Geomorphic Criteria for Defining Depositional Setting:

The Importance of Understanding the Age and Depositional Context of Candidate Landing Sites

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Criteria for Site Selection

- Presence of minerals suggesting water-rich environment
- Well-characterized geomorphic depositional ***context***
- Ability to characterize age and relationship to Martian geologic timescale
- ***Diversity*** of geomorphic environments
- Suitability of depositional ***habitat*** for hosting and preserving evidence of past life – lacustrine and marine environments are the most favorable
- Engineering concerns, accessibility, radiation environment (not to be discussed at this meeting)

A Wide Range of Potential Depositional Environments

- Fluvial deposition
  - Fans
  - Floodplains and channels
  - Deltas (topset)
- Standing water environments
  - Delta (foreset and bottomset)
  - Lacustrine and playa
  - Deep water (Northern ocean, Hellas, Argyre?)
  - Shoreline facies
- Aeolian dunes
- Crater ejecta
- Airfall deposition
  - Loess
  - Volcanic ash (tephra, tuff)
  - Atmospherically-deposited fines from cratering
- Mass wasting and debris flows
- Glacial and glaciofluvial
- TAKE-HOME POINTS FOR SITE SELECTION:
  - CAN WE DETERMINE WHICH ENVIRONMENTS ARE MOST LIKELY PRIOR TO LANDING?
  - WHAT IS THEIR POTENTIAL FOR HOSTING LIFE AND PRESERVING TRACES OF PAST LIFE?

Providing Geomorphic Context

- An important concept in terrestrial geomorphology and sedimentology is that of defining the ***SOURCE TO SINK*** context:
  - **PRODUCTION:** Where and how was the sediment produced by weathering or other processes and what were its mineralogical characteristics?
  - **TRANSPORT:** How was the sediment transported from its source to the depositional location and how was it altered during transport?
  - **DEPOSITION:** What processes and environments deposited the sediment? What is its mineralogy?
  - **DIAGENESIS:** What processes have affected the sediment since original deposition?
  - **EXPOSURE:** What processes have exposed deposits?
- TO THE DEGREE THAT WE CAN DEFINE THE SOURCE TO SINK CONTEXT OF A SITE THE BETTER WILL BE OUR ABILITY TO JUDGE ITS POTENTIAL FOR HABITABILITY AND PRESERVATION.
- In the following slides, a green font highlights those environments and processes most likely to have harbored life and to have preserved its traces.

PRODUCTION

What processes produced transportable debris?

- Physical weathering (reduction in grain size/strength without chemical change)
  - Freeze-thaw, salt-fretting, glacial scour
- Chemical weathering (Are observed clay minerals produced on upland slopes or during transport/deposition?). Clays produced by weathering have strong implications for paleoenvironments.
- Impact cratering
- Volcanic eruptions (ash, tuff, tephra)
- Landsliding

TRANSPORT

How was sediment brought from site of production to site of deposition?

- Fluvial transport: bedload, suspended load, dissolved load
- Aeolian transport (saltation (traction), suspension)
- Glaciers
- Landslides and debris flows
- Turbidity currents and hyperpycnal flows (deep water environments)
- Crater ejecta (ballistic emplacement, basal surges)
- Explosive volcanism
- Waves and tides (shallow water environments – reef, backbay and swamp environments)

DEPOSITION

What was the process and environment of final deposition?

- Deposition from fluid traction on bed (generally sand size and larger)
  - Streamflow
  - Aeolian
  - Waves and currents
  - Density currents
- Deposition from suspension (generally silt size and smaller)
  - Floodplains
  - Lakes and Oceans
  - Atmospheric deposition (e.g. loess, volcanic ash)
- Deposition from bulk flow (generally unsorted)
  - Landslides, avalanches (wet, dry or hot as in nuees ardentes)
  - Glaciers
  - Debris flows
- Precipitation from solution

DIAGENESIS

What processes have affected deposits since deposition?

- Weathering of subaerial exposures (soils, hardpans)
- Compaction and cementation, including soft-sediment deformation
- Recrystallization, including concretions and large crystal growth
- Oxidation and reduction
- Chemical changes due to groundwater or hydrothermal flows – But very chemistry and temperature-dependent

EXPOSURE

How have deposits become exposed in cross-section at site?

- Unmodified – exposed as deposited
- Differential aeolian erosion (generally sand size or smaller grain size, poorly cemented)
- Faulting, uplift
- Landslides
- Impact cratering (disordered exposure in ejecta, crater walls, and central peaks)
- Fluid erosion (streams, currents, waves)

Some Complications

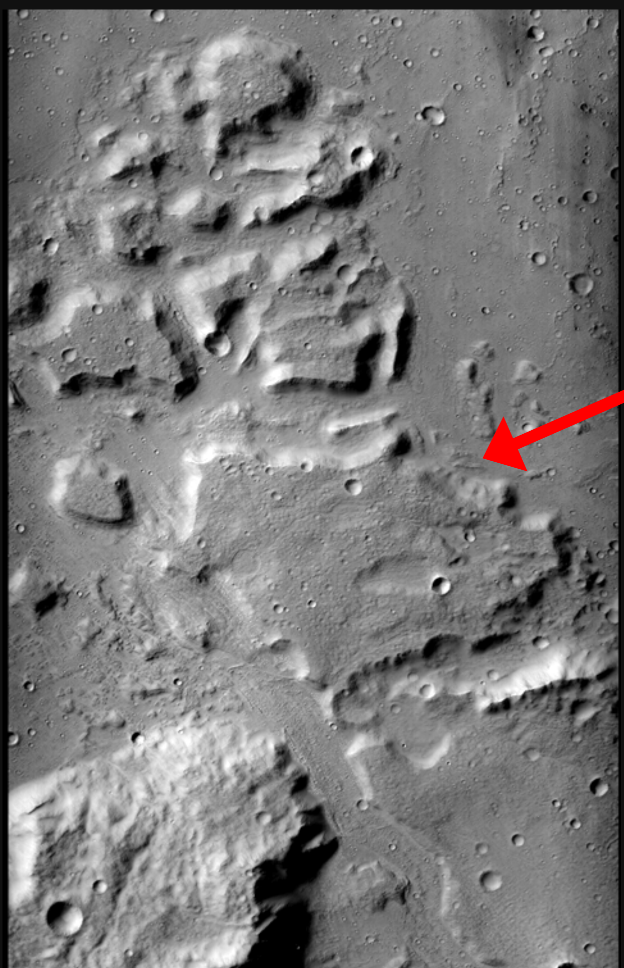
- Significant temporal intervals can occur between *source to sink* steps
- The steps are not mutually exclusive, e.g., chemical and physical weathering can occur during transport
- The same geomorphic agent can be involved in more than one step, e.g., erosion, transport, and deposition of till by glaciers
- Multiple cycles of transport and deposition can occur before the final deposition (aeolian recycling of dust and dunes)

Caveats about Site Selection

- We may be surprised by what we discover about the formative environment (the volcanic context of Gusev crater)
  - Although a volcanic involvement was one of the possibilities considered prior to landing (e.g. *Milam et al.* [2003])
- Landing at a site may not provide a larger geomorphic context or well-defined age constraints (the Meridiani site)
  - What was the upwind source of the dune deposits?
  - The age of the dune deposits may range from late Noachian to possibly Amazonian
  - What is the nature and depositional environment of the thick, sulfate-rich layers underlying the Meridiani dunes?

