Mars Exploration Program Analysis Group (MEPAG)

chartered by NASA HQ to assist in planning the scientific exploration of Mars

Mars: Current State of Knowledge and Future Plans and Strategies

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July 30, 2009

Note: This document is a draft that is being made available for comment by the Mars exploration community. Comments should be sent by Aug. 7, 2009 by e-mail to Jack Mustard, Dave Beaty, or Rich Zurek (John_Mustard@brown.edu, dwbeaty@jpl.nasa.gov , rzurek@jpl.nasa.gov).

What Were Our Goals for the Past Decade?

MEPAG's Goals and Strategies, 2001-2011

I. Determine if life ever arose on Mars
II. Understand the processes and history of climate on Mars
III. Determine the evolution of the surface and interior of Mars
IV. Prepare for eventual human exploration

2001 Strategy

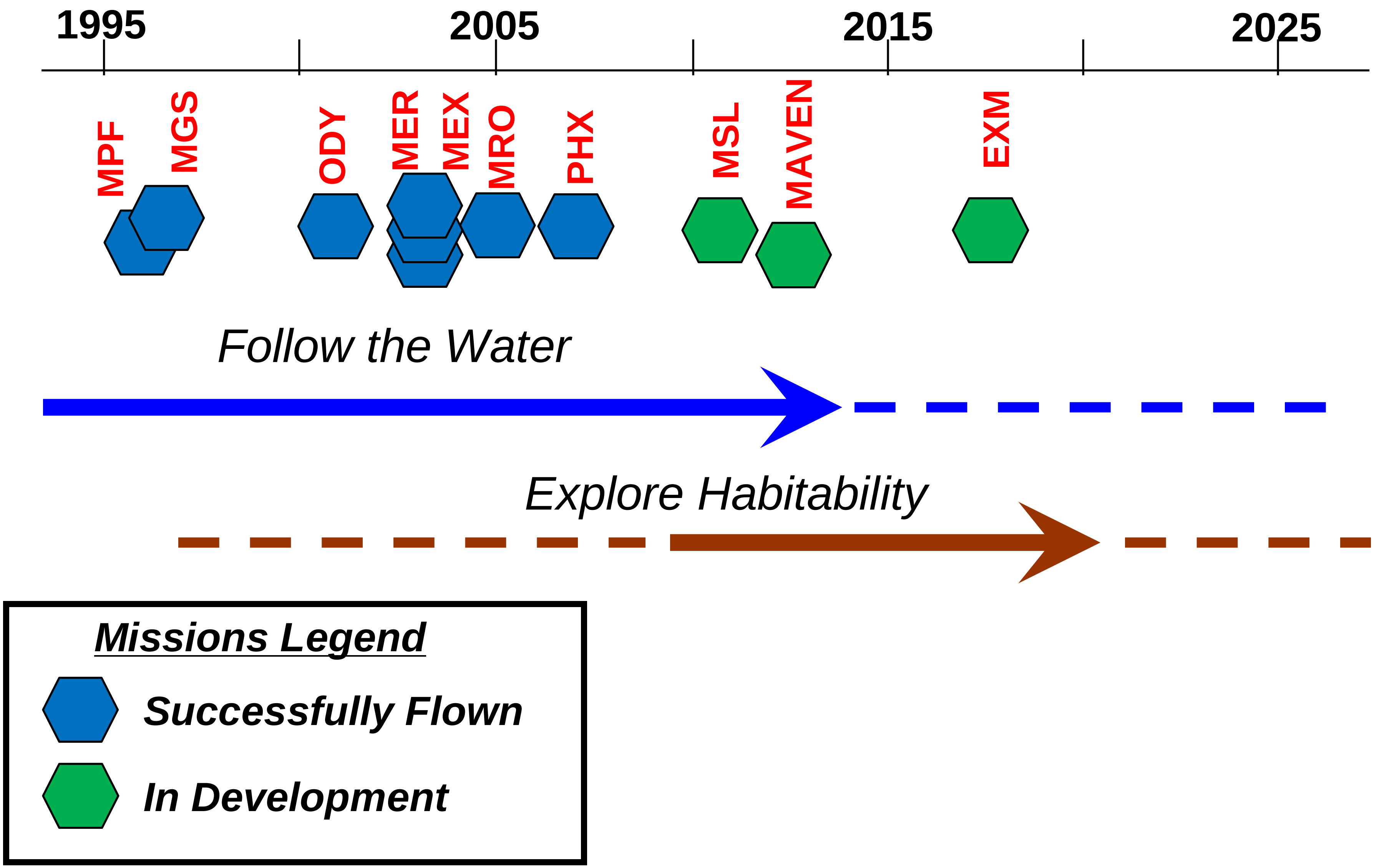
Follow the Water

→

2005 Strategy

Explore Habitability

Missions In Progress to Address Goals



What Did We Learn?

