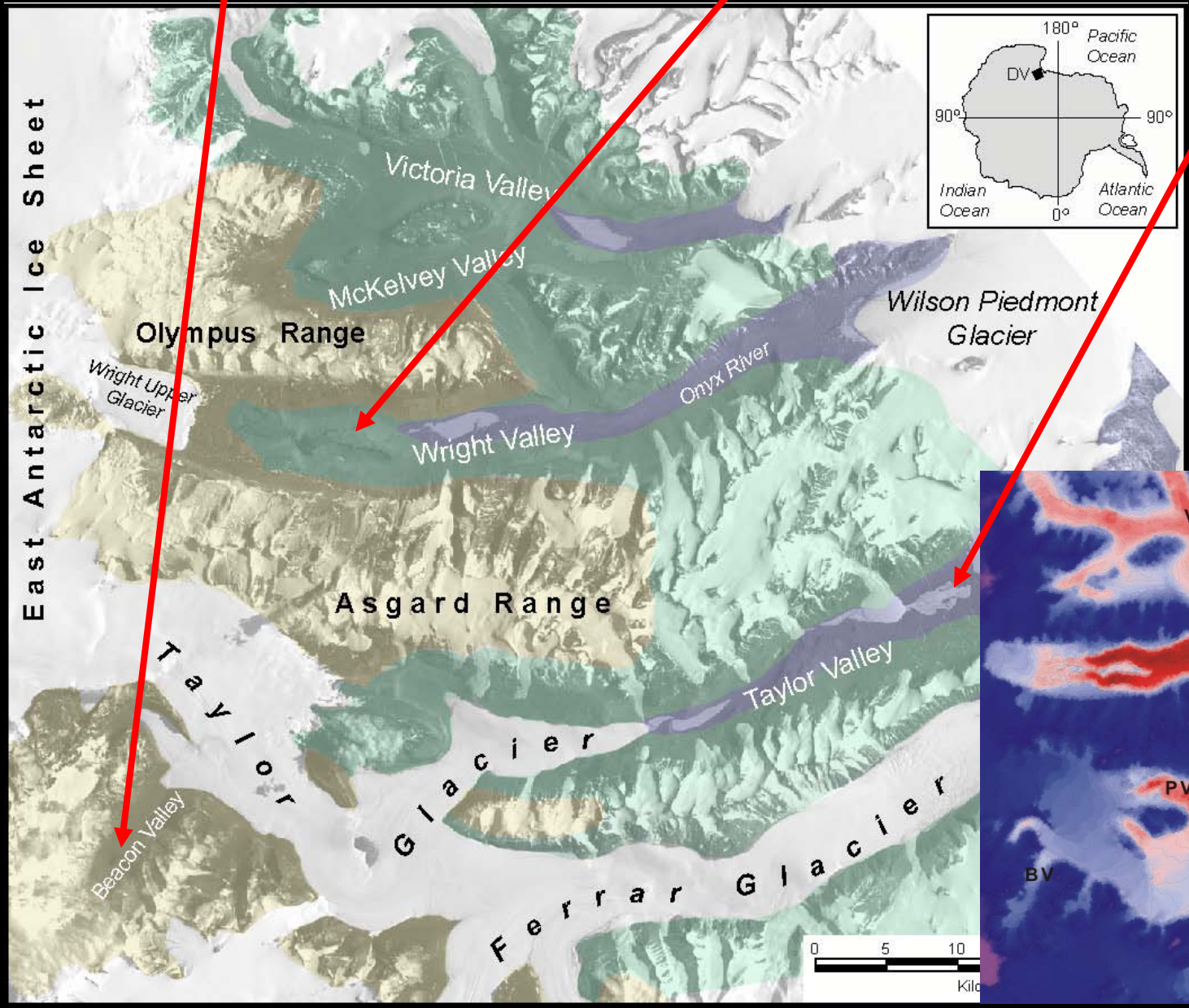


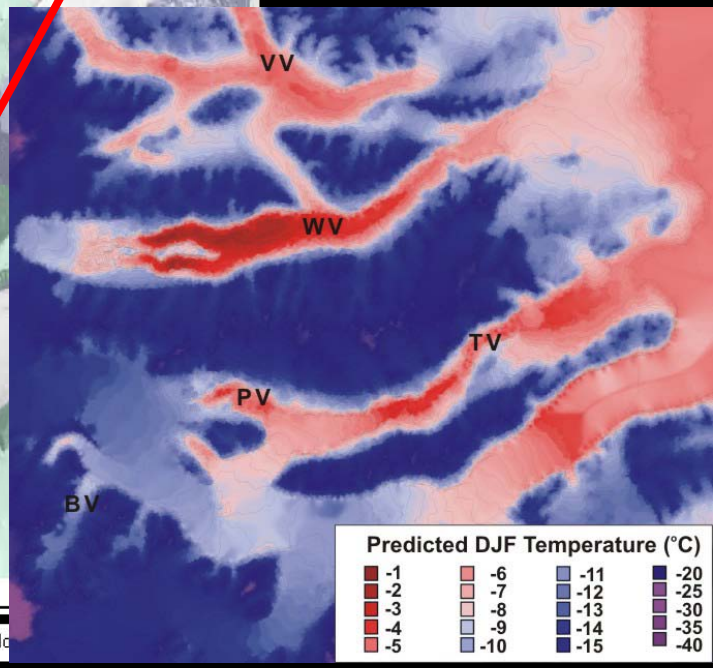


(Doran et al., JGR, 2002

Microclimate Zones

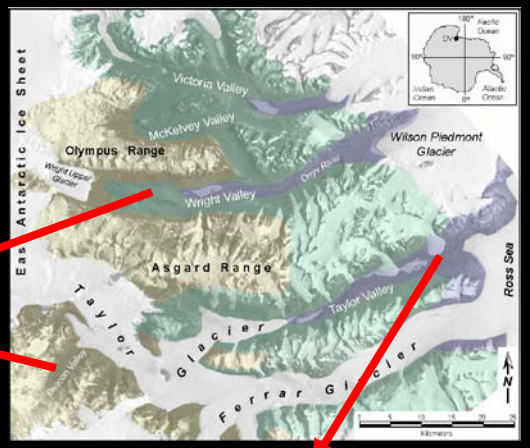
Stable Upland Zone ***Inland Mixed Zone*** ***Coastal Thaw Zone***





Marchant and Head (2007)

Distribution of Surface Meltwater



No traditional “active layer”.
No segregation ice.
Regions with soil moisture < 3%.

< -30 C to -35 C

Stable Upland Zone

Beacon Valley

Discontinuous A. L.
Ice and sand wedges.
Soil moisture variable.

-20 C to -27 C

Inland Mixed Zone

Upper Wright Valley

Dynamic Active Layer with
segregation ice and wedges
Soil moisture ~ 30 to > 50%

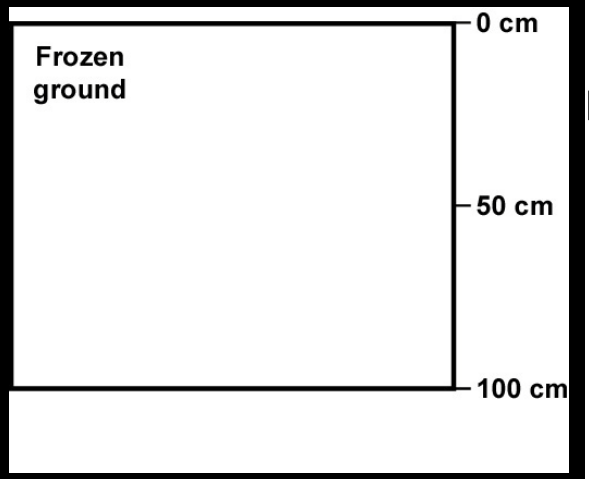
-14 C

Coastal Thaw Zone

Lower Taylor Valley

Distribution of Surface Meltwater

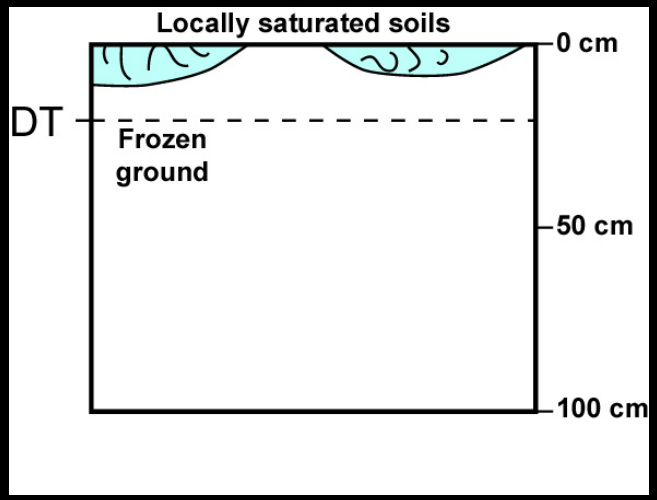
No traditional active layer.
No segregation ice.
soil moisture <3%.



-8°C (<-30 C)

Stable Upland Zone

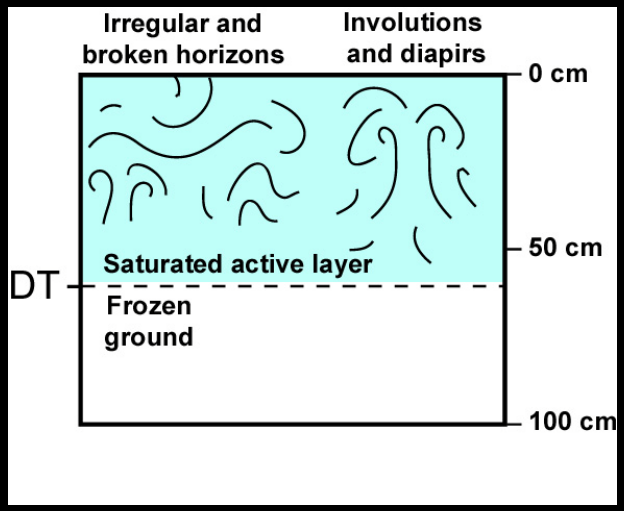
Discontinuous A. L.
Sand wedges.
Soil moisture variable.



-4°C (-22 C)

Inland Mixed Zone

Dynamic active layer with segregation ice and wedges.
Soil moisture ~30 to >50%



-2°C (-14°C)

Coastal Thaw Zone

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-The MDV represent a polar desert in which rainfall does not occur.

-Annual snowfall averages less than 50 mm water equivalent.

-Most snowfall precipitation is lost through immediate sublimation.

2) <u>Hypothermal</u>:

-The MDV have an extremely low mean annual temperature (-18ºC).

-MDV have lower diurnal temperature *ranges* than temperate climates.

-These conditions severely limit the abundance and effects of:

-Liquid water at all scales and biology at all scales.

3) <u>Extreme Seasonality</u>:

-Temperate-climate diurnal solar insolation variations (day and night):

-Become seasons in MDV due to the very high latitudes.

-Daytime is summer and nighttime is winter.

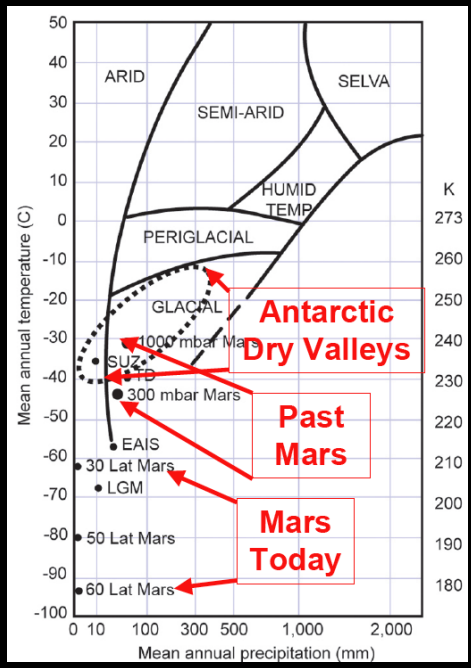
4) <u>Asymmetrical Solar Illumination Geometry</u>:

-The very high latitudes of the MDV cause pronounced asymmetries:

-In daily and mean annual solar energy input (thus surface temperatures).

-Equator-facing slopes receive significantly more daily and annual solar radiation than pole-facing slopes.

-This creates microenvironments and profoundly influences the presence of liquid water and geological and biological processes operating there.



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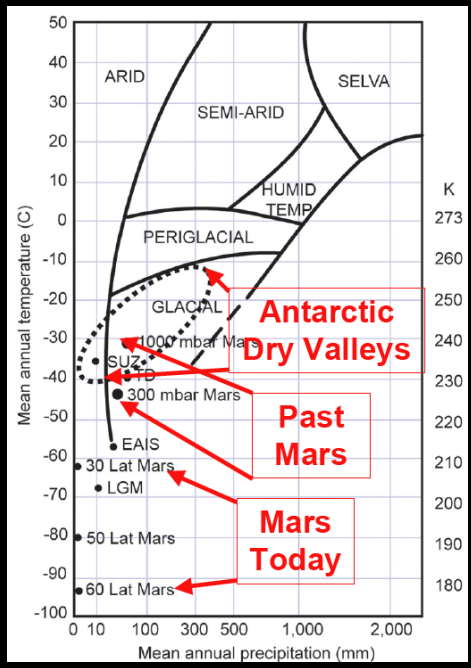

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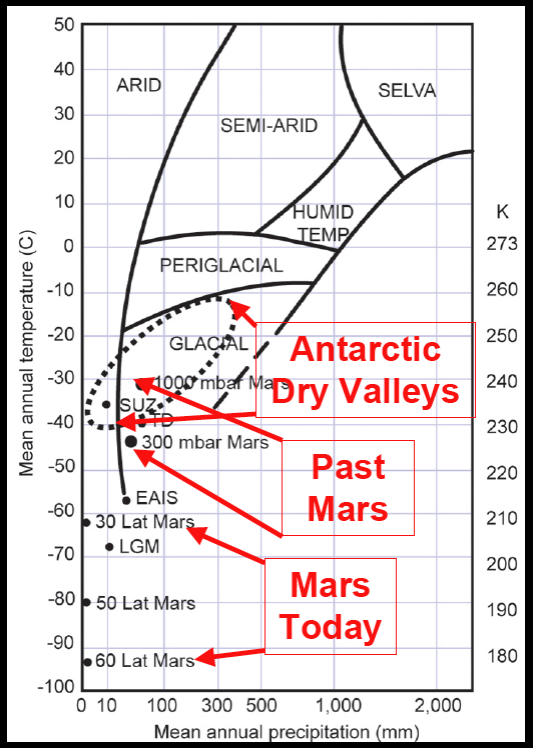

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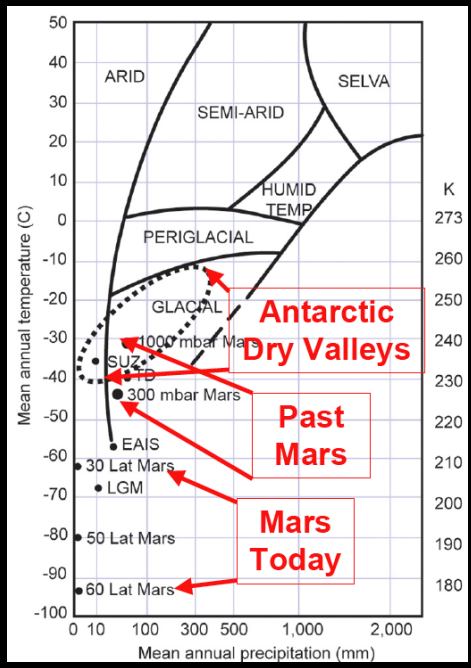

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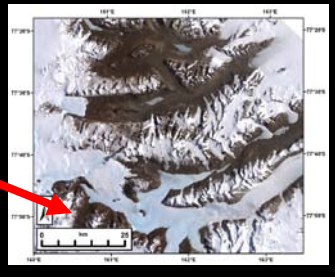