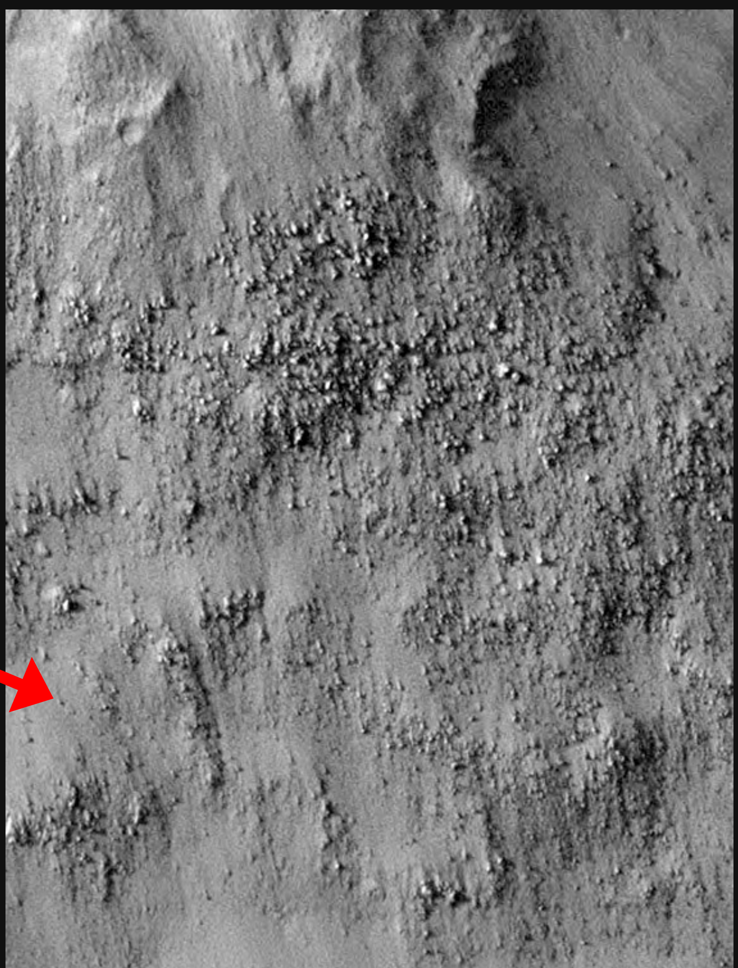
The tantalizingly out-of-reach probable flood delta of Ma’adim Valles in Gusev Crater

- The HiRISE image shows multi-meter scale boulders in flood deposit
- Boulders probably contain excellent samples of highlands materials and possible uprooted samples of fluvial, spring, or lacustrine deposits from Ma’adim Valles
- But Gusev does not contain well exposed, layered, probable lacustrine deposits with phyllosilicates as do the candidate basin sites for MSL



CTX image of Ma’adim Valles flood delta in Gusev crater

HiRISE image of Delta Deposits



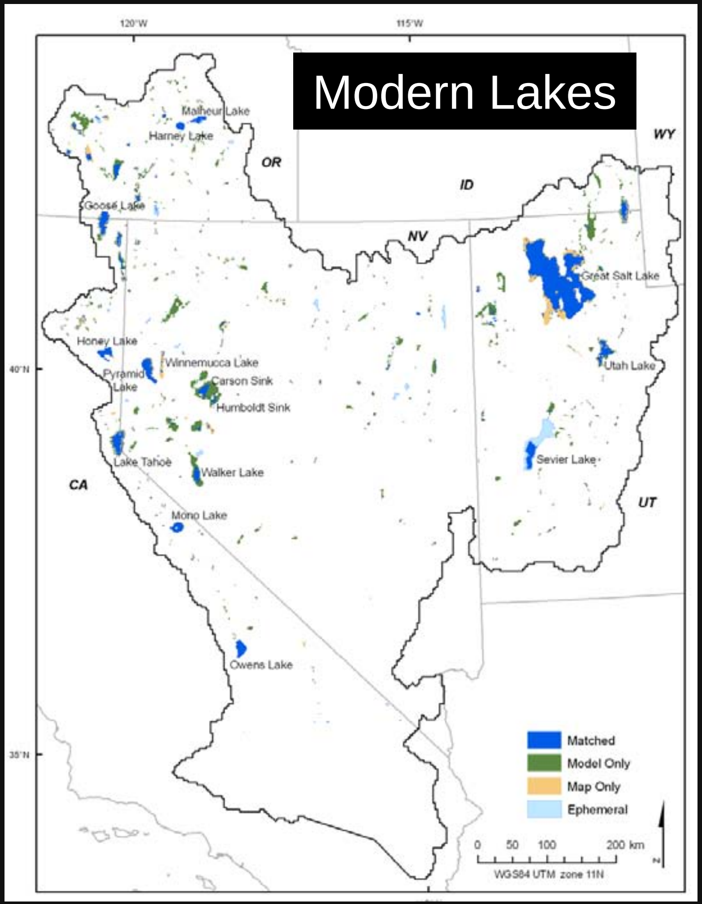
Geomorphic Context of Proposed Landing Sites

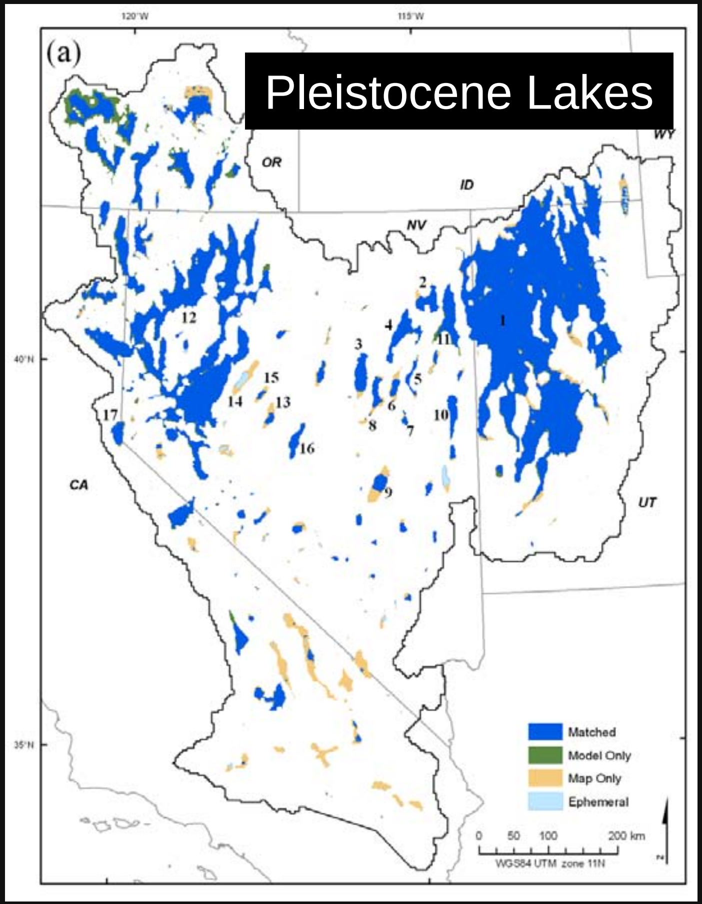
- The proposed landing sites have differing degrees of interpretability of the *source to sink* context and the associated geologic history
- The sites with the best constraints are those in relatively closed (basin) depositional environments (Holden, Gale, Eberswalde, and to a lesser degree, Miyamoto)
- These sites also have the greatest diversity of geomorphic environments, probable rock types, and associated ages.
- For these types of sites we are best able to define probable depositional environments from orbit as well as from terrestrial analogs
- Lakes and their associated fluvial systems one of the best environments for preserving biosignatures on Earth
- These basin sites have informative partial analogs in the terrestrial Great Basin region