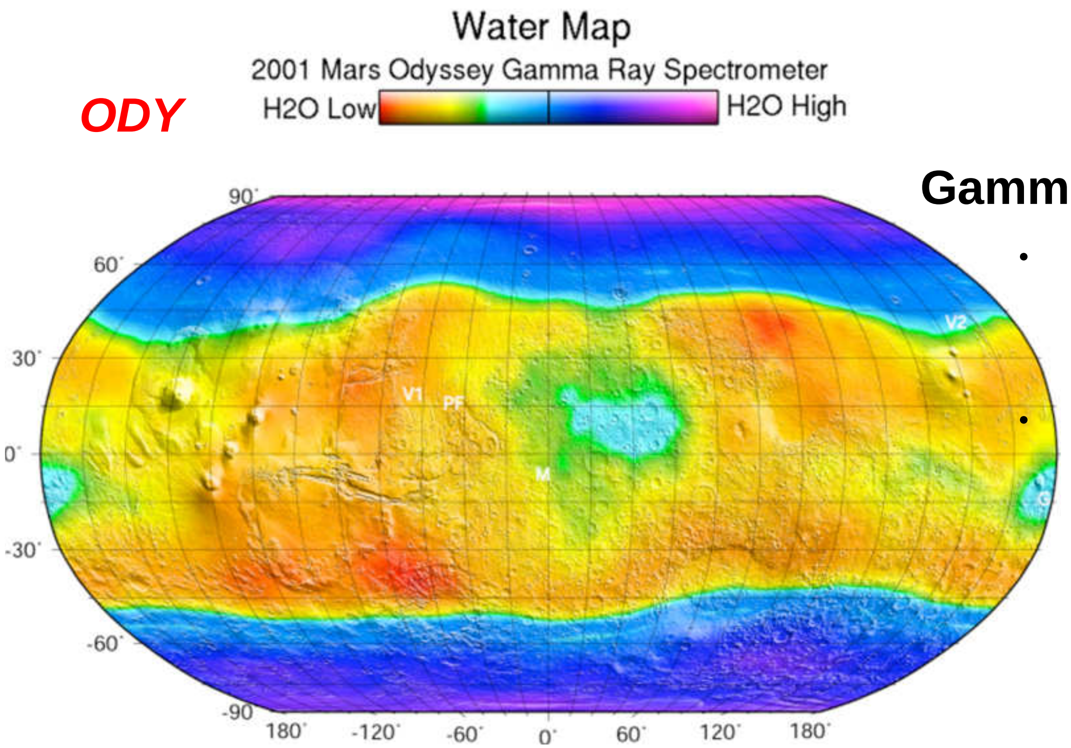
Last Decade Discoveries: Introduction

- **These discoveries have revealed a diverse planet with a complex history. Here are a few highlights:**
  - **Areas with diverse mineralogy, including alteration by water, with a change in mineralogy over time [MGS, ODY, MER, MEX, MRO]**
  - **In situ confirmation of Wet (Warm?) Climate in the past [MER]**
  - **Pervasive water ice in globally distributed, near-surface reservoirs [ODY, MRO, MEX, PHX]**
  - **Increasing evidence for geologically recent climate change: stratified layers in ice and in rock [MGS, ODY, MEX, MRO]**
  - **Sources, phase changes, and transport of volatiles (H_2O, CO_2) are known & some are quantified [MGS, MEX, MRO, PHX]**
  - **Dynamic change occurring even today: landslides, new gullies, new impact craters, changing CO_2 ice cover [MGS, ODY, MEX, MRO]**
  - **Presence of methane indicative of active chemical processes either biogenic or abiotic [MEX and ground-based]**
- **In general, the *Potential for past Life* has increased, and *Modern Life* may still be possible.**