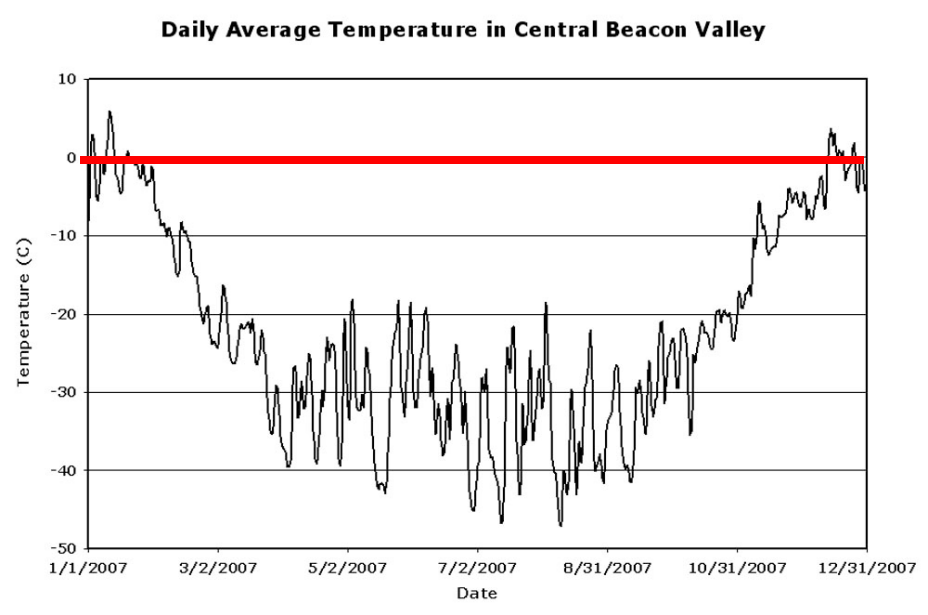

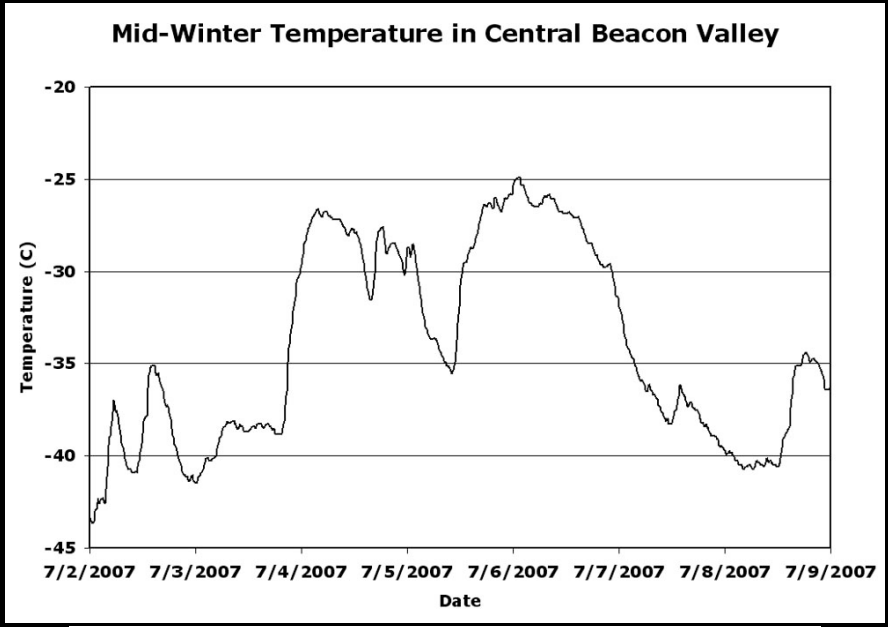

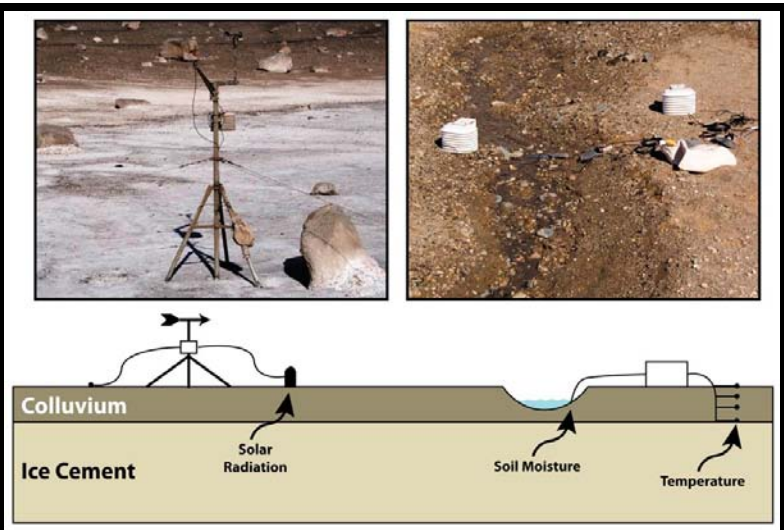

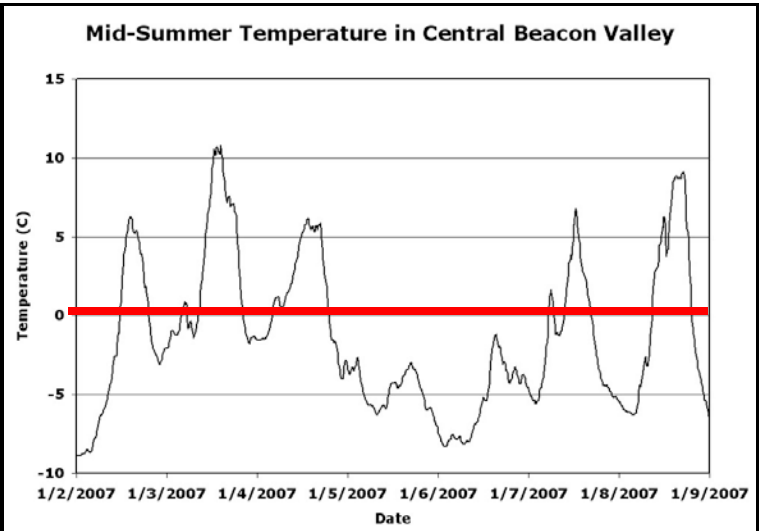

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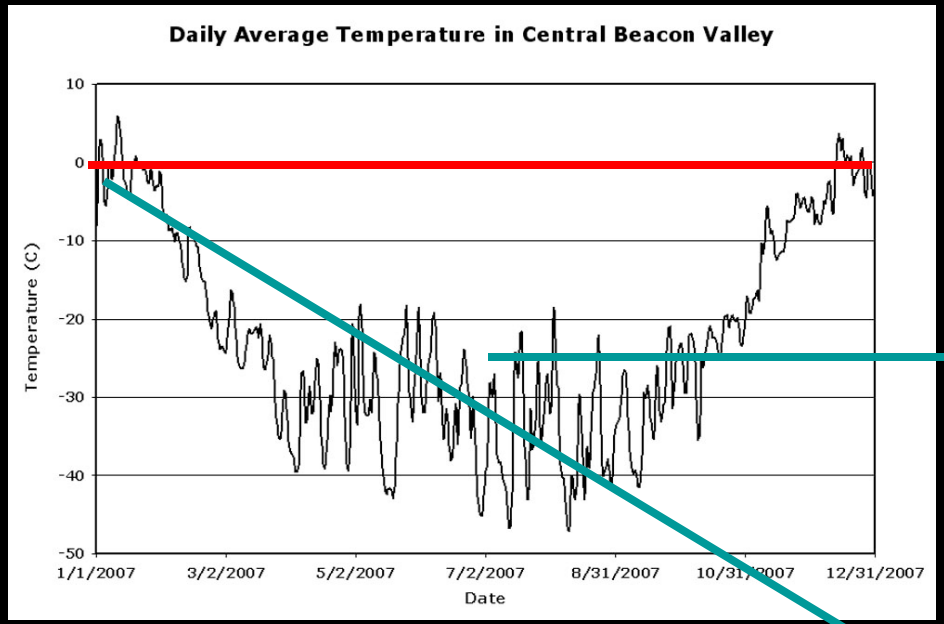

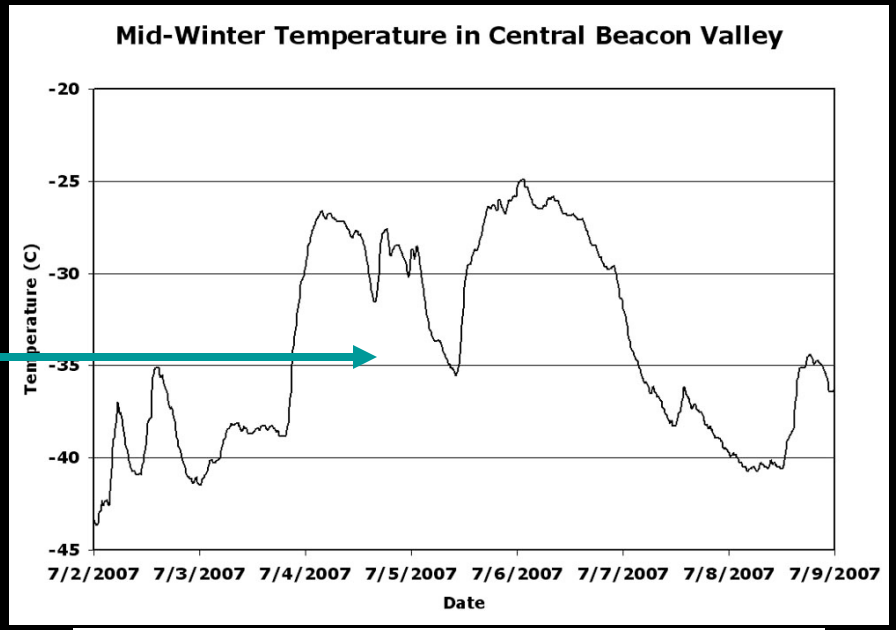

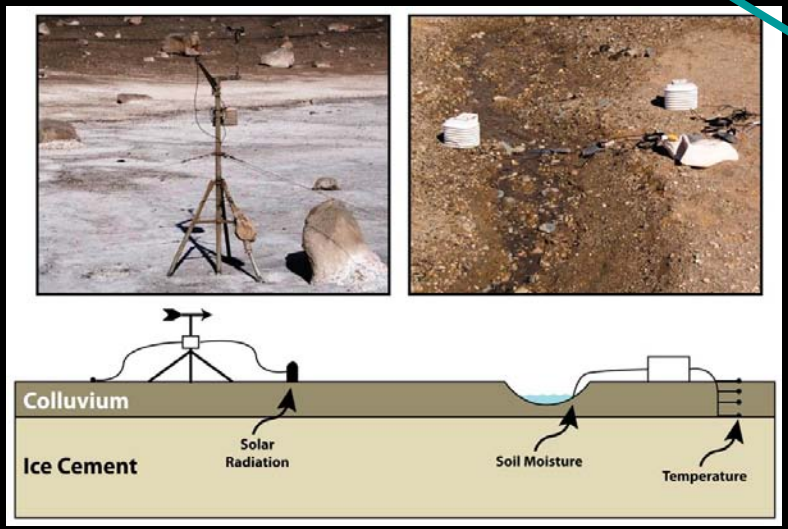

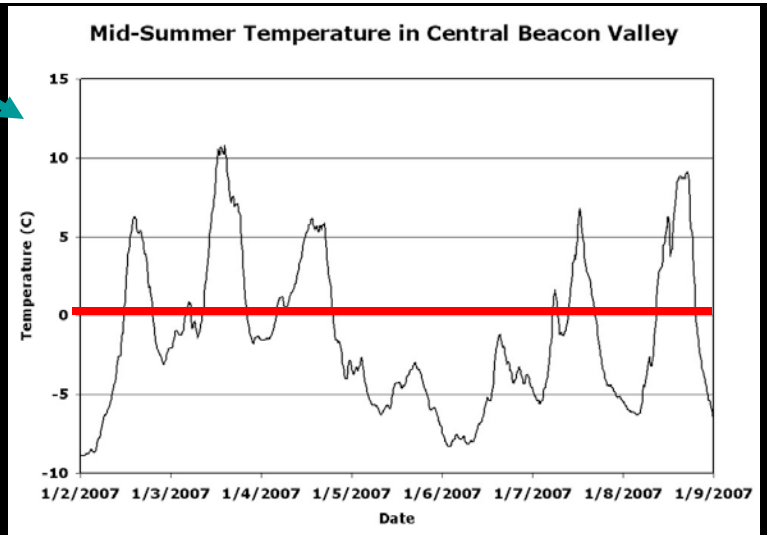

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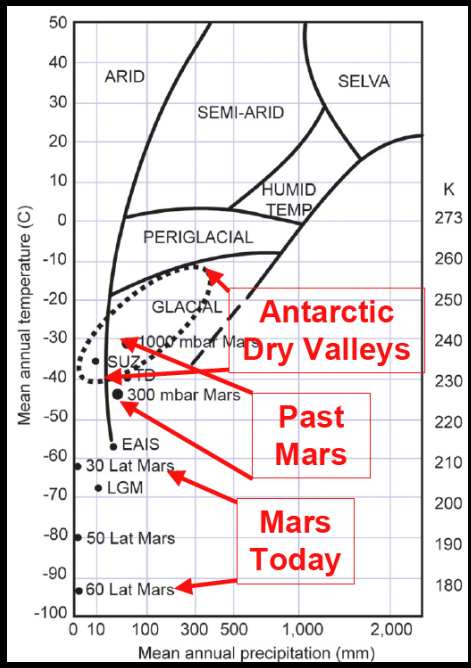

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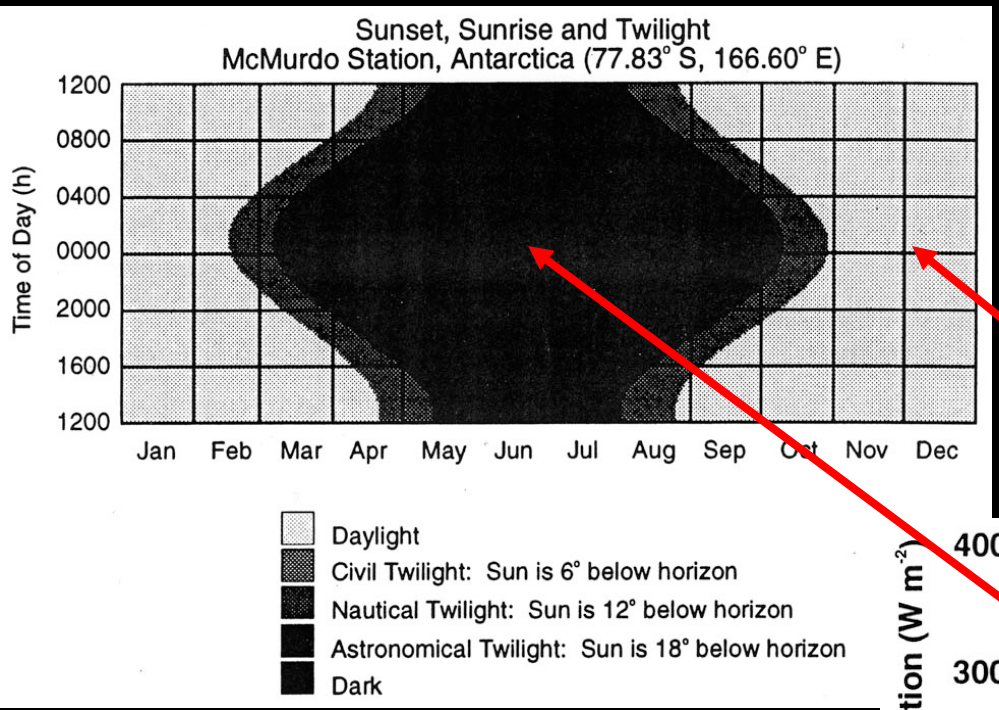
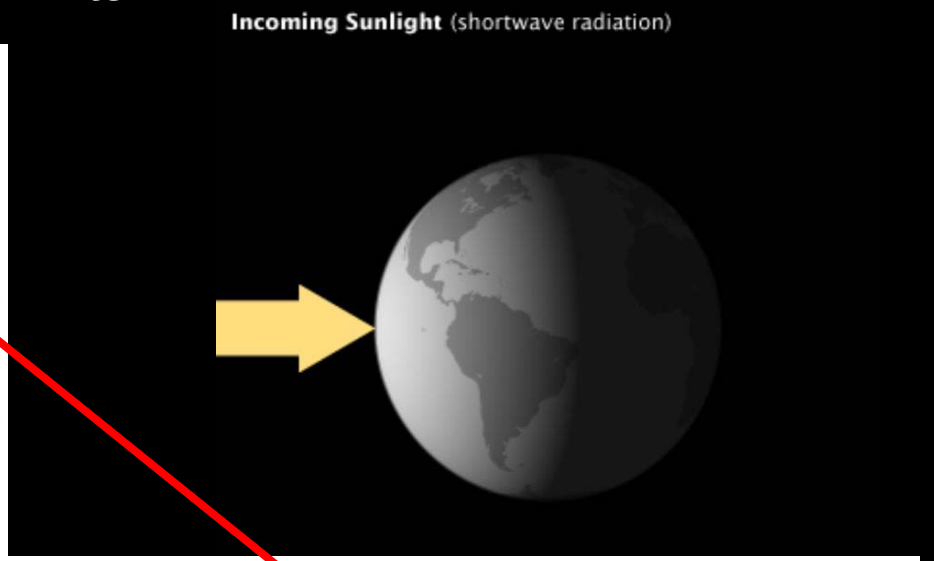
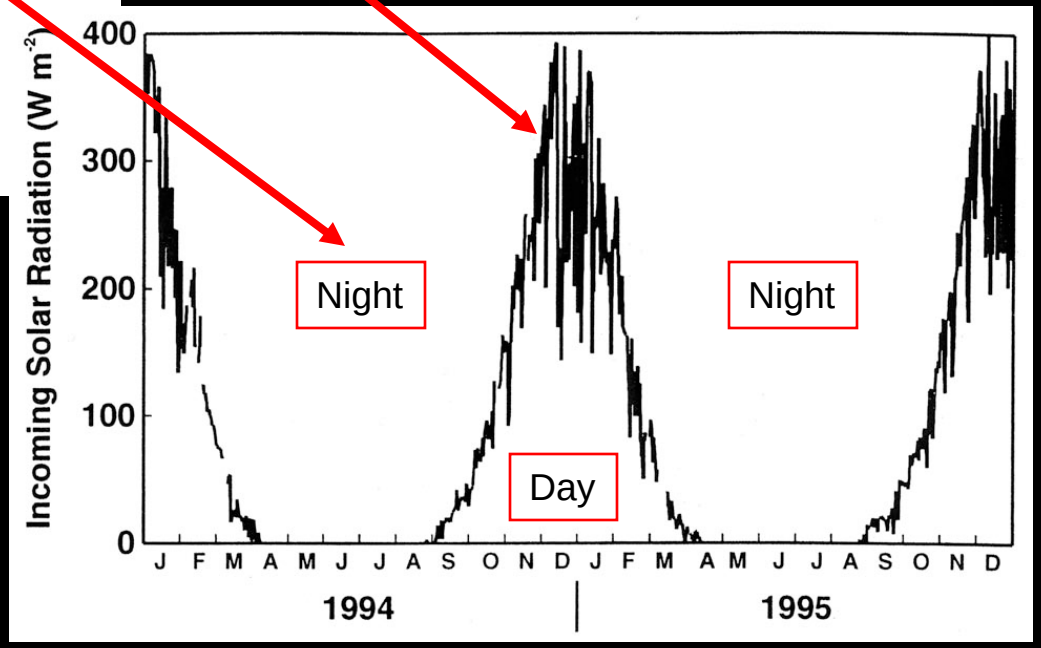






MDV Environmental Conditions Contrast Profoundly with Temperate Climates:

1) <u>Hyperarid</u>:

-The MDV represent a polar desert in which rainfall does not occur.