Great Basin Analogs

- The Great Basin shares several characteristics of the proposed enclosed-basin MSL landing sites
  - Enclosed basins
  - Fine-grained lake and playa sediments, including evaporites
  - A strong climate signature in basin-center deposits
  - Alluvial fans
  - Possible analogs in dunes, air-fall tephra deposits, shoreline facies, and aeolian erosion

Enclosed Lakes and Playas

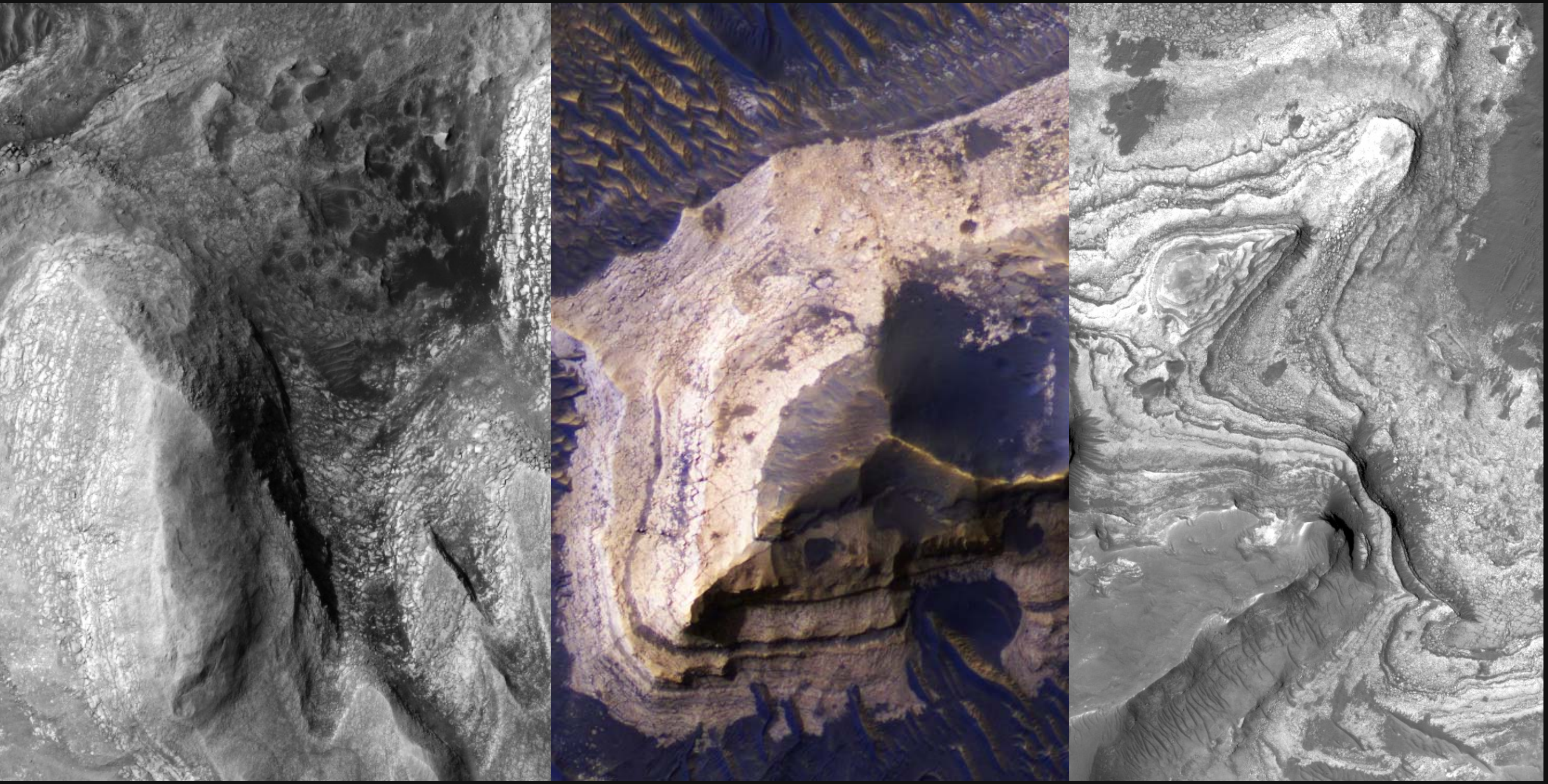




The enclosed basins on Mars presumably underwent similar variations in the balance of precipitation and evaporation due to orbitally-driven quasi-periodic climate changes or other causes. Many Martian crater basins episodically overflowed [*Fassett et al., in press*]

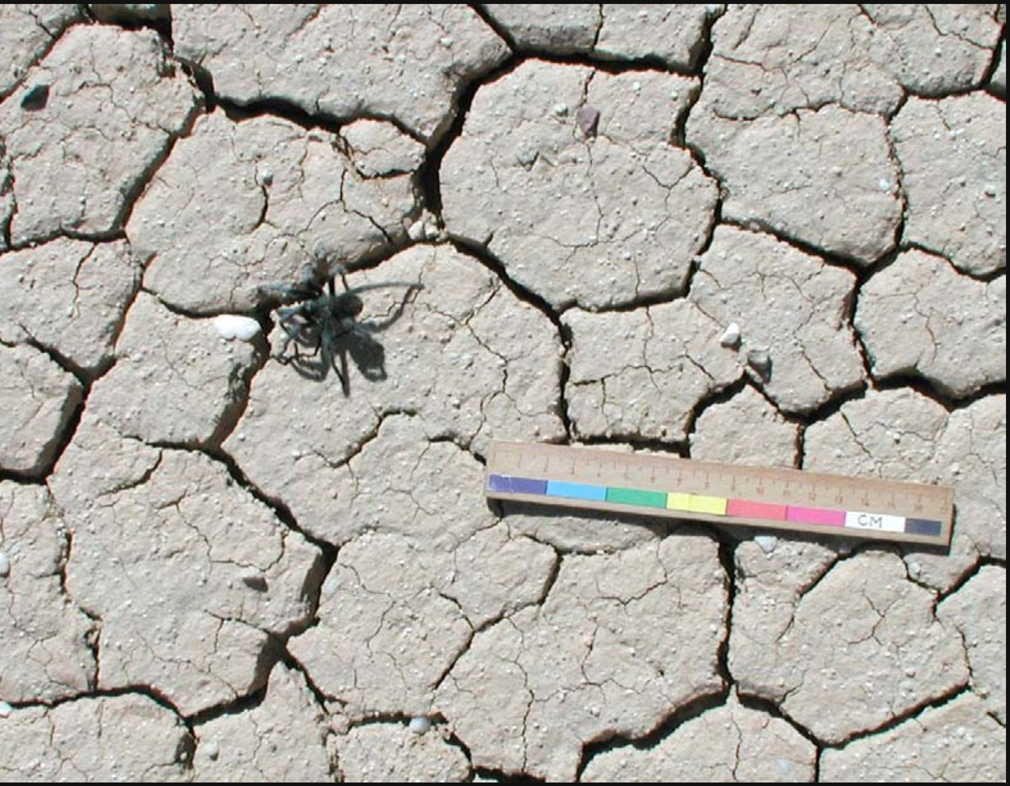
Fine-grained Lake and Playa Deposits

The fine-grained, layered sediments in Holden, Eberswalde, and Gale have probable analogs in playa and lake deposits in the Great Basin