Past Decadal Results:

Distribution of Modern Water

ODY



Global Near-Surface Reservoirs of Water

Gamma Ray Spectrometer

- Global hydrogen abundance and equivalent H_2O
- Ground ice to +/-60° in high abundance

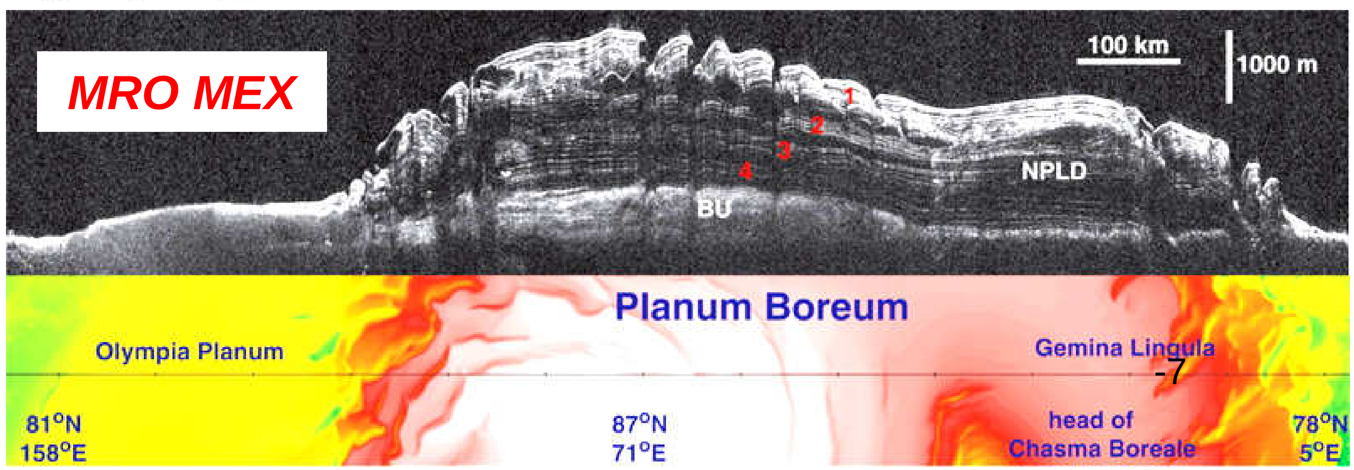
Phoenix results

PHX

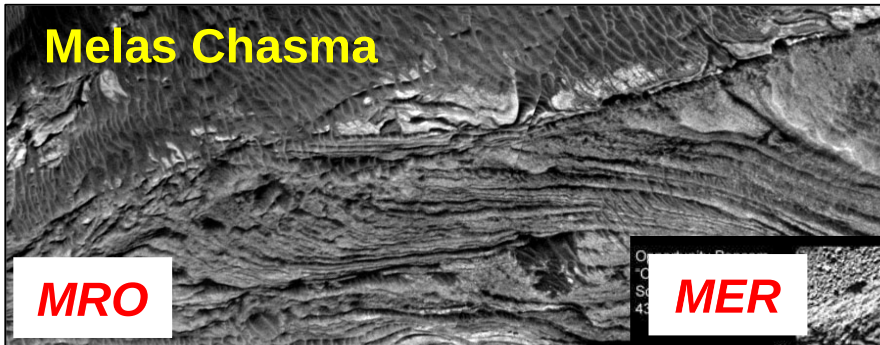
SHARAD and MARSIS

- Nearly pure water ice
- Distinct layering
- No deflection of crust
- Ice-cored lobate debris aprons in mid-latitudes