-Annual snowfall averages less than 50 mm water equivalent.

-Most snowfall precipitation is lost through immediate sublimation.

2) <u>Hypothermal</u>:

-The MDV have an extremely low mean annual temperature (-18ºC).

-MDV have lower diurnal temperature *ranges* than temperate climates.

-These conditions severely limit the abundance and effects of:

-Liquid water at all scales and biology at all scales.

3) <u>Extreme Seasonality</u>:

-Temperate-climate diurnal solar insolation variations (day and night):

-Become seasons in MDV due to the very high latitudes.

-Daytime is summer and nighttime is winter.

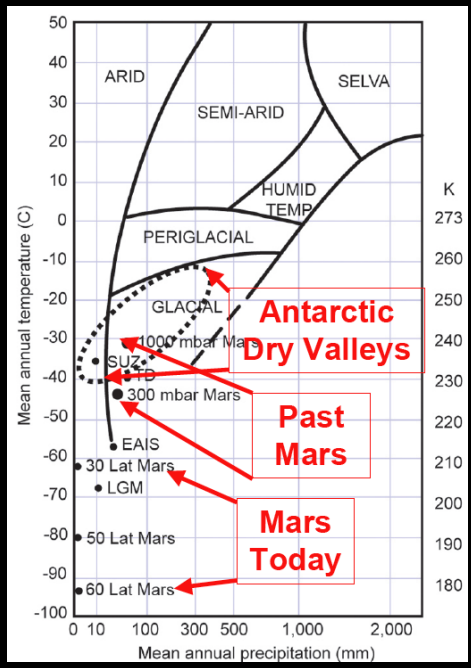
4) <u>Asymmetrical Solar Illumination Geometry</u>:

-The very high latitudes of the MDV cause pronounced asymmetries:

-In daily and mean annual solar energy input (thus surface temperatures).

-Equator-facing slopes receive significantly more daily and annual solar radiation than pole-facing slopes.

-This creates microenvironments and profoundly influences the presence of liquid water and geological and biological processes operating there.



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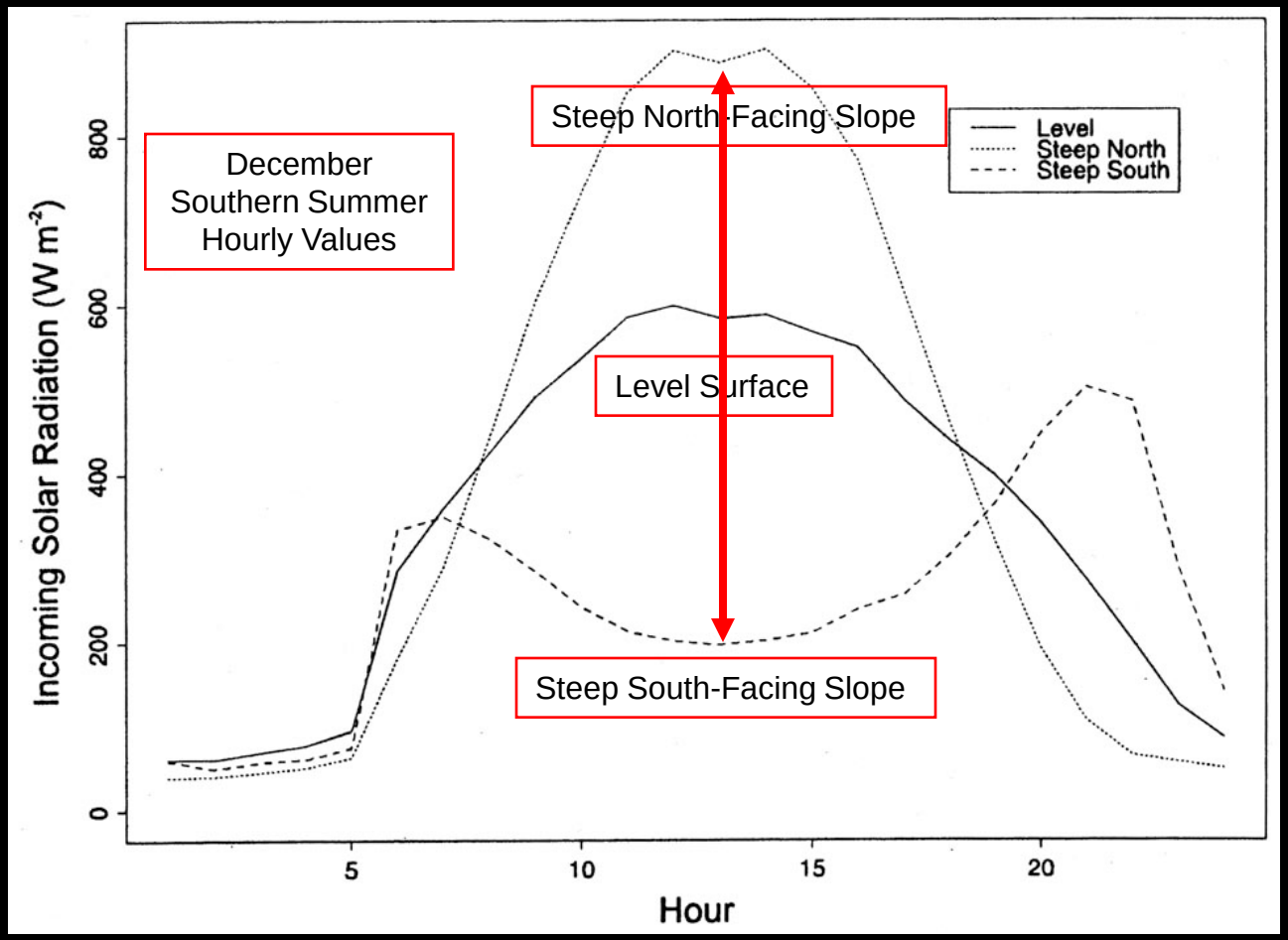

Four Additional Factors Modulate the Effects of These Extreme MDV Environmental Factors

1) Topographic Fabric:

-The basic nature and configuration of topography:

-Regional and local altitude variation.

-Valley depths and orientations.

-Closed versus open.

-Hypsometry of elevation and slope.

-All affect and often magnify the role of certain insolaton/wind related geological processes.

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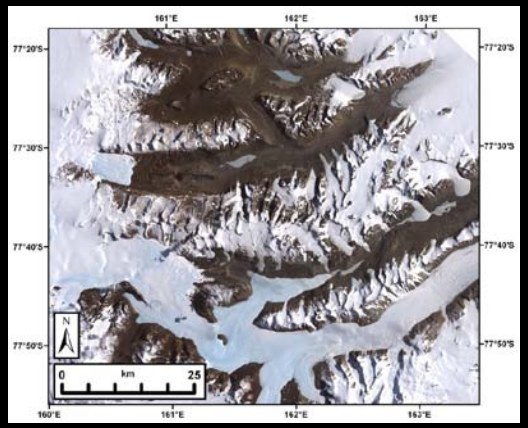

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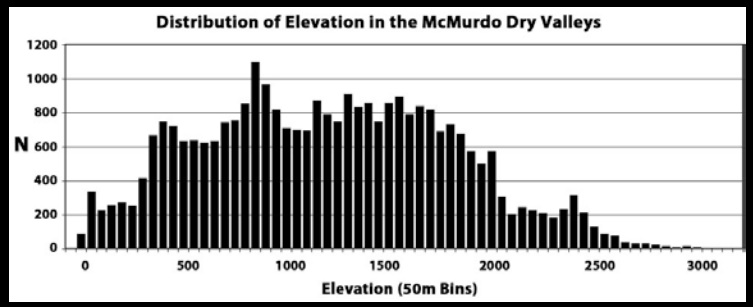

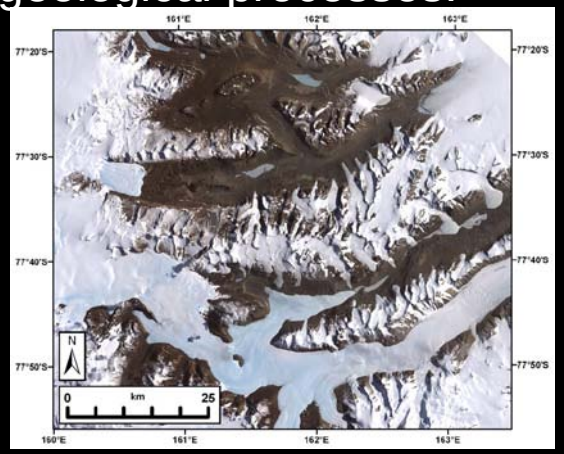

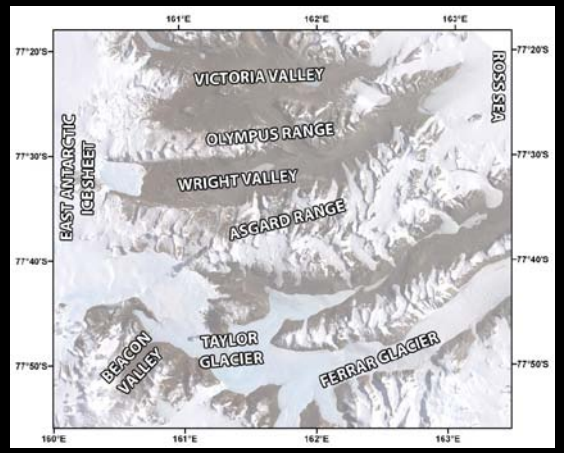

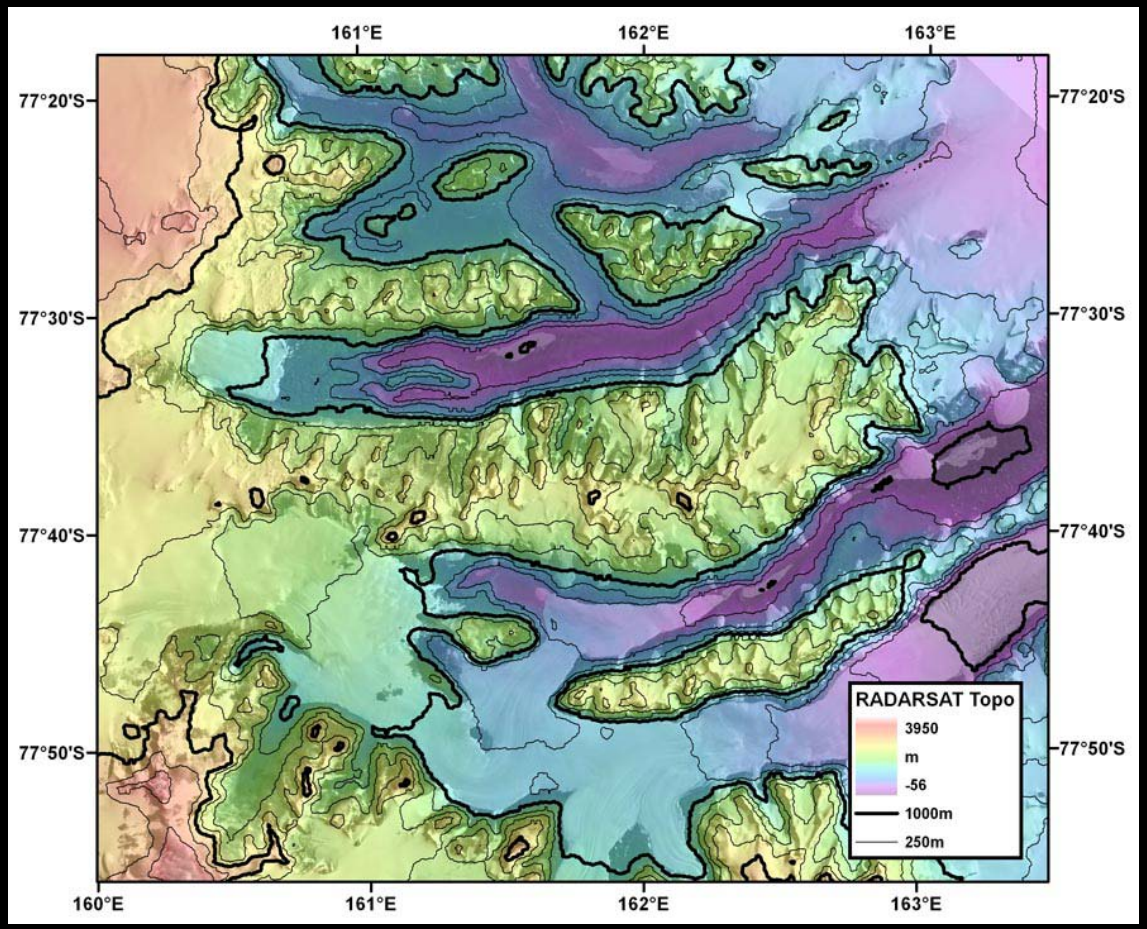

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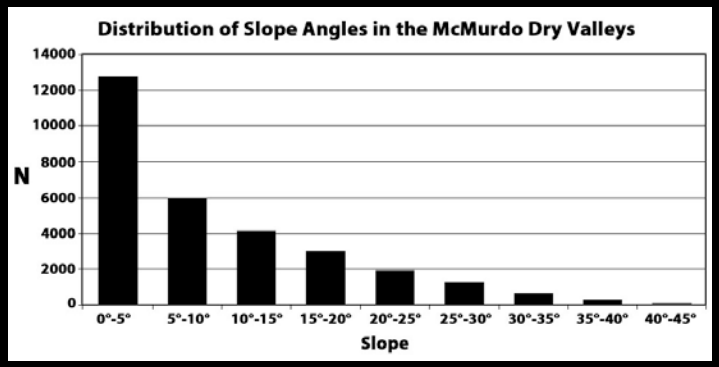

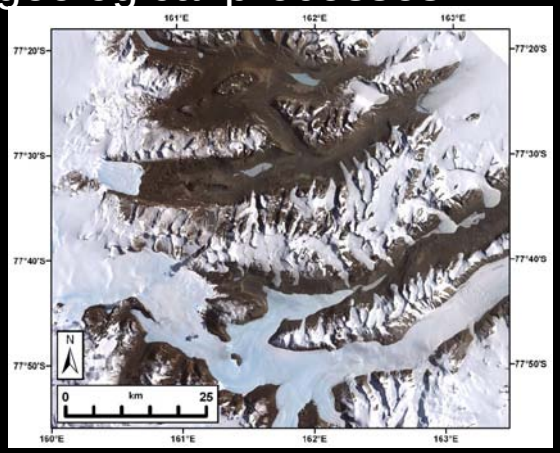

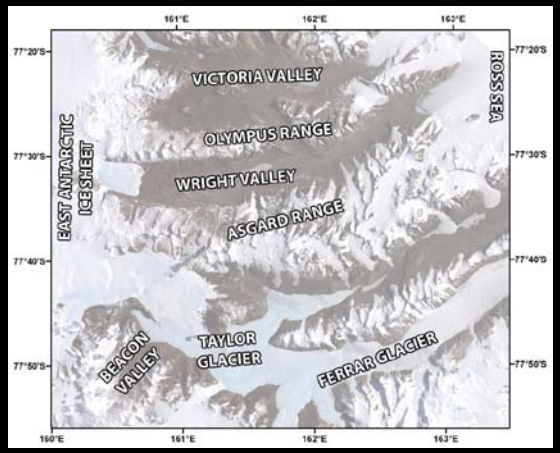

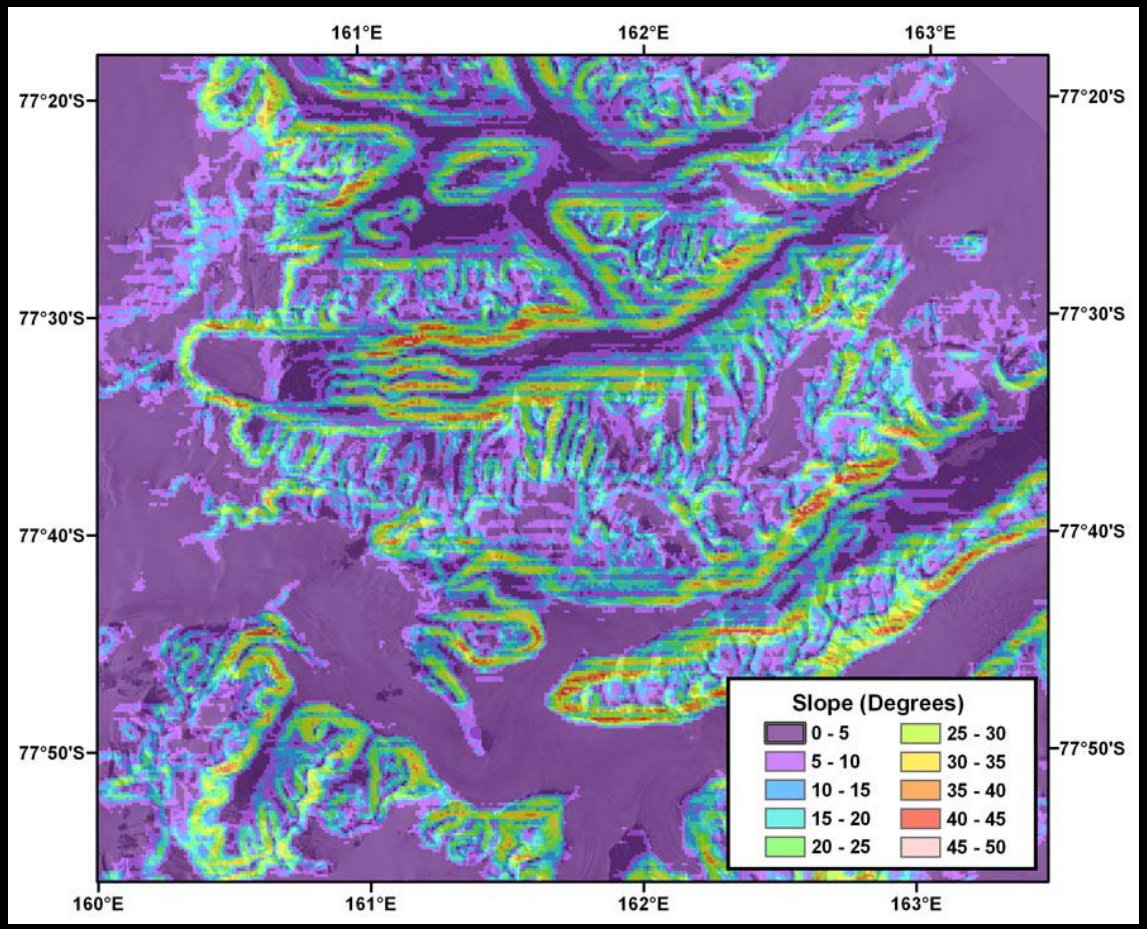

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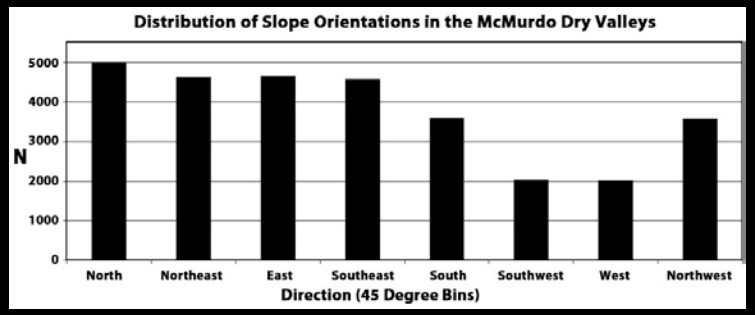