GALE HOLDEN EBERSWALDE

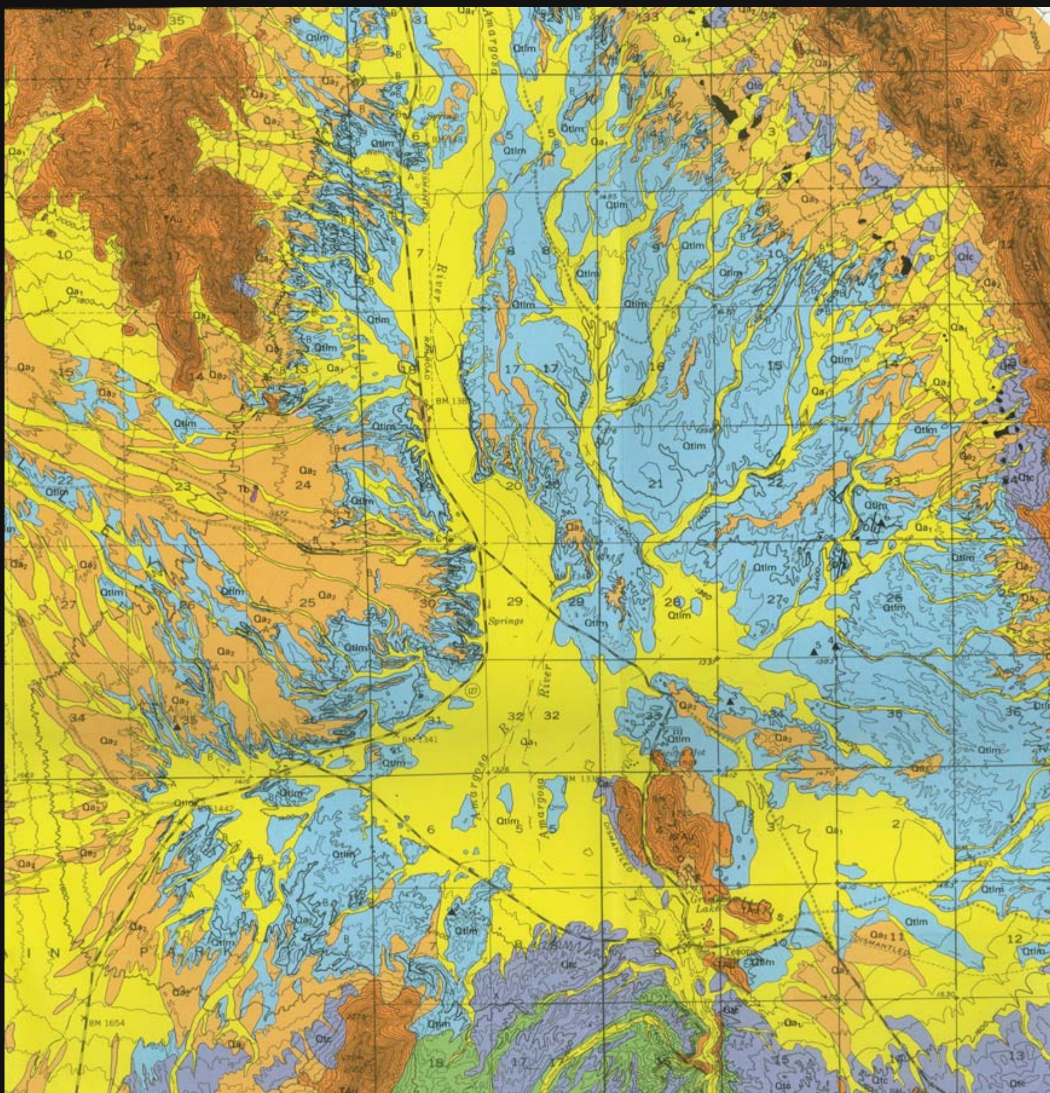
- During dry times, like the present, playas may be episodically flooded with up to a few meters of water.
- During wet times they may host lakes up to hundreds of meters deep.
- They are the repositories for fine grained sediment eroded from the basin as well as evaporite minerals, sometimes fed by groundwater.
- Sediment can also be delivered as aeolian silts and volcanic tephra

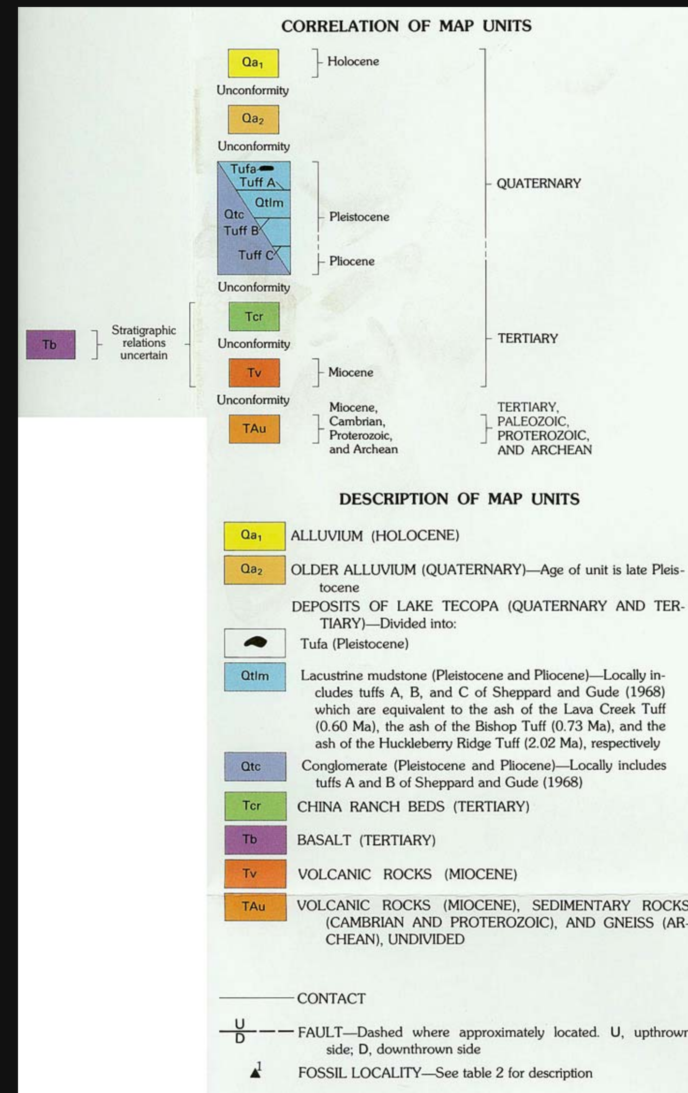


Playa deposits may primarily consist of silts and clays, such as these, or…

They may also include appreciable evaporites of a wide range of mineralogy, often not found in other environments (e.g., Borax) and mixed with clays