MRO MEX

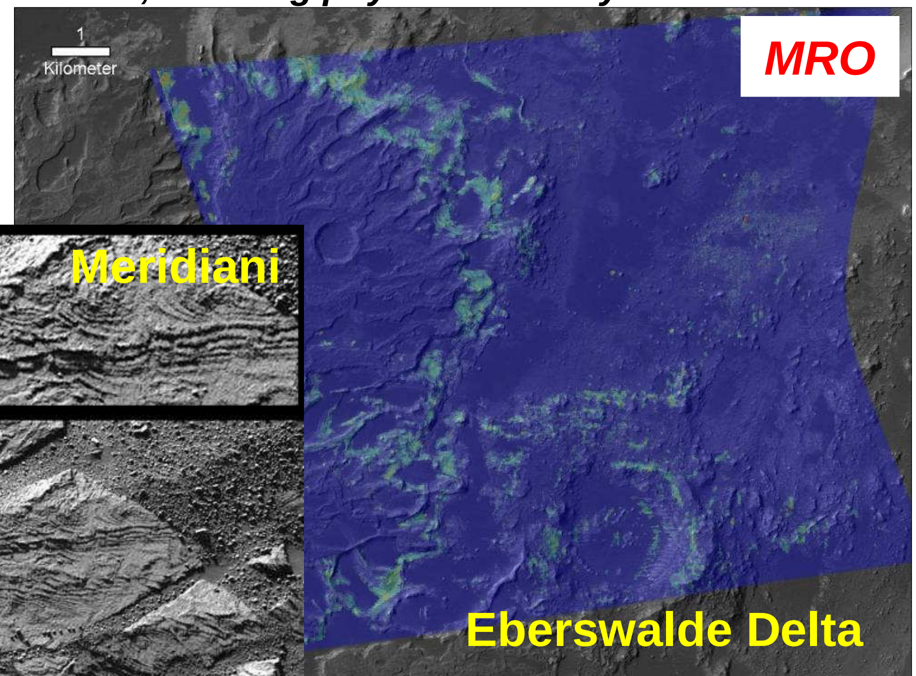


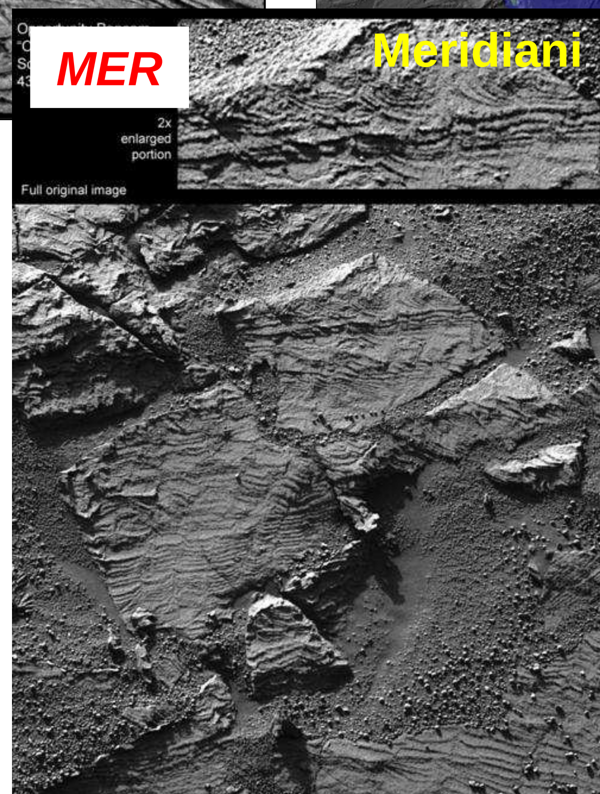
Past Decadal Results:
Ancient Mars Was Wet (Episodically?)