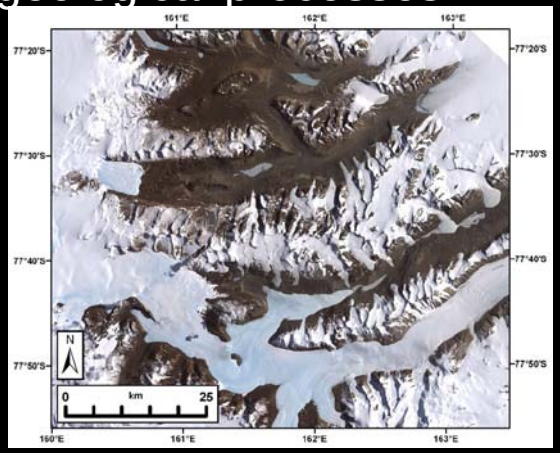

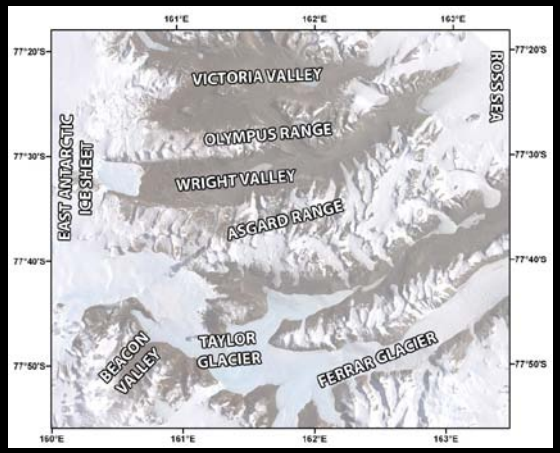

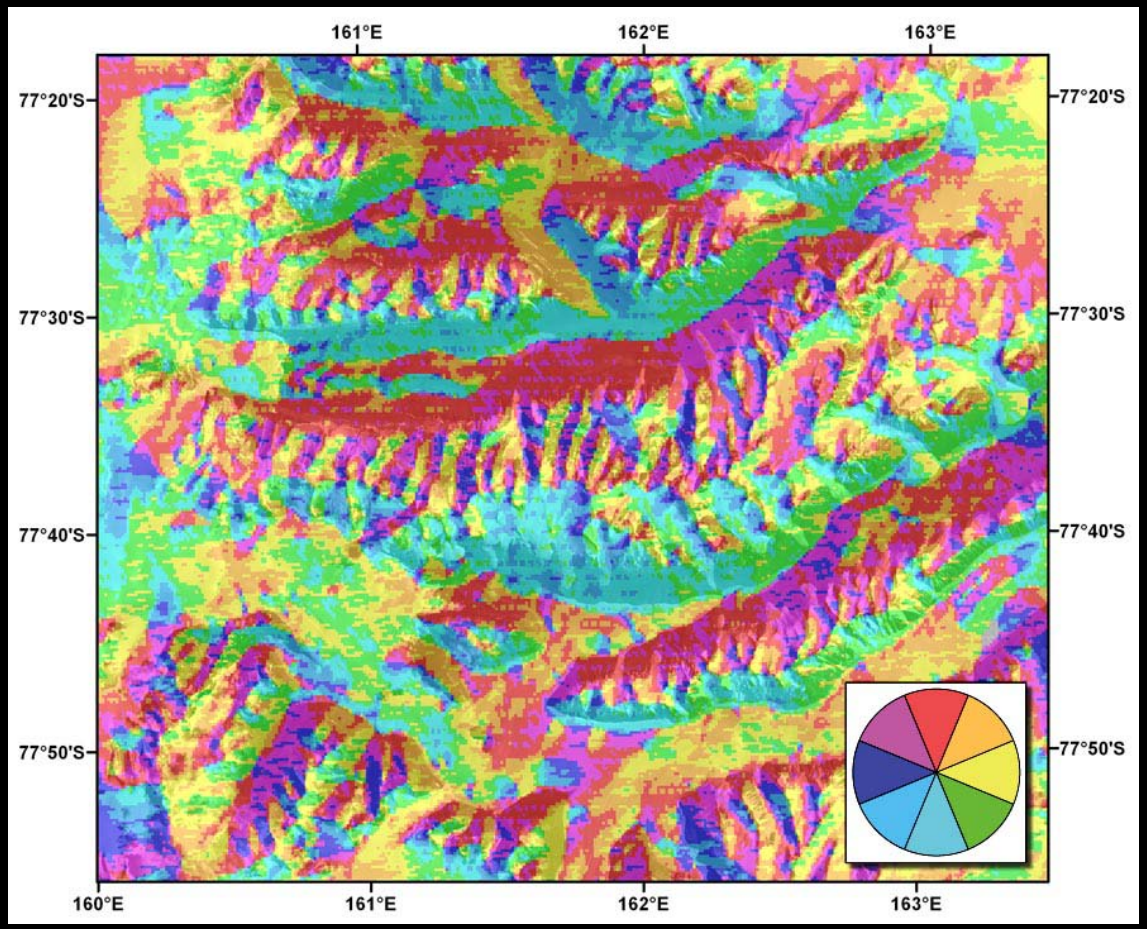

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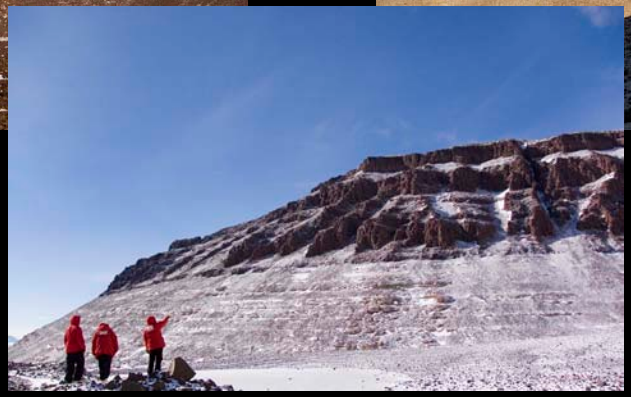

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These Eight Factors Have Profound Effects on All Aspects of the MDV.

1) Temperate Climate Hydrologic System and Cycle:

-Rainfall, runoff, groundwater.

-Very high rates of lateral and vertical water movement.

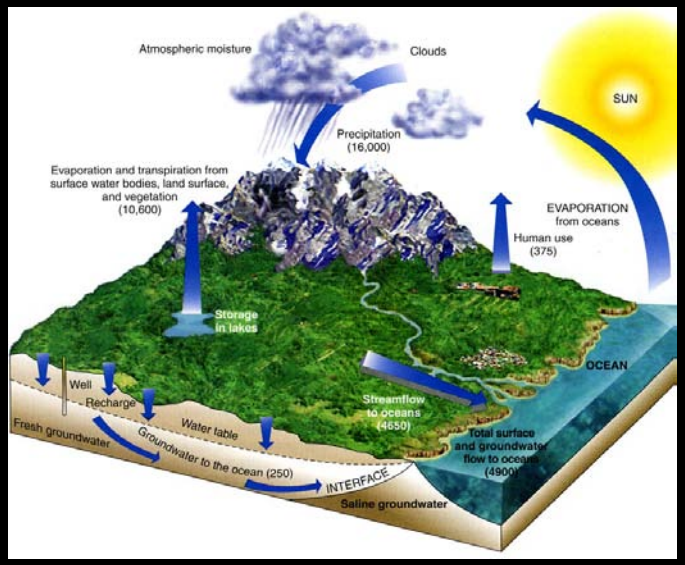
-Supports diverse, pervasive and abundant biota.

-Vertically integrated hydrologic system and cycle.

-High rates of chemical and physical weathering.

-High rock erosion and landscape denudation rates.

-Does huge amounts of “geomorphic work”.



2) MDV Hydrologic System and Cycle:

-There is no pluvial activity - no rainfall and runoff.

-Snowfall only, and this is very limited.

-Snow and ice represent the only volumetrically significant meltwater sources.

-These water sources are severely areally limited in distribution.

-A thick layer of permafrost separates the surface from deeper groundwater.

-The extreme aridity creates an upper dehydrated zone of permafrost tens of cm thick.

-The top of the ice table forms an aquiclude.

-A limited amount of local liquid water (snow and ice meltwater) occurs seasonally.

-The dehydrated zone then becomes a shallow perched aquifer.

-The MDV hydrologic system/cycle is horizontally stratified (NOT vertically integrated).

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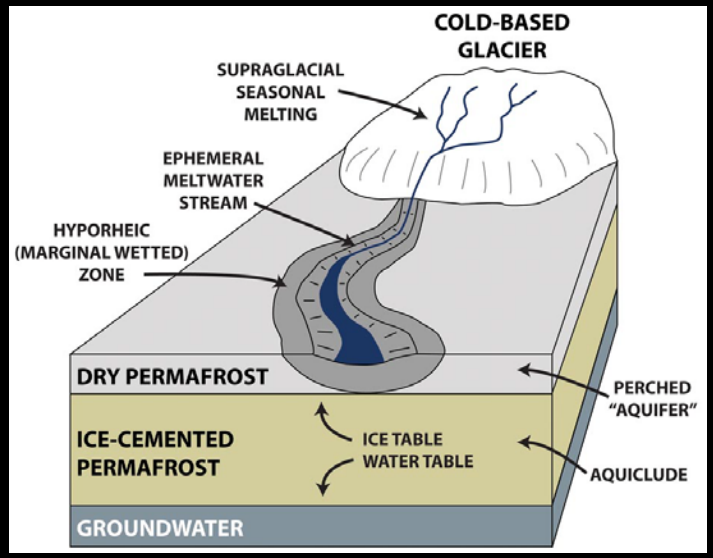

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-Abundant liquid water translates into:

-Diverse, abundant and pervasive biota.

-High rates of chemical weathering.

-High-energy environments (e.g., rivers).

-Significant geomorphic work.

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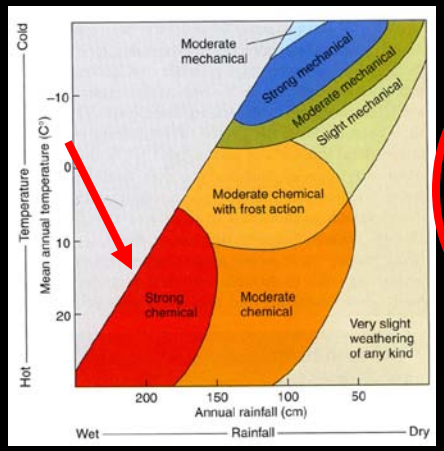

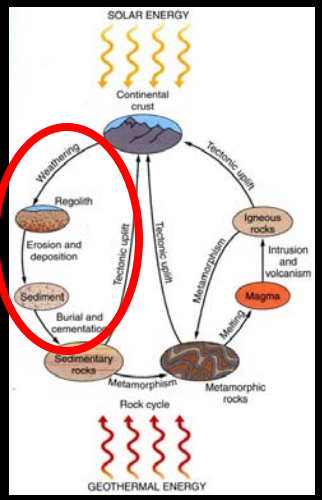

2) **Weathering Part of the Rock Cycle: MDV Hyperarid-Hypothermal Climate:**

-There is no pluvial activity - no rainfall and runoff.

-Precipitation limited to nivial (snow) and this sublimes, rather than melting.

-Extreme paucity of liquid water:

-Chemical weathering processes are severely curtailed.

-Physical weathering processes dominate, but are limited.

-Weathering and erosion rates are several orders of magnitude lower.

-Very sparse biota (lack of vascular plants and low abundance of organic carbon):

-This further limits chemical weathering.

-Development and diversity of soils limited by these factors.

-MDV soils are dominated by *anhyorthels*.

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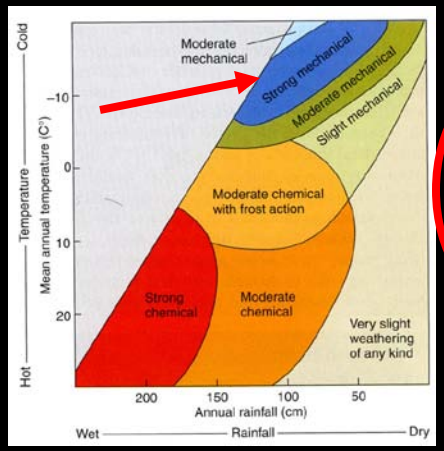