The physiographic, sedimentologic, and historic context of these environments are well characterized





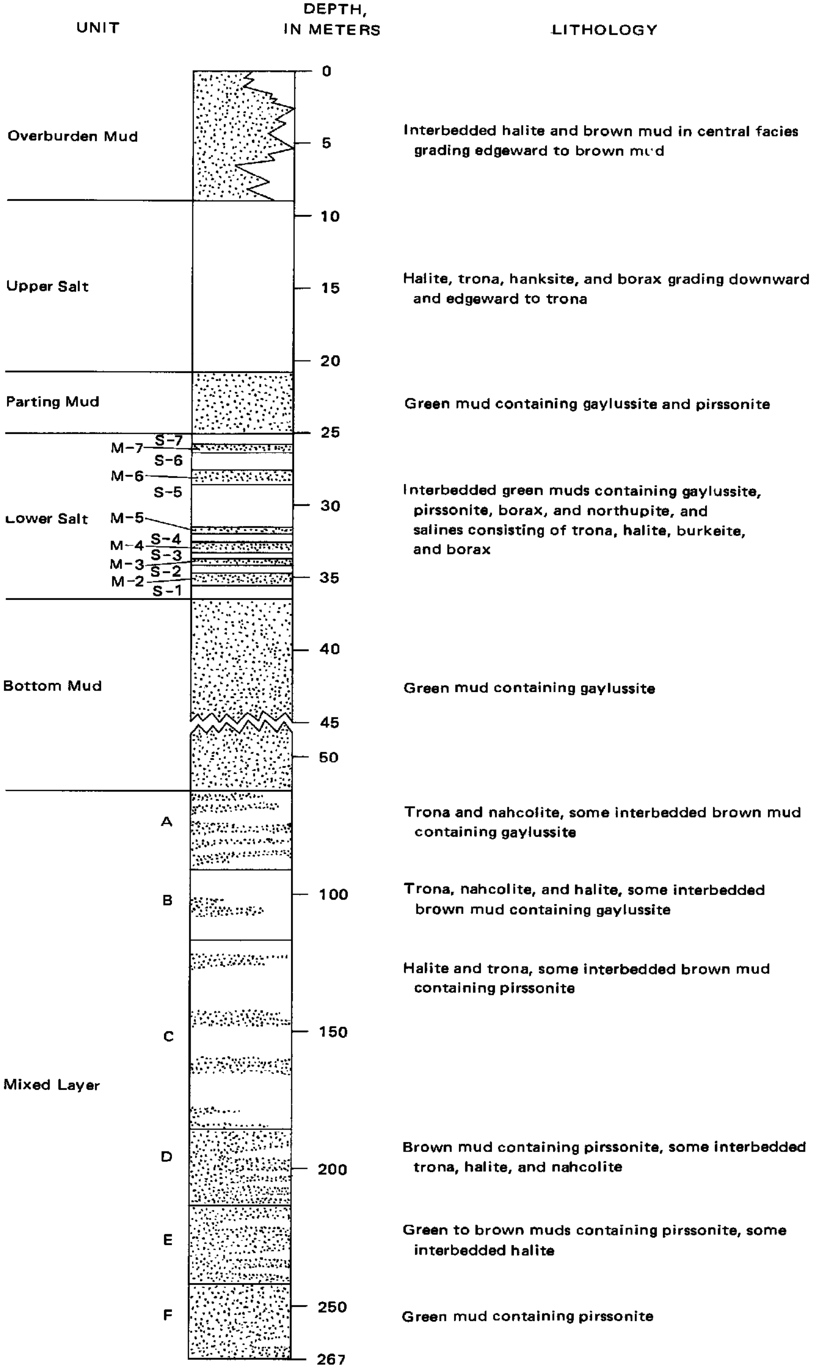
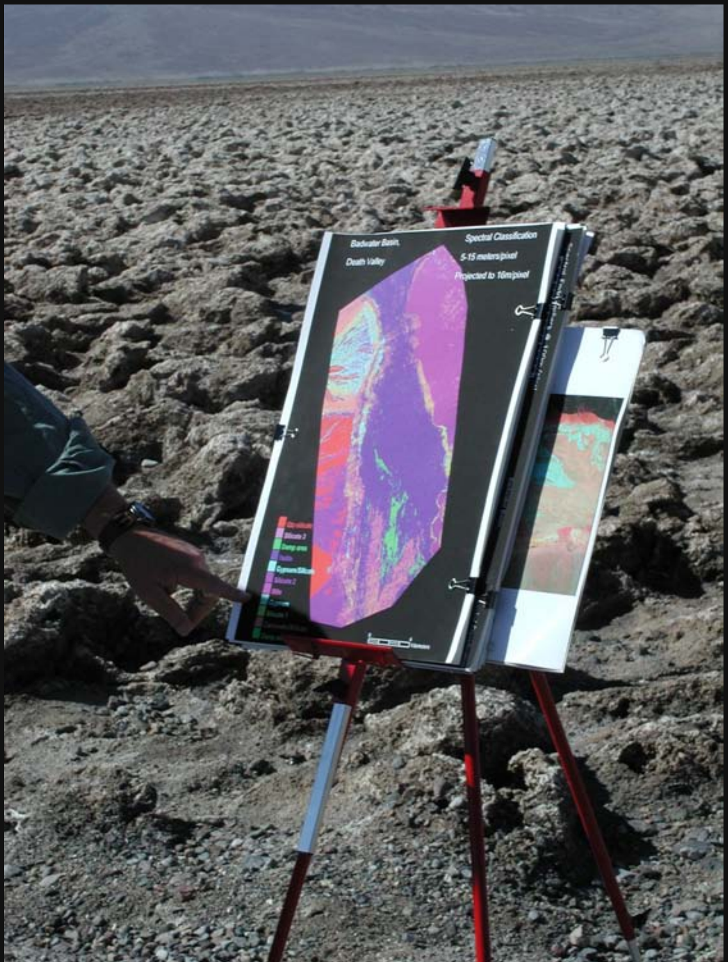


FIGURE 4.—Summary of stratigraphic units in Searles Lake evaporite sequence.

- In many cases we have good subsurface records of the facies and age of playa and lake deposits, such as this ~40,000 year sequence at Searles Lake
- Note the large inventory of evaporite minerals (formed during more arid times when the lake was closed) and fresh-water muddy facies when the lake overflowed during pluvials and hosted fresh water.
- On Mars similar sequences from climate changes could record 10’s to 100’s of millions of years of the Martian environment.