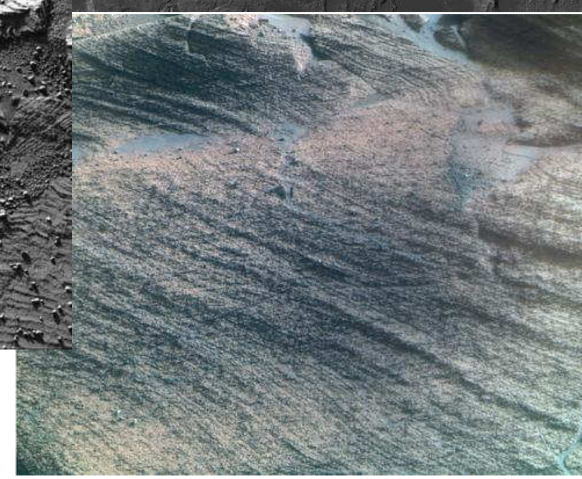
Large-scale sedimentary structures

Delta, showing phyllosilicate layers





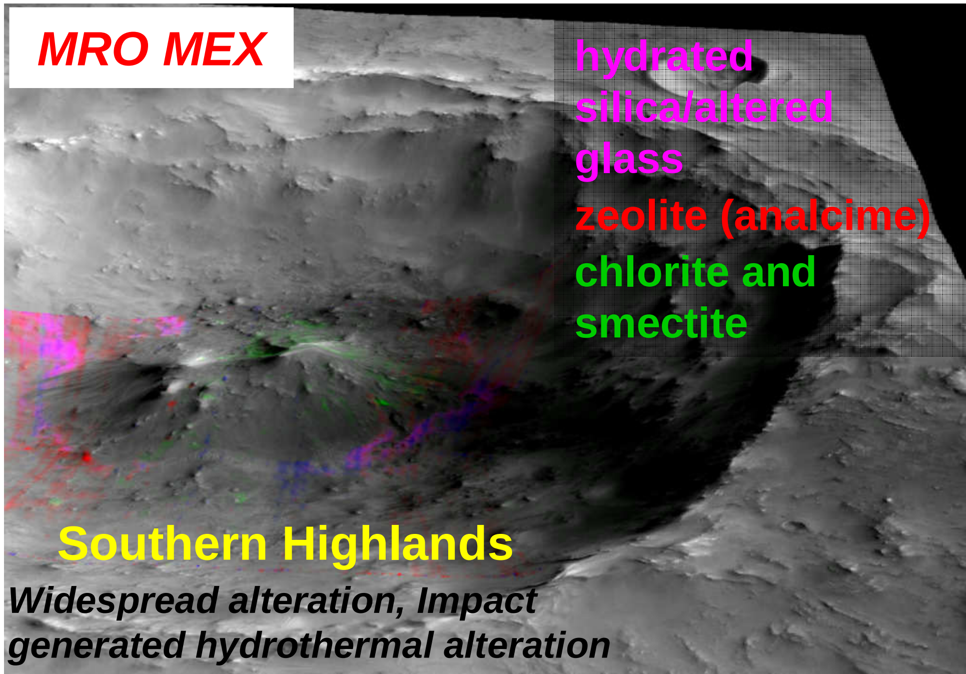
Fine-scale sedimentary structures

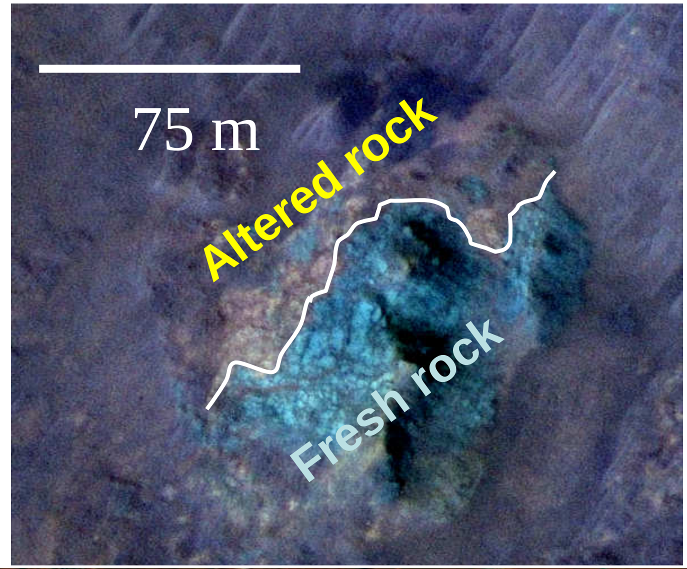


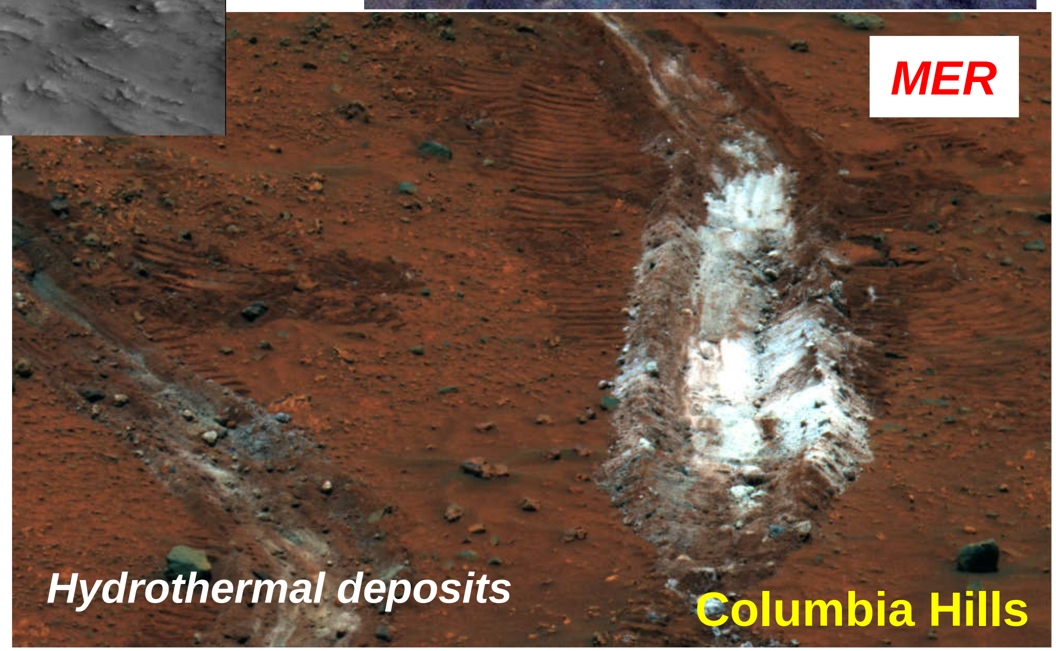
- **Depositional processes created a sedimentary record**
  - Developed in topographically low areas