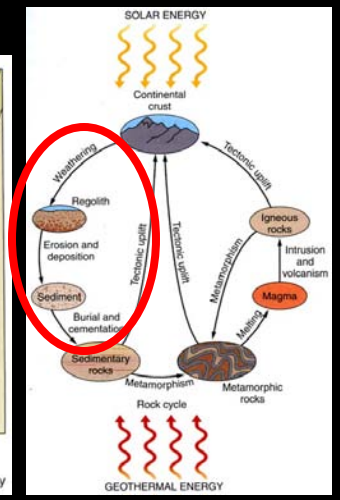

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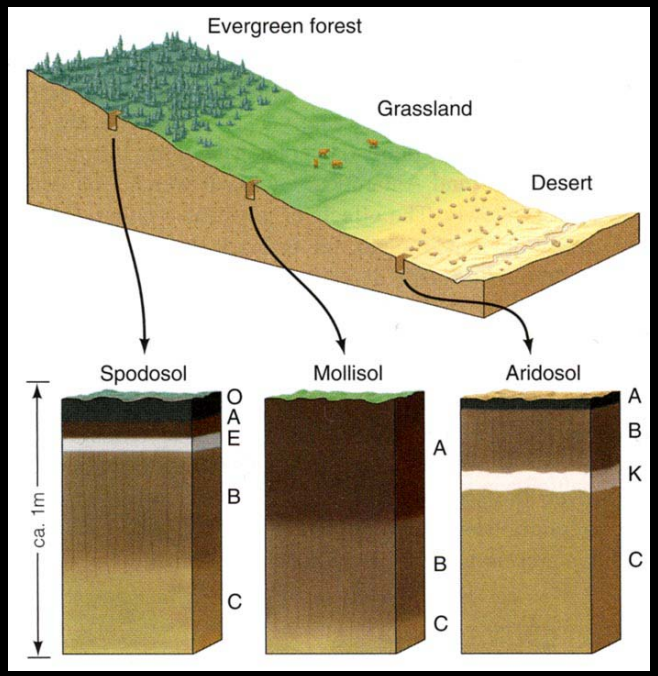
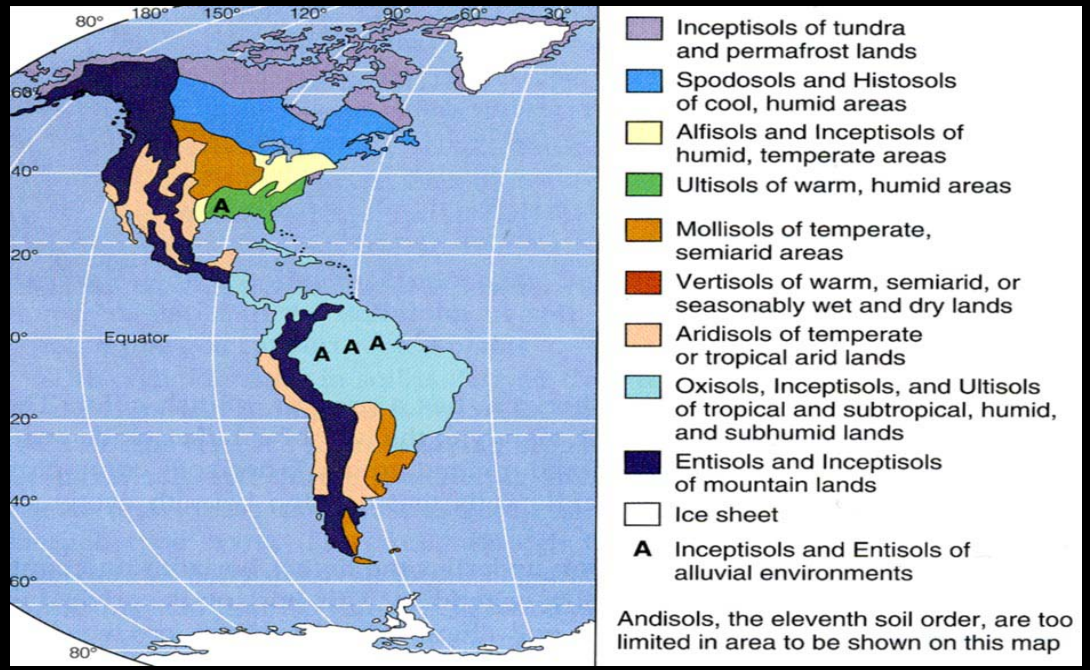
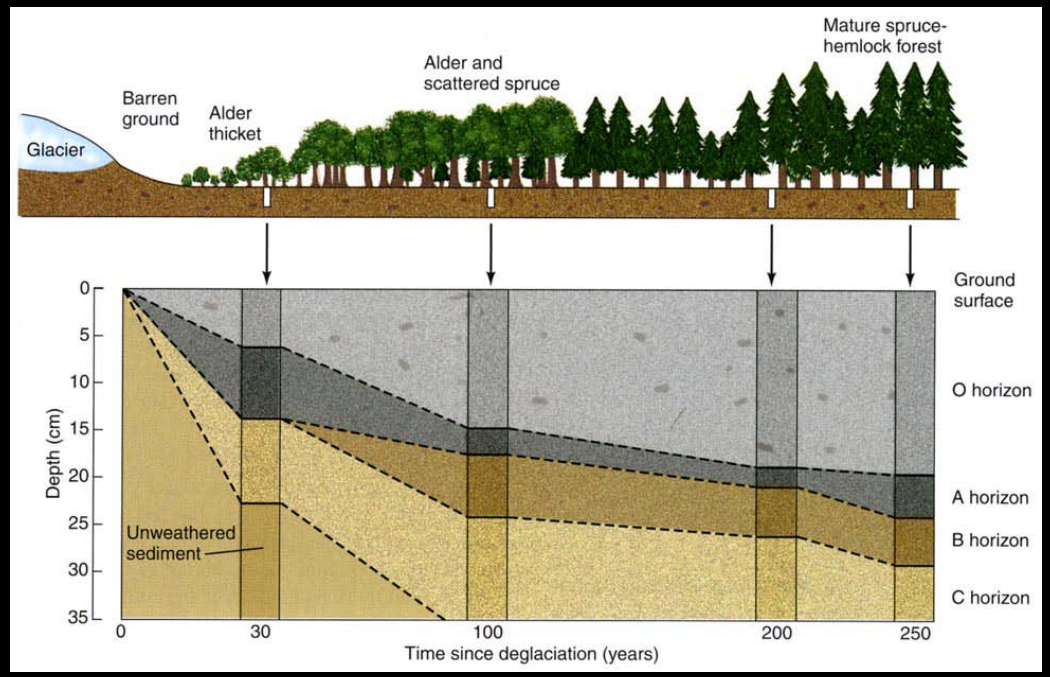
Rock Weathering and Denudation Rates

Rock weathering rates in the MDV have been estimated to be between 0.2 and 1 x 10^{-6} mm/1000 yr (Summerfield et al., 1999).

Soil Development in Non-Polar Regions







Evolution of a Soil Profile: Glacier Bay, Alaska

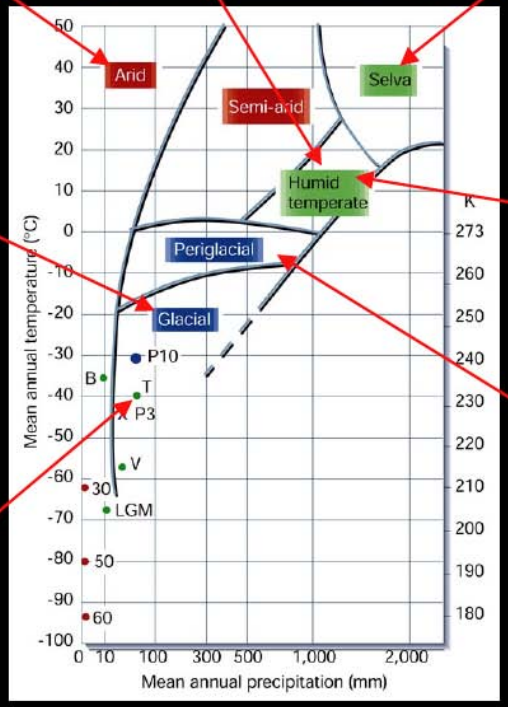
- O= organic layer.

- A Horizon = humus-rich.
- B Horizon = enriched in clay.
- C Horizon = weathered rock.

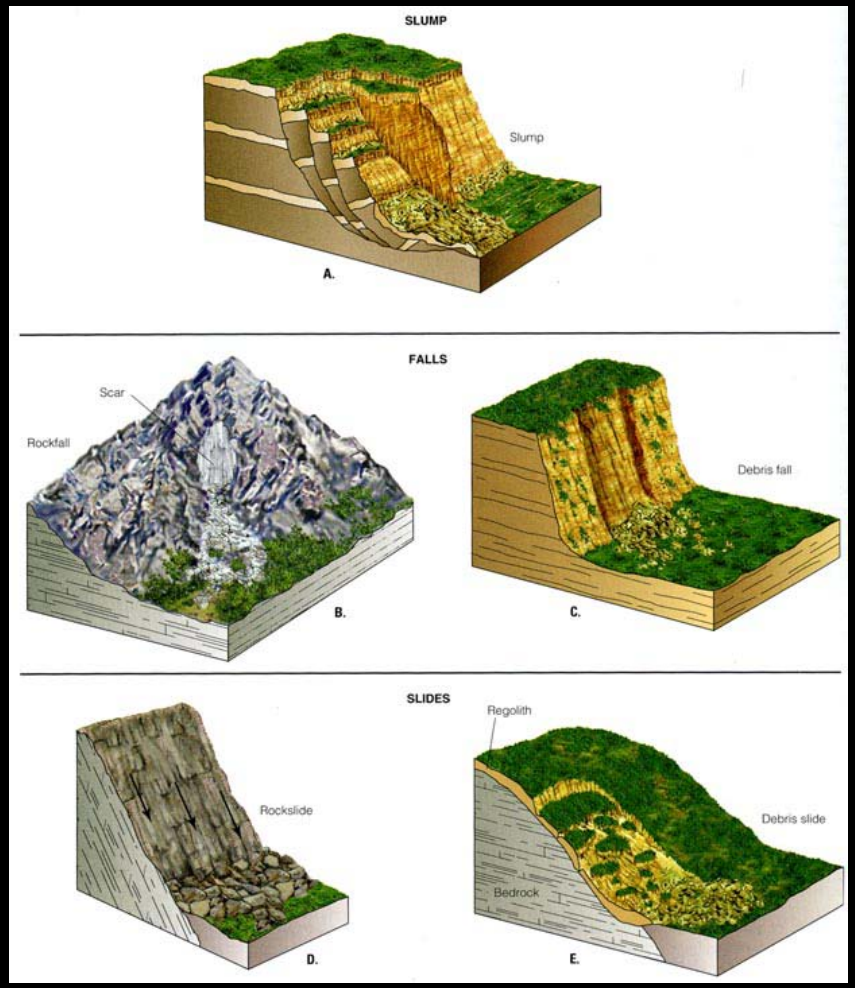
These Eight Factors Have Profound Effects on All Aspects of the MDV.

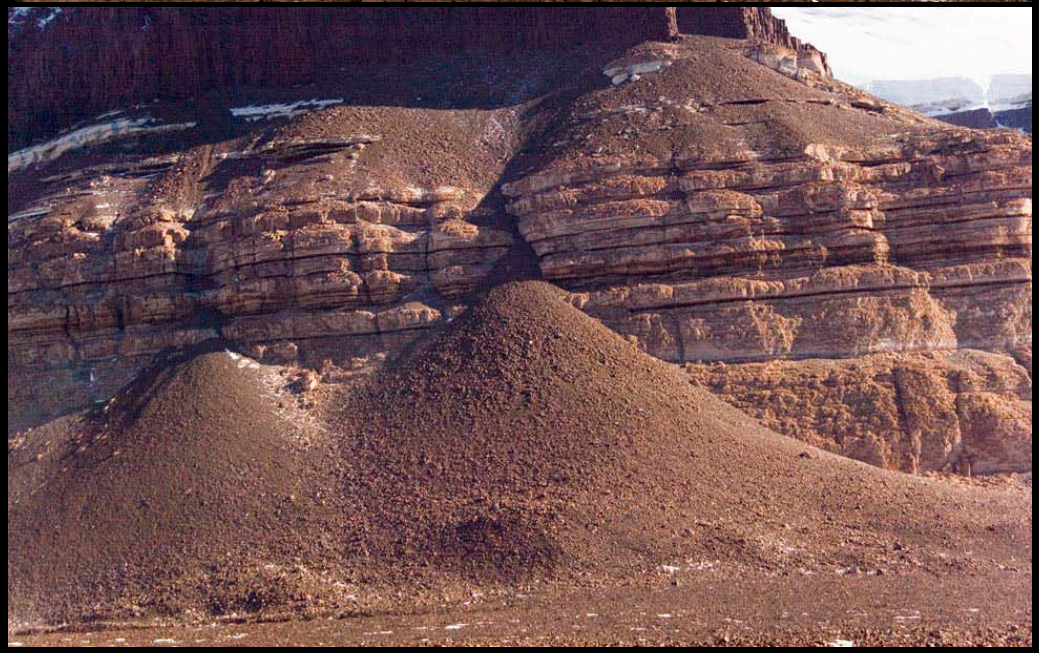
Map out into fundamental differences in geological and biological processes compared to temperate environments.

1) **Mass Wasting and Slope Processes:**
2) **Eolian Processes:**
3) **Glacial Processes:**
4) **Periglacial Processes:**
5) **Groundwater Processes:**
6) **Fluvial Processes:**
7) **Lacustrine Processes:**

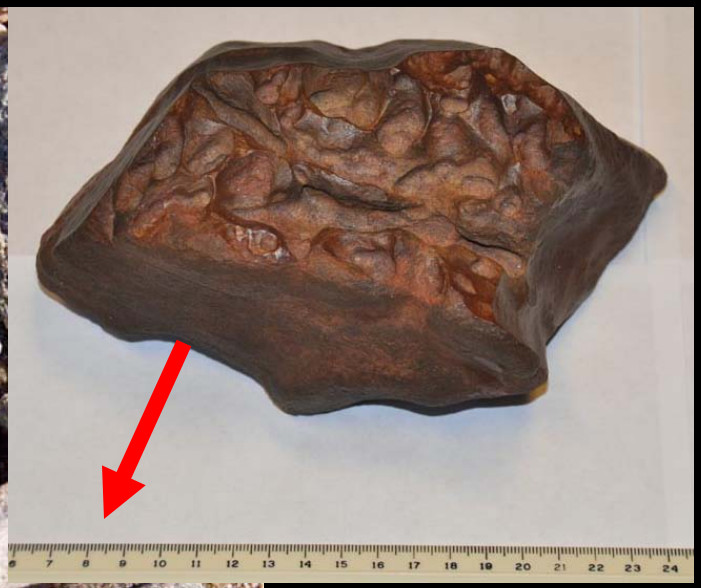


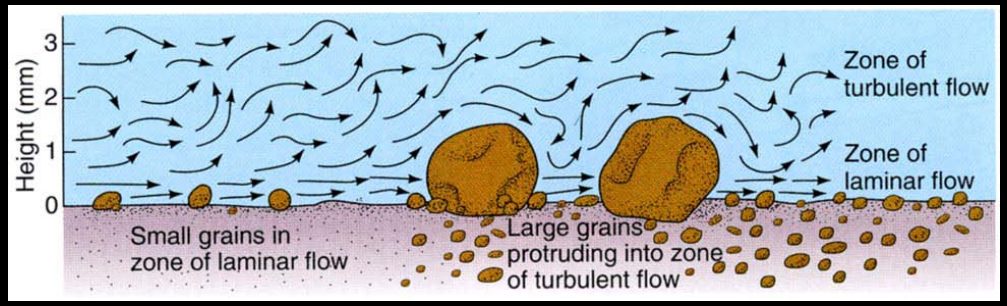
1) <u>Mass Wasting and Slope Processes</u>: Dominated by freeze-thaw and salt weathering; gravitationally driven transport of unconsolidated dry debris.





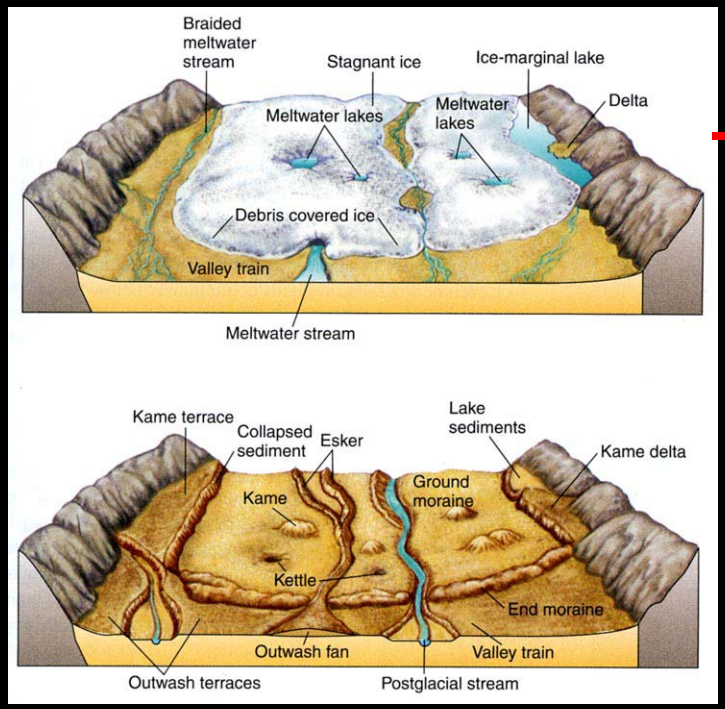
2) <u>Eolian Processes</u>: Enhanced by katabatic winds and lack of vegetation; desert pavements dominate; ventifacts and asymmetrical weathering are common.

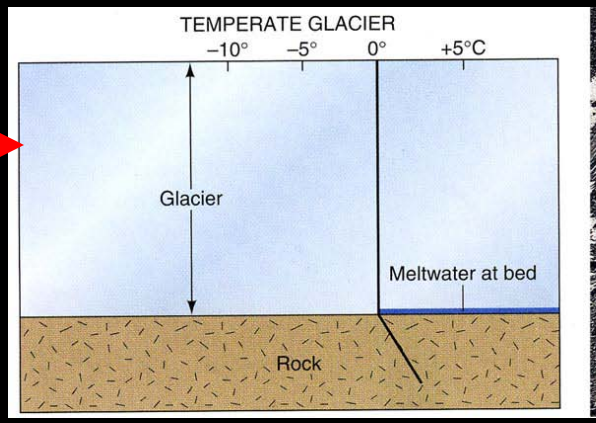


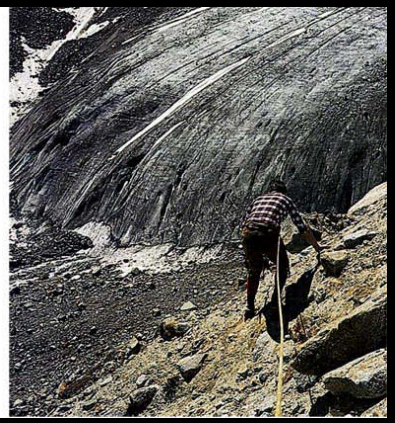


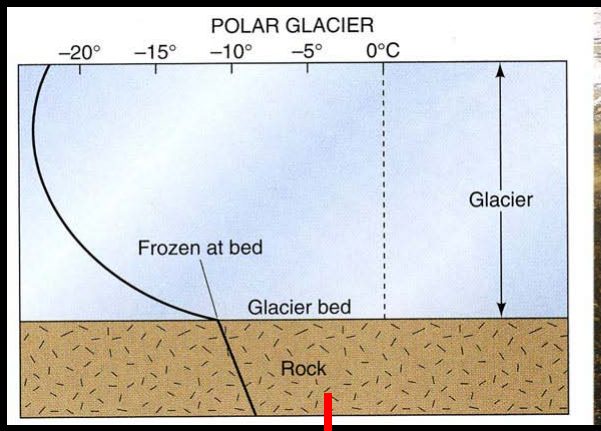
-Katabatic winds: Peak 20 m s^{-1} with gusts to over 30 m s^{-1}.
-Values up to 70 m s^{-1} (250 km h^{-1}) have been reported).