We also have extensive experience correlating spectral signatures with surface materials in the Great Basin, including playas and alluvial fans

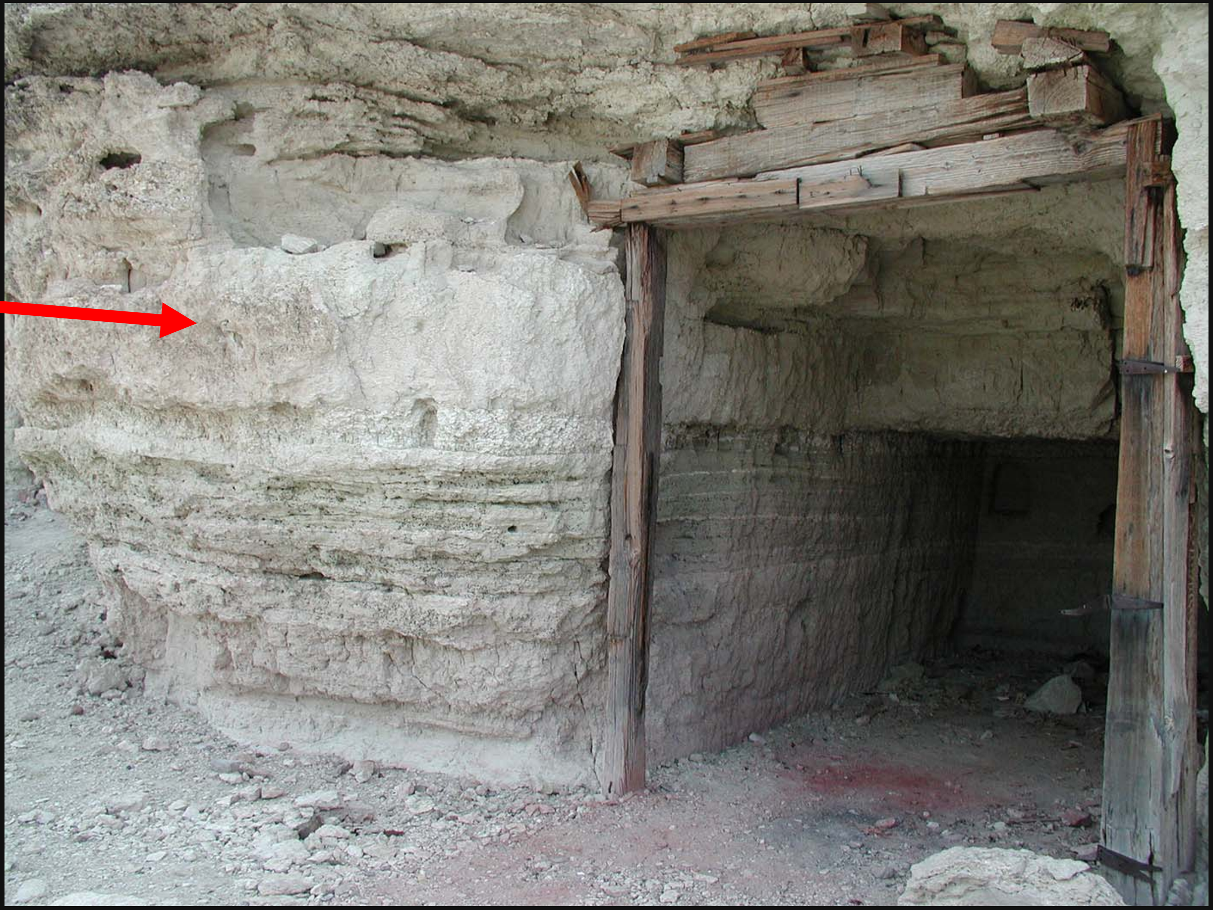


• There are excellent exposures of lake and playa deposits due to drops in lake level or subsequent fluvial dissection

• The bottom picture (from Searles Lake) shows fine bed layering in a near-shore sequence, together with coarse interbeds of tufa shed from superjacent slopes and wave-disrupted bedding.

Tectonically uplifted and tilted basin deposits at Zabriskie Point, Death Valley, including relatively finely-layered beds (left) and massive bedding (right)

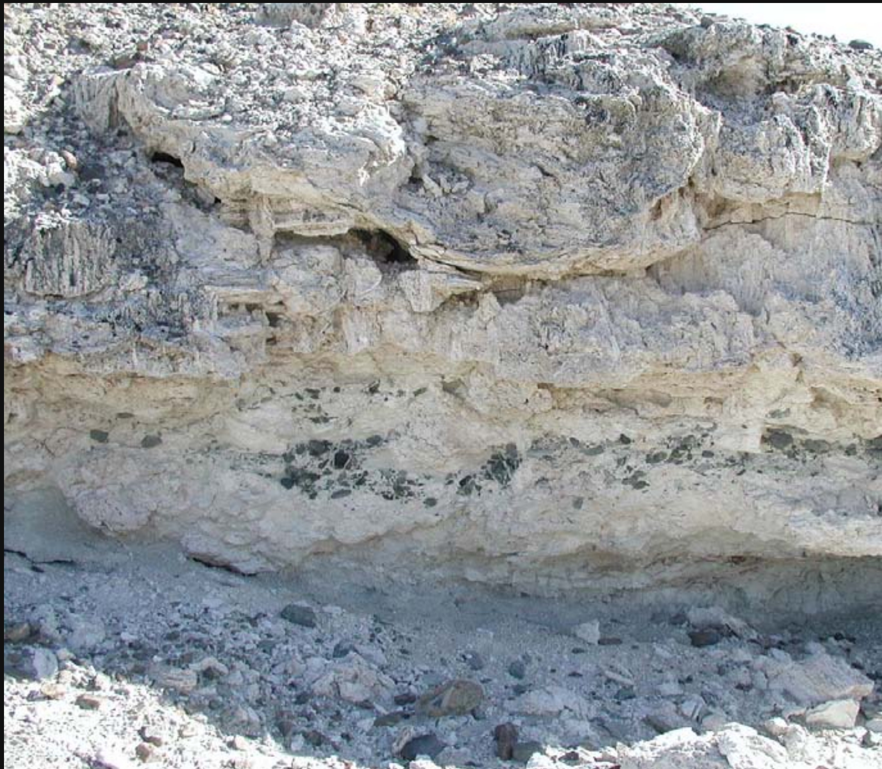
Lake deposits may include ash or tuff from explosive volcanism, often reworked by fluvial or lacustrine processes



Lacustrine deposits can also include tufa either from springs or as shoreline deposits.