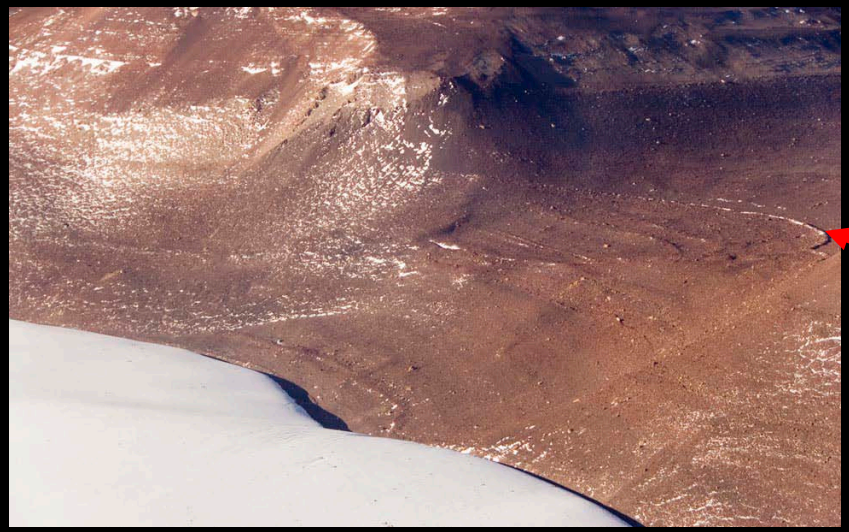
3) Glacial Processes: Glaciers are cold-based and form minor drop moraines and extremely slow-moving debris-covered glaciers.











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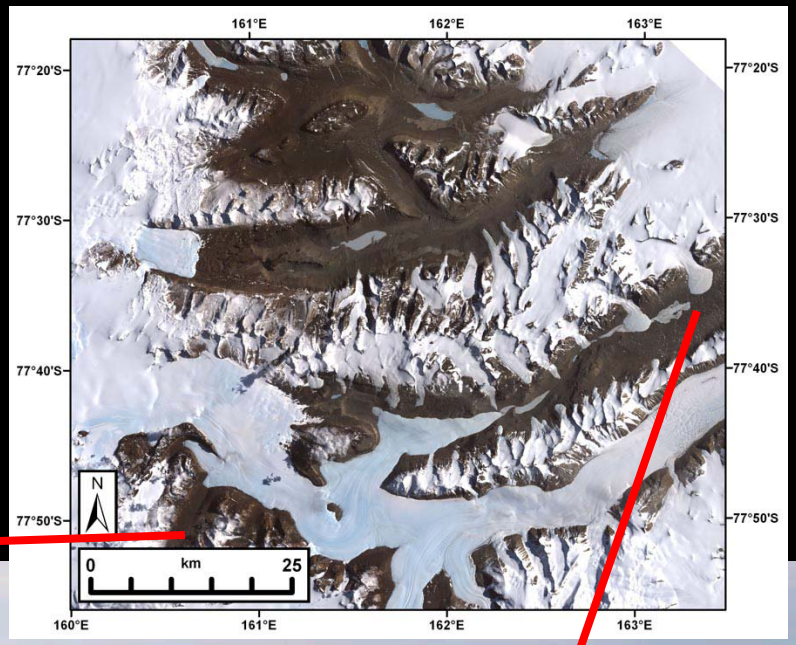
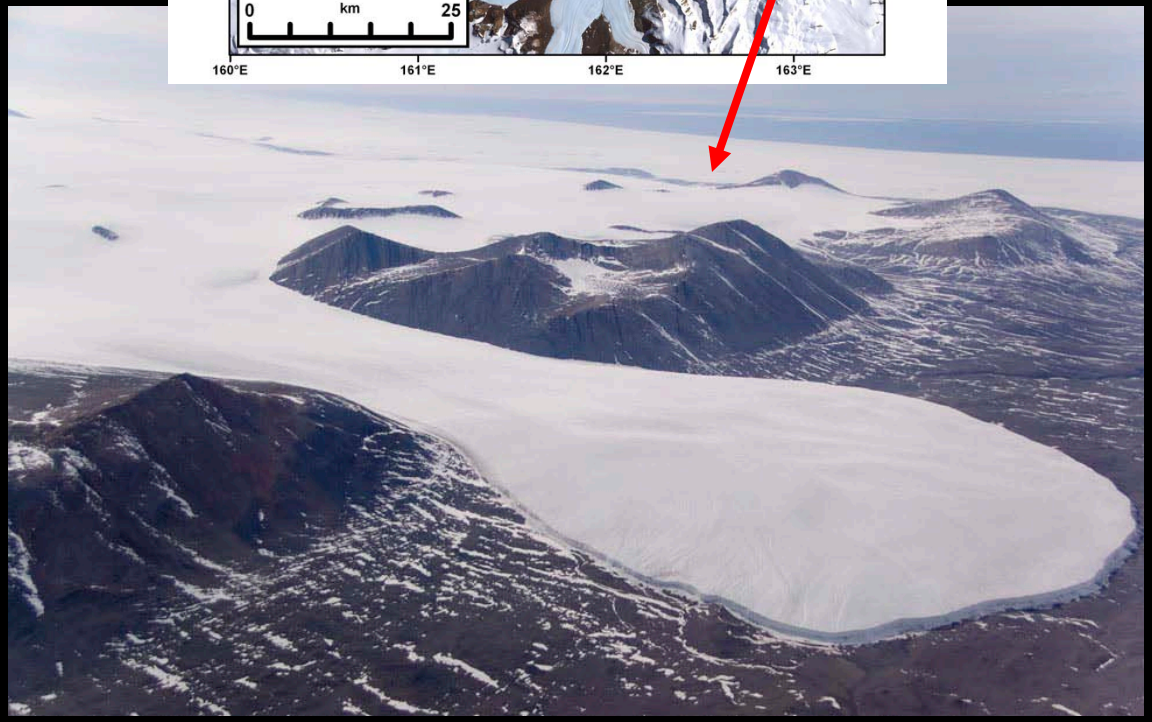
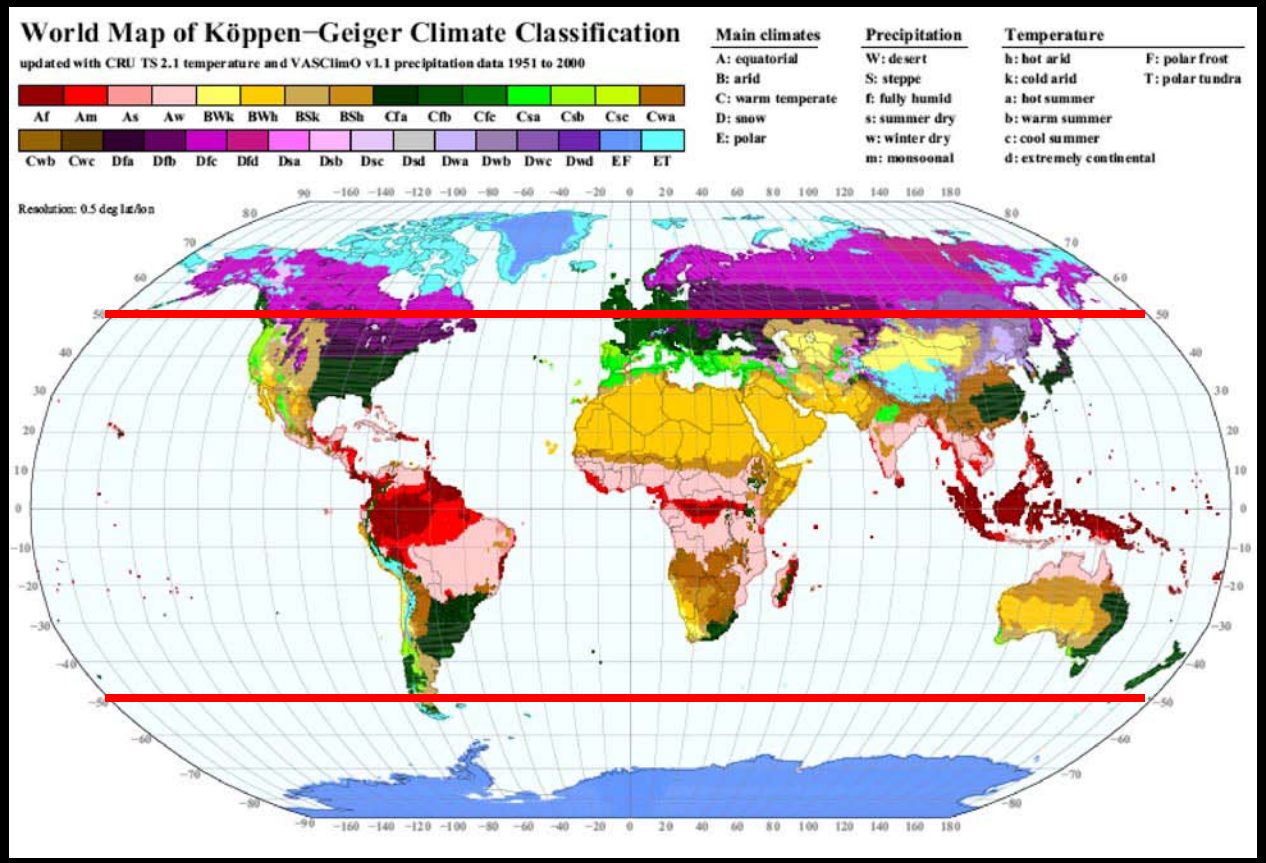




4) <u>Periglacial Processes</u>: Produce a range of polygonally patterned ground, but very limited meltwater involvement restricts periglacial features to a small subset of those seen in the Arctic.



Pingos

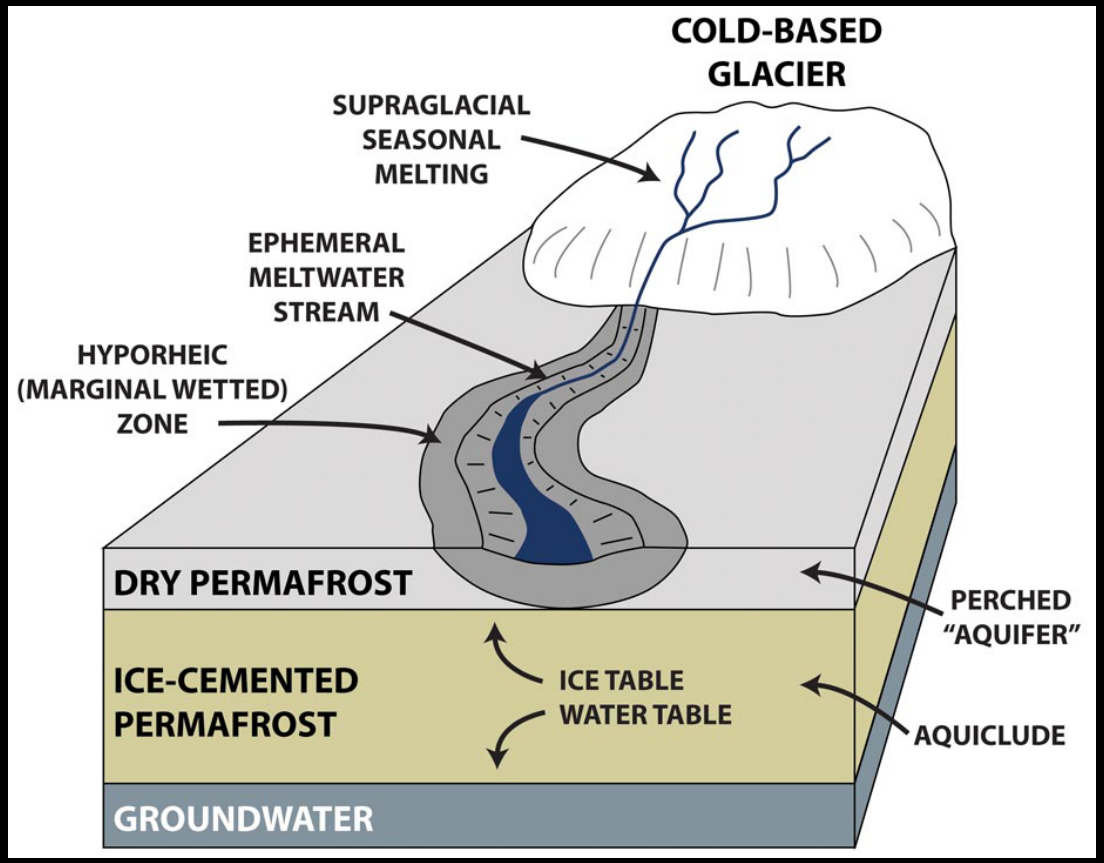
Frost-Sorted
Stone
Circles

Thaw Lakes in Polygons

4) <u>Periglacial Processes</u>: Produce a range of polygonally patterned ground, but very limited meltwater involvement restricts periglacial features to a small subset of those seen in the Arctic.

Contraction-Crack
Polygons

5) Groundwater Processes: Limited to a shallow perched aquifer above the ice table and are further restricted to areas of meltwater generation and flow.



Sources of Meltwater:
-Annual snowfall.
-Sequestered annual snowfall.
-Perennial snow.
-Glacial melting.
-Permafrost Melting.

6) Fluvial Processes:

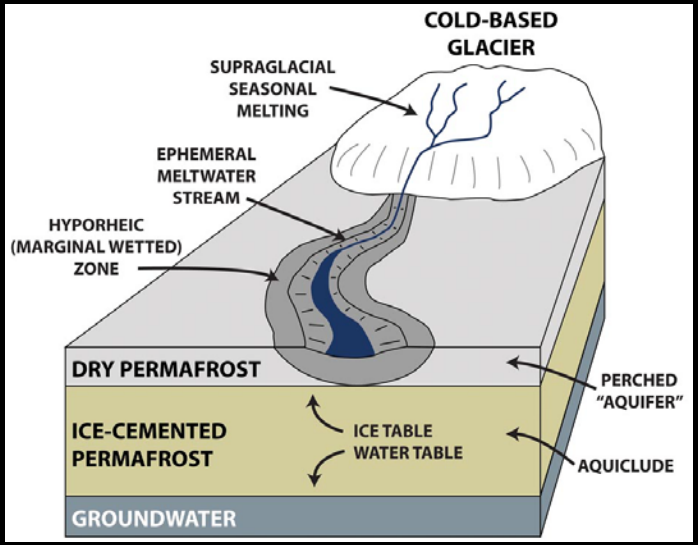
-Lack of rainfall, extremely limited nivial activity.

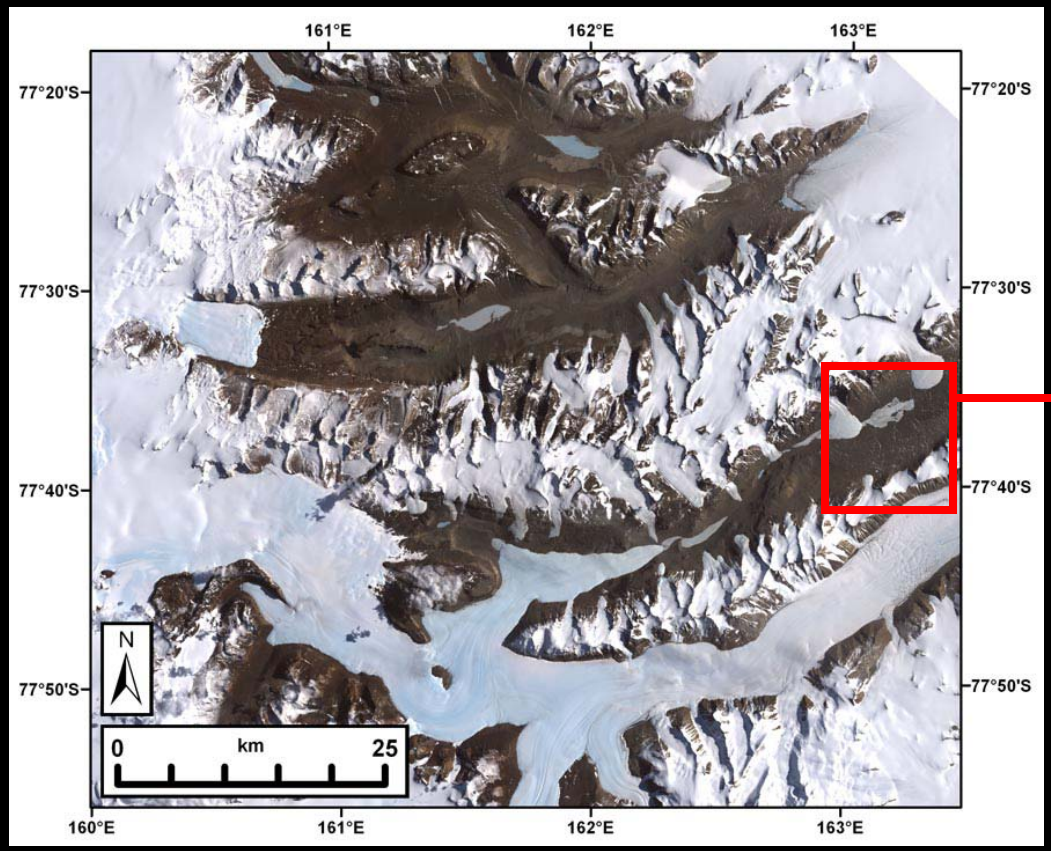
-Sublimation dominates: The short period of time during which meltwater occurs means that fluvial processes are minimal, and effects extremely localized.

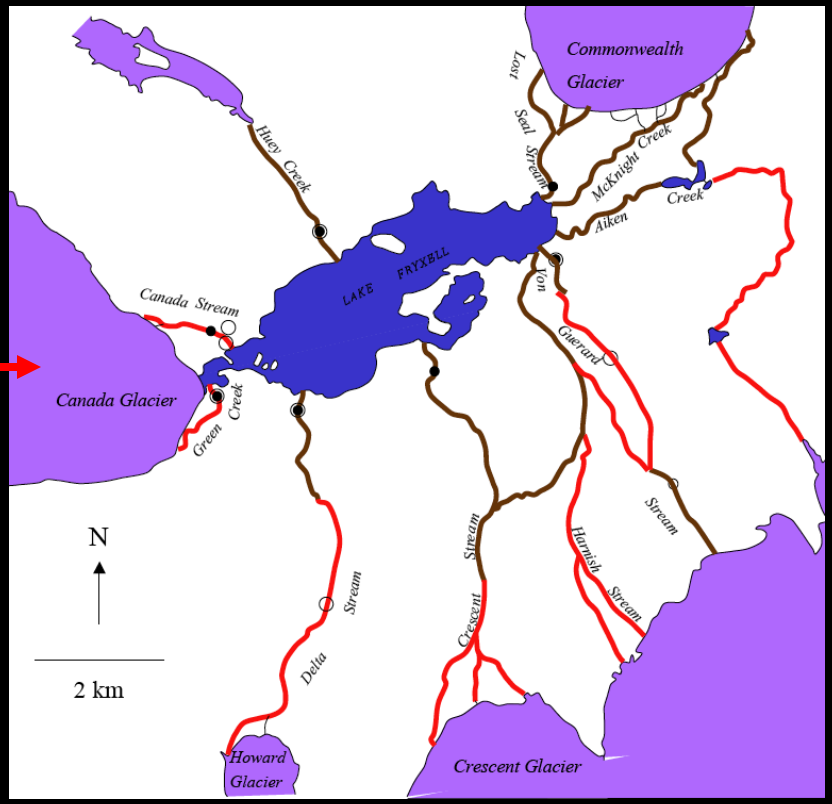
-Catchment basins are very small, streams are low order.

-Streams are influent; highly intermittent and ephemeral.

-Hyporheic zones are created in adjacent shallow perched aquifers.







6) Fluvial Processes:

-Lack of rainfall, extremely limited nivial activity.

-Dominance of sublimation, and the short period of time during which meltwater occurs means that fluvial processes are minimal and effects extremely localized.

-Catchment basins are very small, streams are low order.

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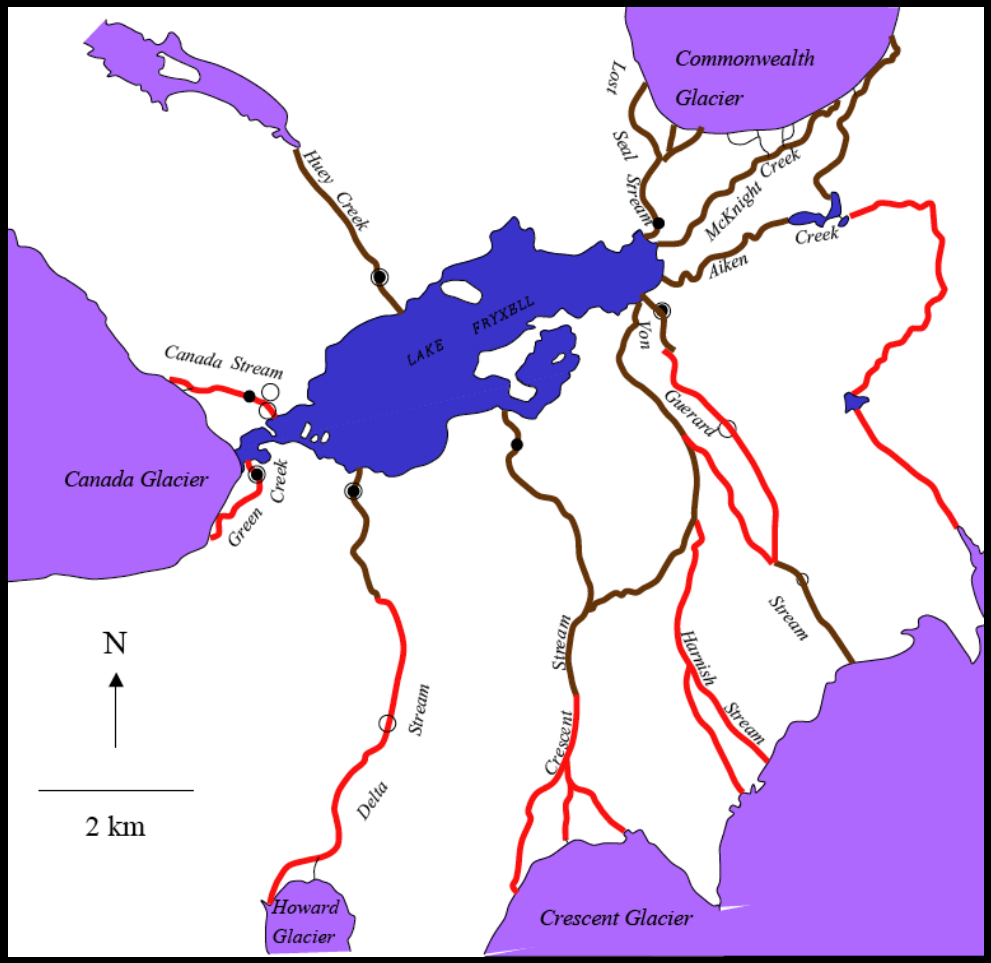
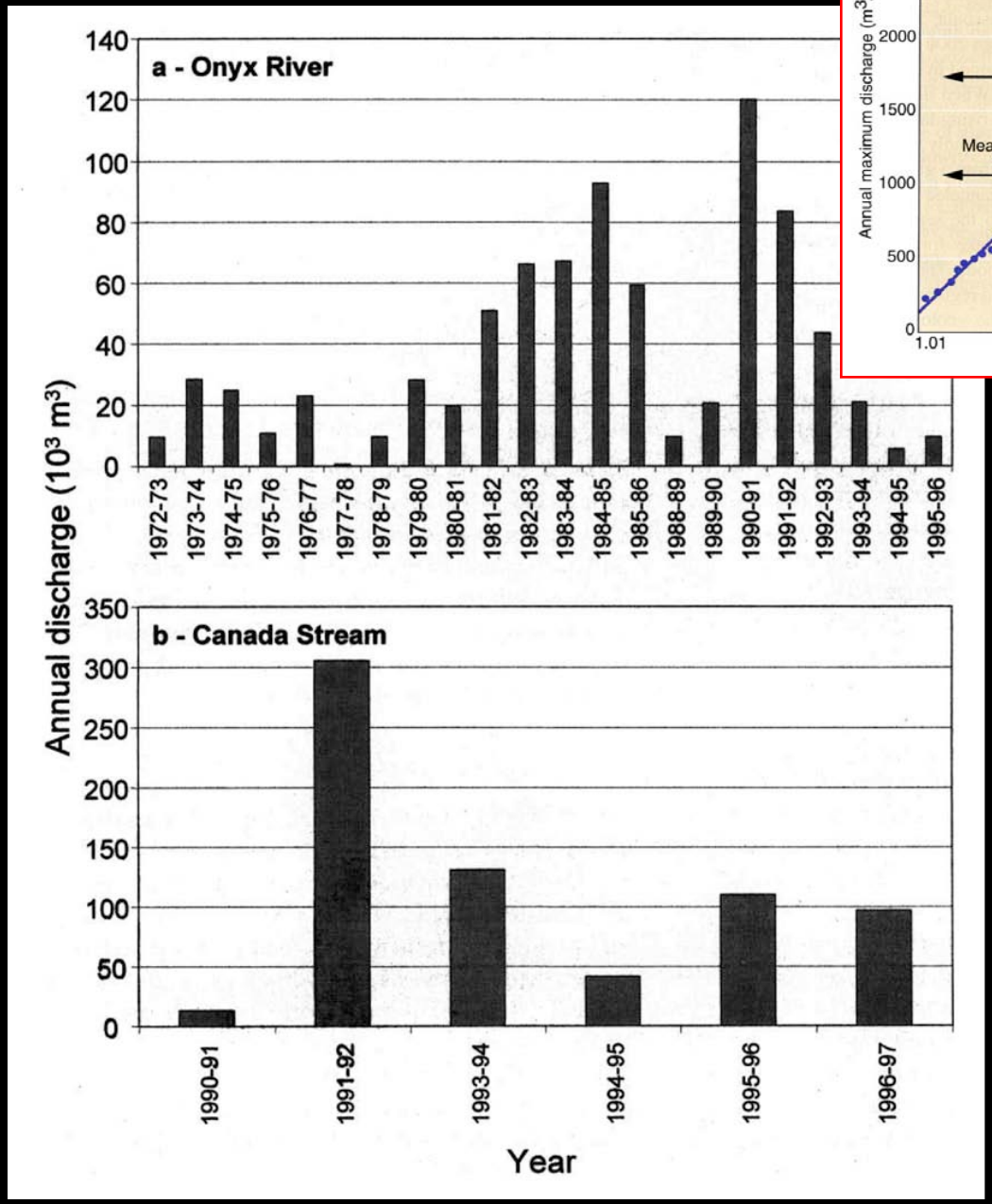
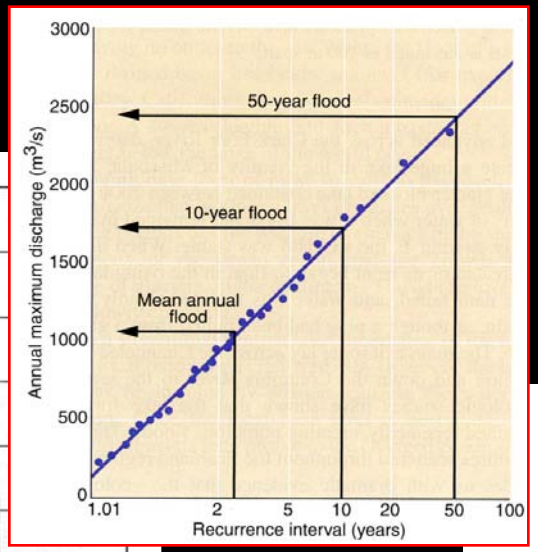


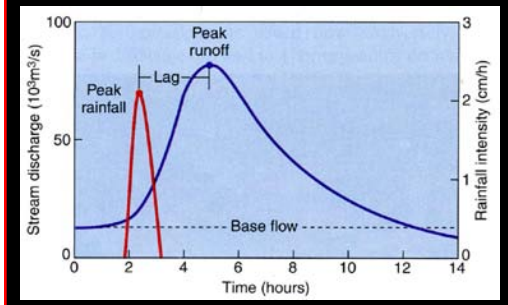
- Streams fed by melting glaciers.
- Flow for only up to 10 weeks per year.
- Vary in length from 1 km to 30 km.
- Largest is the Onyx River in Wright Valley.
- Limited interactions between streams and surrounding barren landscape.
- Despite extreme and barren conditions, microbial communities persist (McKnight et al.).

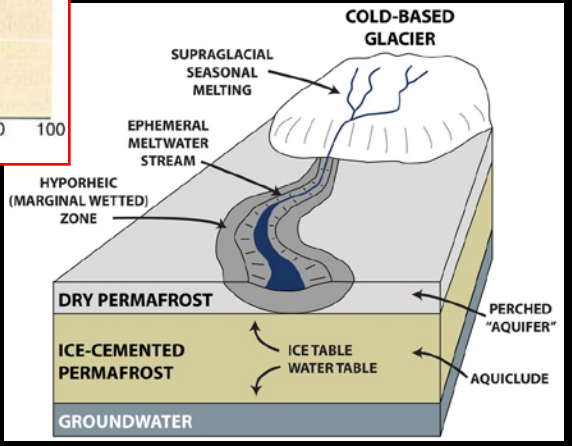
6) Fluvial Processes: Discharge





Skykomish River, WA





Ecosystem: The interaction of a biological community and its non-living environmental surroundings.

Temperate regions:

-Moderate climates with distinct seasons, abundant liquid water generally throughout ecosystem.

-Thus support some of the most abundant and diverse biological communities on Earth.

McMurdo Dry Valleys:

-In contrast are one of the coldest and driest ecosystems on Earth.

-Extremes in aridity and temperature limit the availability of liquid water and solar energy.

-This severely limits the diversity and abundance of life (Kennedy; Moorhead, Priscu, McKnight).

-No vascular plants, insects, and vertebrates in the MDV.

-The biological communities are simple and dominated by microbiota.

-The biota is dominated by prokaryotes (unicellular bacteria).

-Eukaryotes also occur and these tend to be restricted to the less environmentally stressful sites, such as rocks, some soils, streams, and glacial and lake ice meltwater pools.

-Among the higher life forms present in the MDV are bryophytes, rotifers, tardigrades and nematodes, all displaying various types of polyextremophile characteristics.

The extremely harsh environmental conditions in the MDV place unusual constraints on microenvironments favorable to organisms:

1) Enough heat is required to produce liquid water,
2) Enough solar energy is required to drive photosynthesis (PAR, photosyntheticly active radiation),
3) Frequent and/or continual desiccation due to the low humidity must be tolerated,
4) Rapid freeze-thaw cycles must be accommodated,
5) Long periods of continuous winter darkness must be sustained, and
6) Virtually continuous subzero temperatures must be tolerated.

Polyextremophile characteristics: The Tardigrades

-Polyextremophyles: Effectively respond to wide range of severe environmental changes.

-Tardigrades: A phylum of microscopic (0.1-1.5 mm) segmented animals with eight legs that inhabit a very wide range of environments (polar to equatorial, +6000 m above sea Level to -4000 m below).

-Tardigrades can reversibly suspend their metabolism and enter a state of *cryptobiosis* (metabolic processes essentially cease indefinitely in response to adverse conditions and resume when favorable conditions return).

-Polyextremophyles can survive:

1) Extreme temperatures (for short periods at 151⁻C and -200⁻C) (Kinchin, 1994).

2) Extreme pressures (vacuum to 600 MPa) (Seki and Toyoshima, 1998).

3) Solar/galactic cosmic radiation (Jonsson et al, 2008).

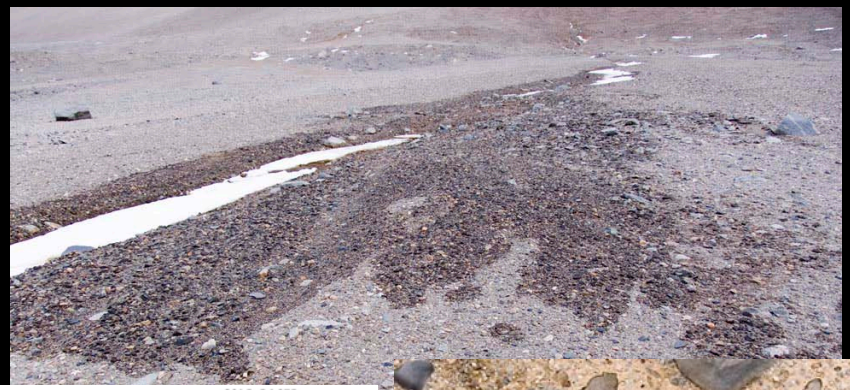
4) Dehydration (years to a decade) (Guidetti and Jonsson, 2002; Hoikawa et al., 2006).

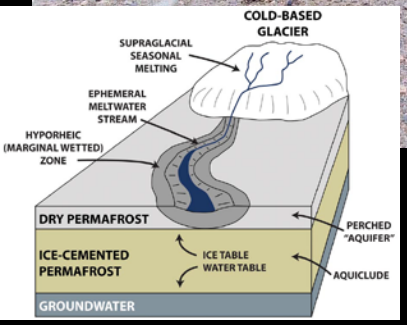
Polyextremophile Characteristics: The Tardigrades
“The Top of the Food Chain!!”

Polyextremophile Characteristics: The Tardigrades: “The Top of the Food Chain Feeding on Ecological Legacies”

6) Fluvial Processes: Biology

-Filamentous cyanobacteria dominate the algal parts of microbial mats in MDV streams and lakes.