These spring deposits are at Mono Lake (left) and Searles Lake (bottom)

The tufa deposits have distinctive bedding

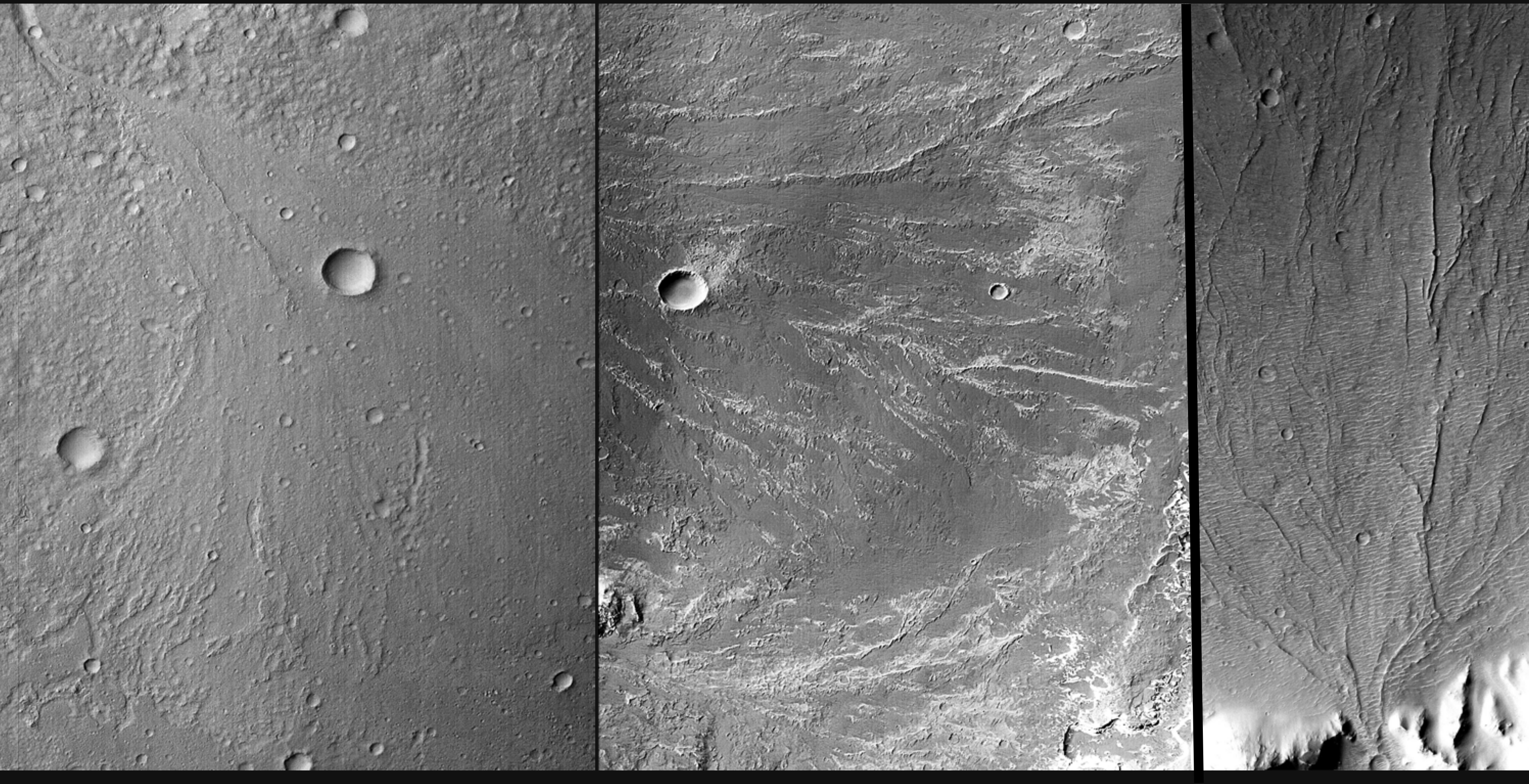


Other potential facies include beach deposits, such as these from the Pleistocene Lake Manly in Death Valley

Alluvial Fans

- A bonus feature of the enclosed basin sites are fringing alluvial fans
- These would include samples of ancient highlands crust
- They are informative about hydrologic conditions prevailing during fan deposition and presumably contemporaneous basin interior layered deposits
- Finer overbank sediments might have hosted or preserved biosignatures. Fluvial gravels may contain reworked spring or lacustrine sediments.

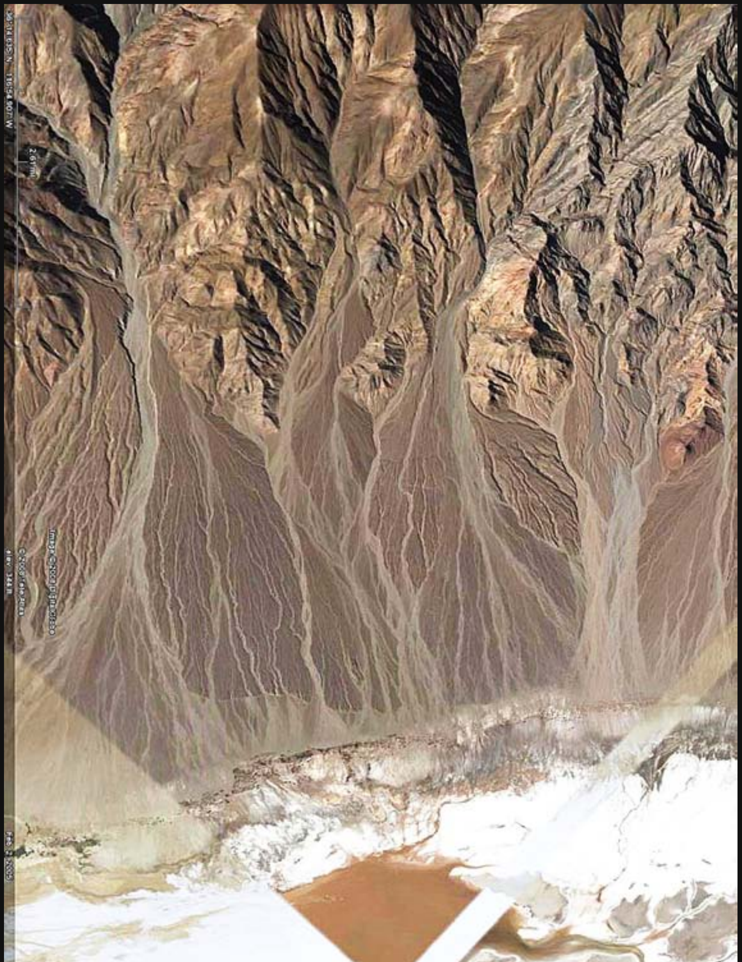
Alluvial fans of sediment deposited from erosion of crater walls are prominent features in the Gale and Holden crater proposed sites. Images show distributaries radiating from fan apices. Wind erosion has eroded presumed fine-grained overbank deposits and raised channel fills in Holden Crater into inverted relief, as is also the case in Crater “L” studied by Moore & Howard [2005]