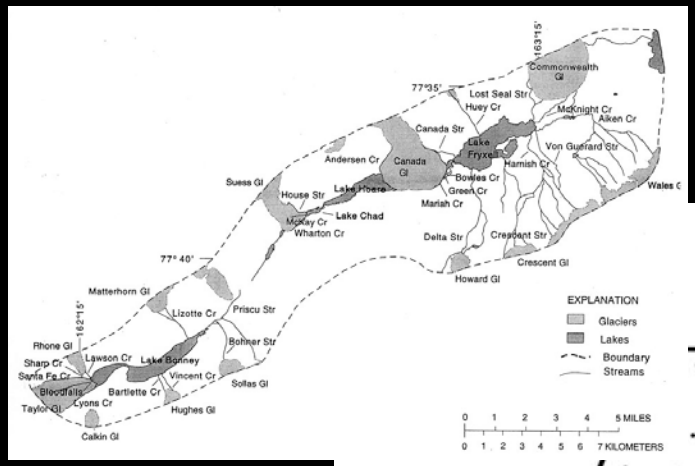


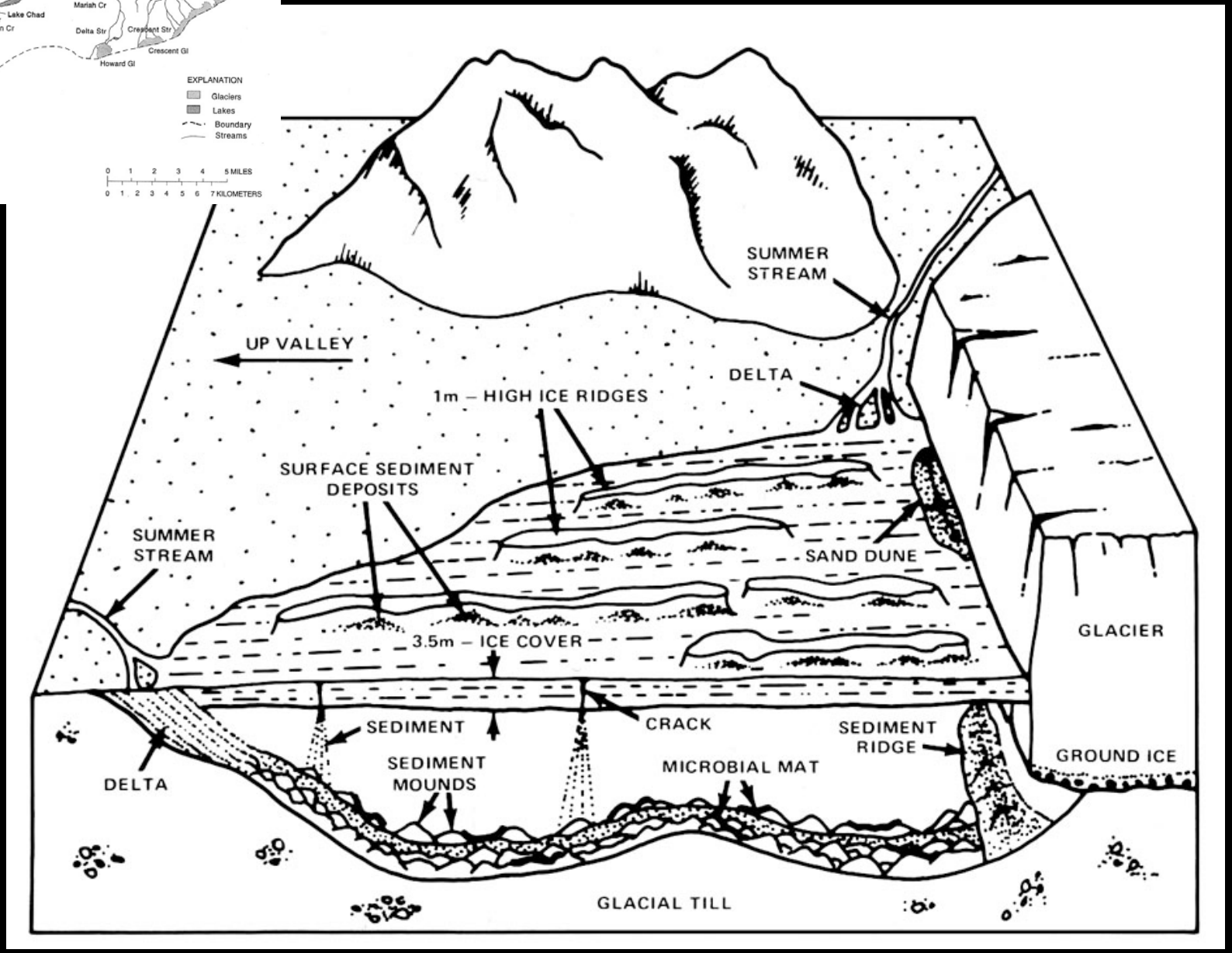
7) Lacustrine Processes:

-Ponds and lakes are small, frozen over, and often closed-basin; seasonal meltwater keeps many lakes liquid at depth.

-Lacustrine processes are currently related to a finely tuned accretion/sublimation balance of lake ice.

Applications to Europa Exploration





Climate History and The Response of MDV Lake Levels

-Climatic fluctuations within the longer-term climatic regime (10^4-10^5 years) can cause variations in amount of glacial meltwater and corresponding areal extent and depth of lakes, ranging from complete desiccation to many multiples of their current size.

Don Juan Pond

-Hypersaline pond.

-About 0.25 km^2.

-Saltiest known water body on Earth.

-40% salinity, 18 X oceans.

-Doesn't freeze in winter (-60º C).

-Calcium and Chloride are major ions.

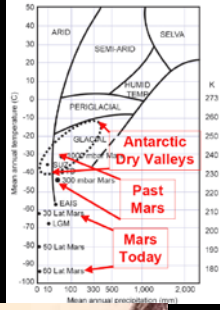
-$CaCl_2$ brine.

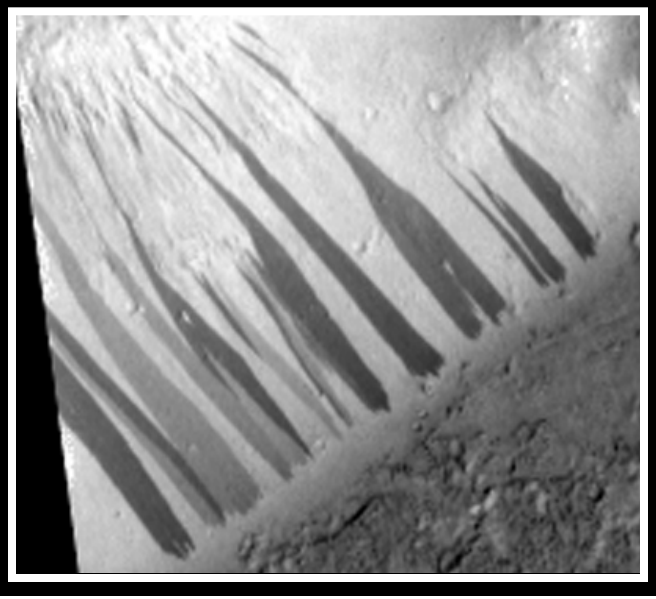
-Contains viable organisms.

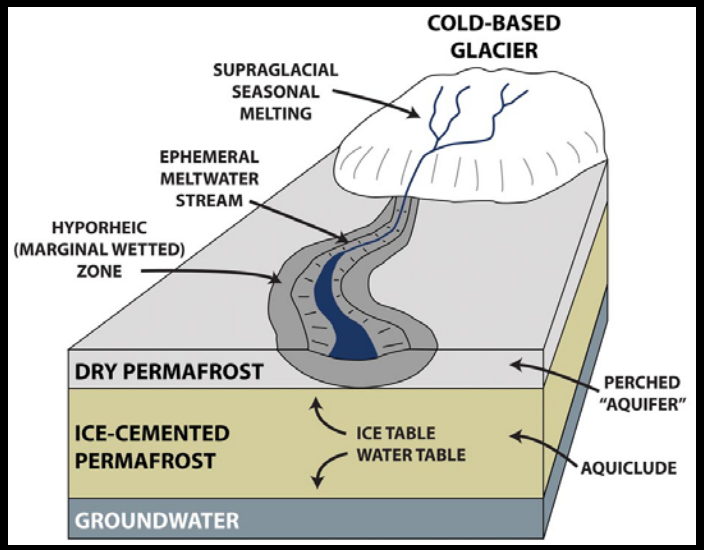
-Calculated composition for DJP water is $CaCl_2$ 3.72 mol/kg and NaCl 0.50 mol/kg, at -51.8°C (Marion, 1997)

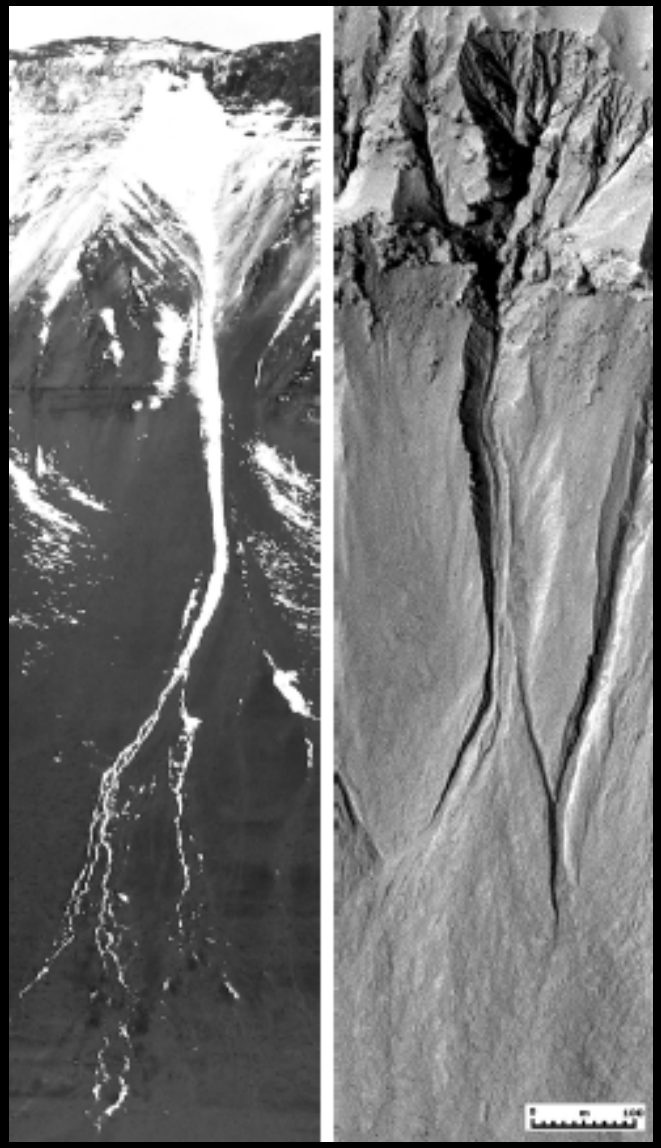
Summary of Scientific Studies and Application to Mars

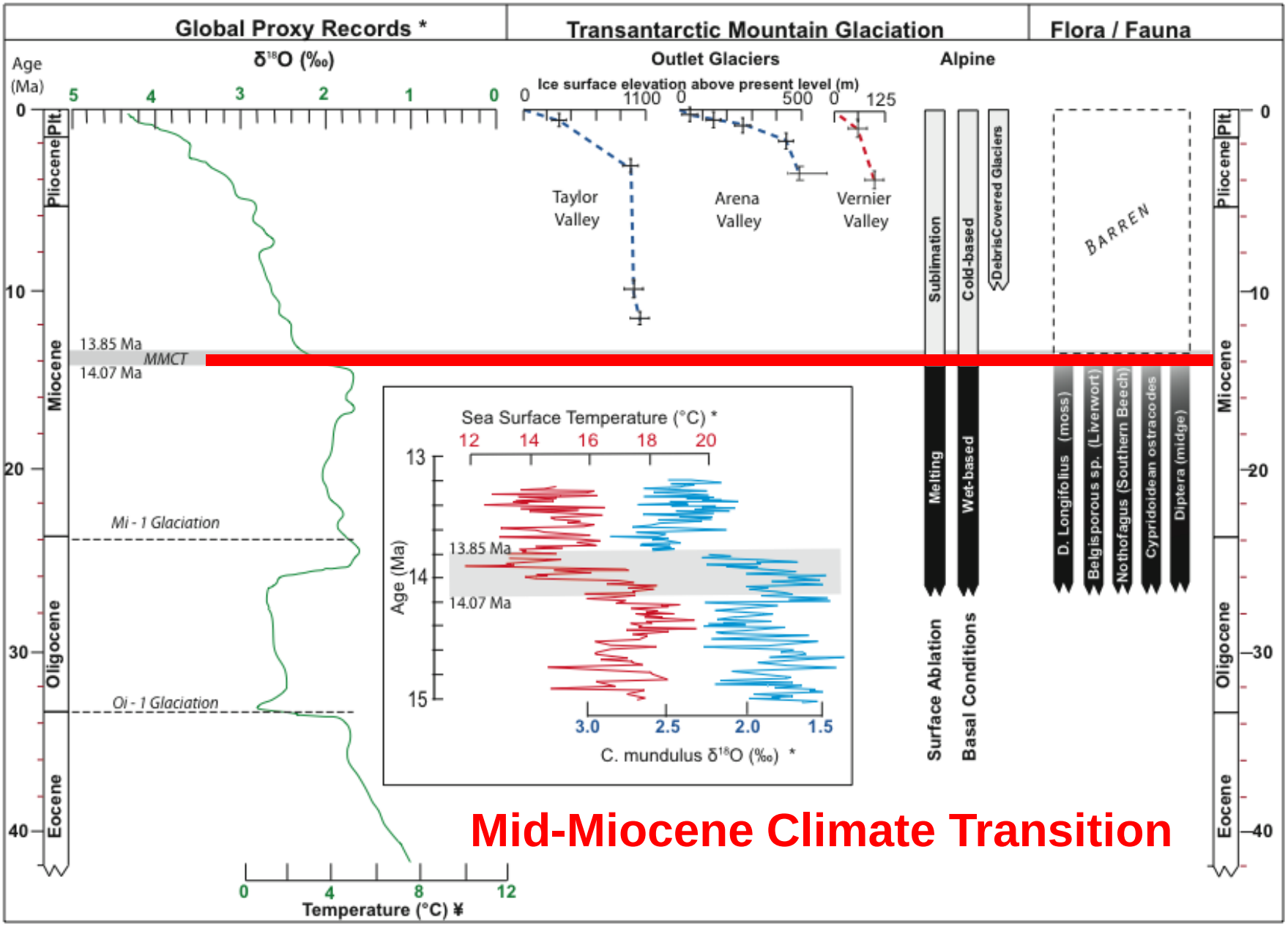
1) Recent Slope Streaks on Mars.
2) Recent Gullies on Mars.
3) Debris-Covered Glaciers: 8 million year old ice on Earth and 200 million year old ice on Mars.
4) Climatic Transitions to hyperarid-hyperthermal desert conditions: Antarctica and Mars.

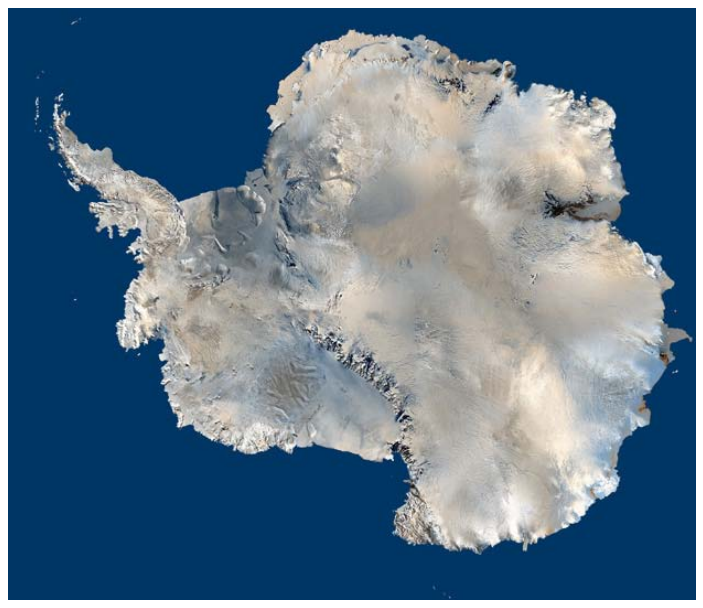


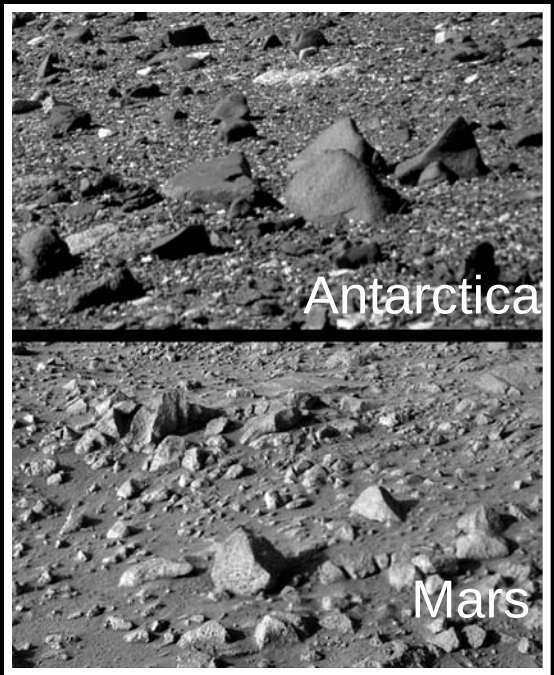


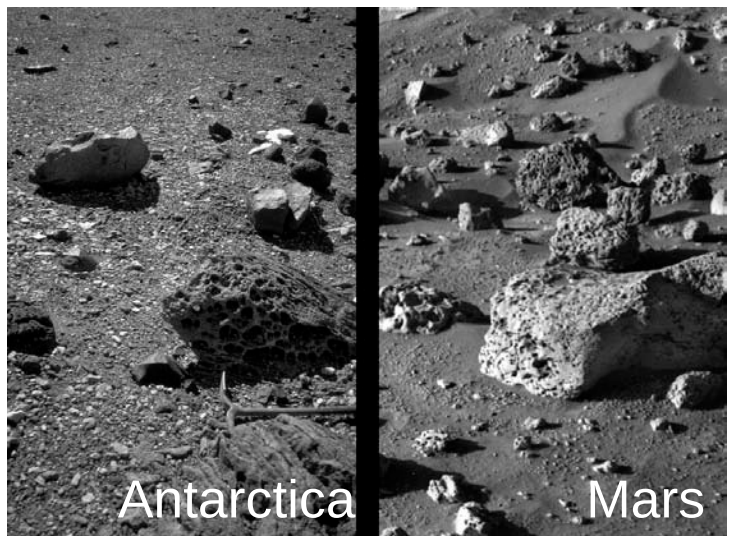





Global Proxy Records *
Transantarctic Mountain Glaciation
Flora / Fauna
Age (Ma)
δ18O (‰)
Outlet Glaciers
Alpine
Ice surface elevation above present level (m)
Taylor Valley
Arena Valley
Vernier Valley
Sublimation
Cold-based
Debris Covered Glaciers
BARREN
Pliocene
Plt.
Miocene
Oligocene
Eocene
13.85 Ma
MMCT
14.07 Ma
Mi - 1 Glaciation
Oi - 1 Glaciation
Sea Surface Temperature (°C) *
Age (Ma)
C. mundulus δ18O (‰) *
Melting
Wet-based
Surface Ablation
Basal Conditions
D. Longifolius (moss)
Belgisporous sp. (Liverwort)
Nothofagus (Southern Beech)
Cyprideidean ostracodes
Diptera (midge)
Temperature (°C) ¥
Mid-Miocene Climate Transition





Antarctic Dry Valleys

And Mars