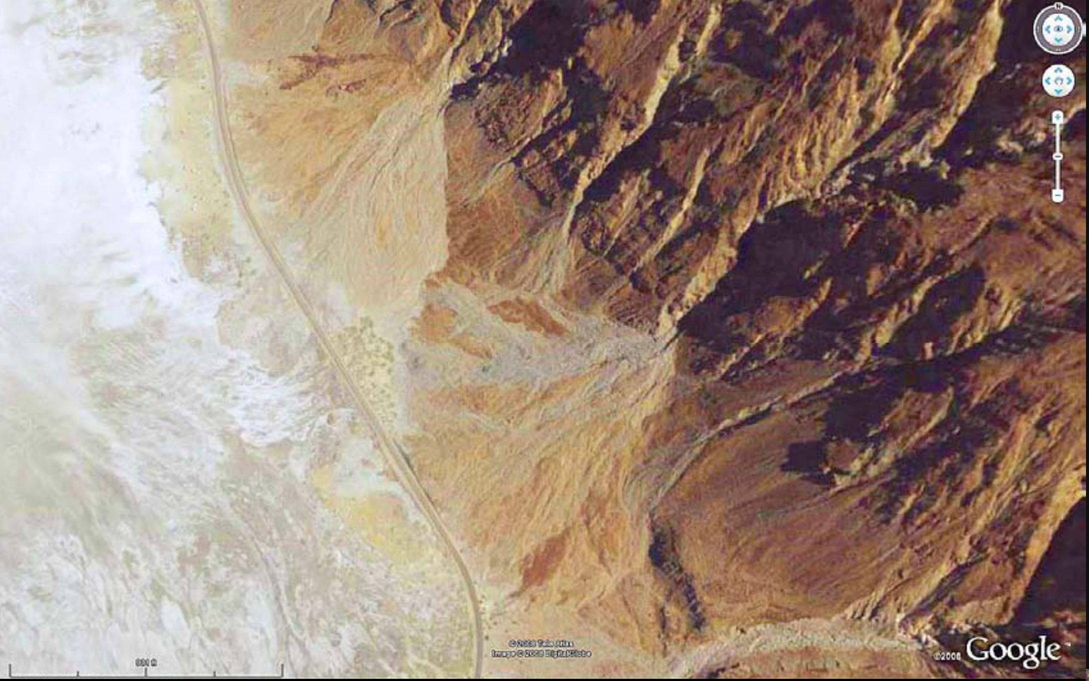


GALE CRATER HOLDEN CRATER CRATER “L”

Alluvial Fans in the Great Basin

These are examples of ***fluvially-dominated*** fans in Death Valley in which most sediment is deposited by dilute streamflow in distinct channels.





These are examples of ***debris-flow*** dominated fans on which thick sediment-laden flows occur.

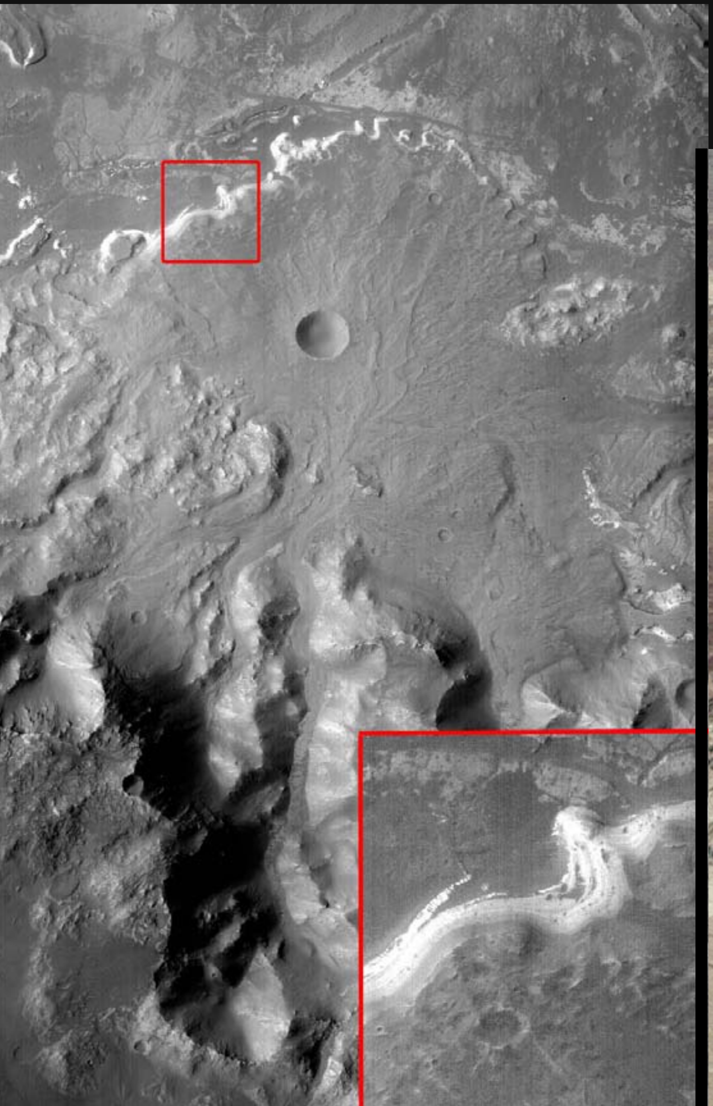
Because of the well-defined channels on the Martian fans, they are probably fluvially-dominated.

- On fluvially-dominated fans, bedding is distinct and deposits are generally well sorted
- Sediment grain size, when combined with estimates of channel dimensions and gradient, can be used to estimate flow magnitudes across the fan surface

- On debris-flow dominated fans, bedding is less distinct and the deposit is poorly sorted, often with significant quantities of admixed silts and clays

- Such deposits generally result from steep headwater sources, short but intense precipitation, or large quantities of fine sediment in the source area.

- The left image shows a CTX view of the south fan in Holden crater that prograded across earlier-deposited light-toned layers which were then exposed by toe-trimming by the breach flood
- The right image shows a fan deposited on terrestrial lake deposits exposed by subsequent fluvial erosion



Limitations of the Great Basin Analog

- Like all terrestrial analogs, the different atmospheric chemistry from Mars implies differences in mineral stability and weathering potential
- The Great Basin at present is probably warmer than early Mars, but the glacial-epoch climates may have been similar
- Basins on Mars are largely created by instantaneous impacts, whereas tectonic faulting and folding dominates in the Great Basin

Geologic Age of Landing Sites

- From the relative freshness of Holden crater and from superposition relationships, the crater can be dated to late Noachian and significant deposition and modification of the deposits ceased near the Noachian-Hesperian boundary.
- Eberswalde was veneered by Holden crater ejecta and shares a similar age.
- The lack of extensive degradation of Gale crater also suggests a late Noachian age, although it may have been mantled for some time by fine sediment (similar to that at the top of the sedimentary mound in the basin center).
- Miyamoto is a more degraded crater and the age context of the fluvial and probable lacustrine deposits is less certain.
- The phyllosilicates in the southern Meridiani site are in fluvially-eroded bedrock and are thus of uncertain, but probably early- to mid-Noachian age
- The age of the Mawrth Valles phyllosilicates is uncertain and may range from early Noachian if the deposits are part of the bedrock sequence to late Noachian if they are a drape deposit.
- Phyllosilicates at the Nili Fossae site are of uncertain Noachian age and may have formed both by deposition and hydrothermal alteration.

Implications of Age for Site Selection

- The basin sites contain phyllosilicates that are probably of depositional origin and are of late Noachian age
- The remainder of the sites are of less certain age, but probably partially pre-date the basin site deposits

Concluding Thoughts

- The basin sites (Holden, Gale, and Eberswalde) share the following characteristics:
  - A well-understood depositional context involving fluvial and lacustrine processes
  - Phyllosilicates that probably formed through chemical weathering processes within the basin
  - An excellent potential for past habitability and organic preservation
  - A relatively well-constrained age during the wet Late Noachian
  - A diversity of geomorphologic and sedimentary environments
- The geomorphological and depositional context of the remaining sites is, at present, not as well constrained