  - Spectacular stratification at multiple scales
  - Evidence of persistent standing water, lakes
  - Sediments systematically change in character with time
  - Multiple facies recognized

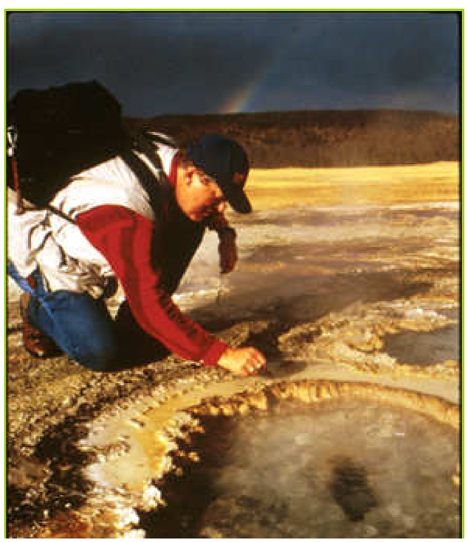
Past Decadal Results:

Evidence for Water/Rock Interaction



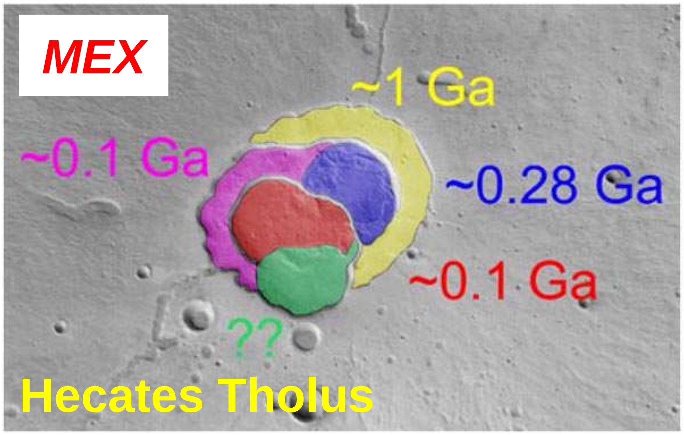


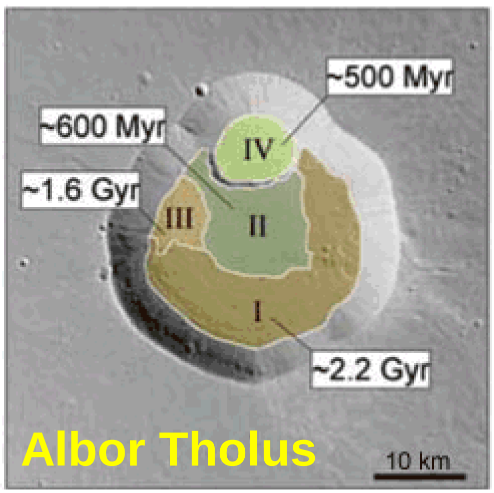




Past Decadal Results:

Mars Still Active Today

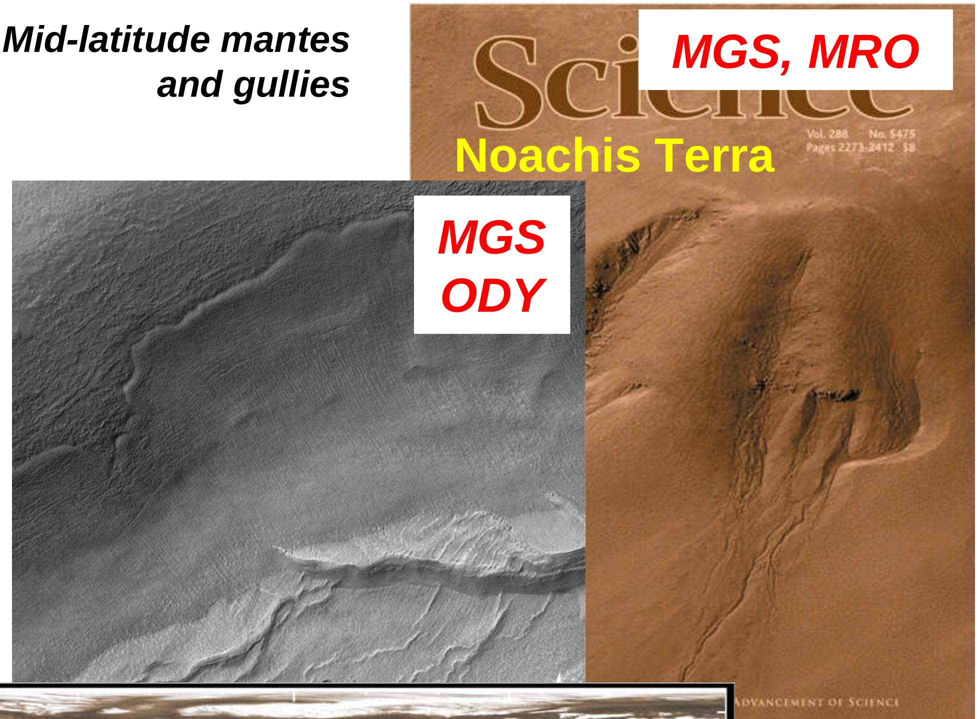


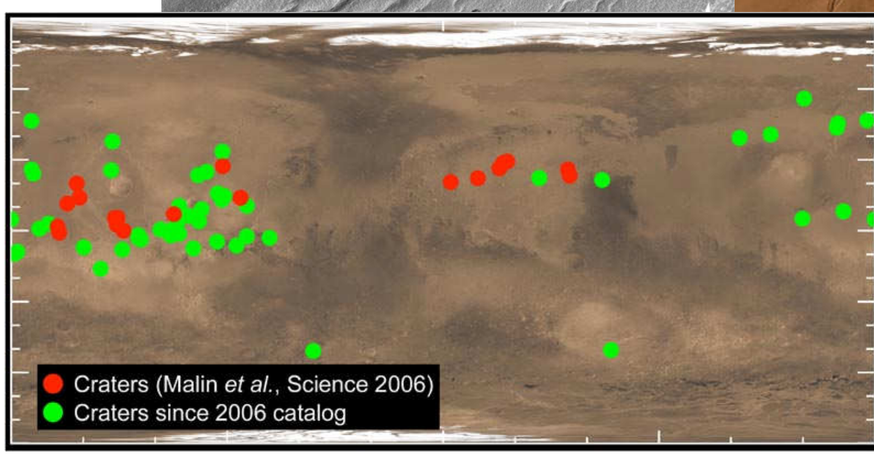


Lava Flows

Volcanic activity spans most or all of martian geologic history

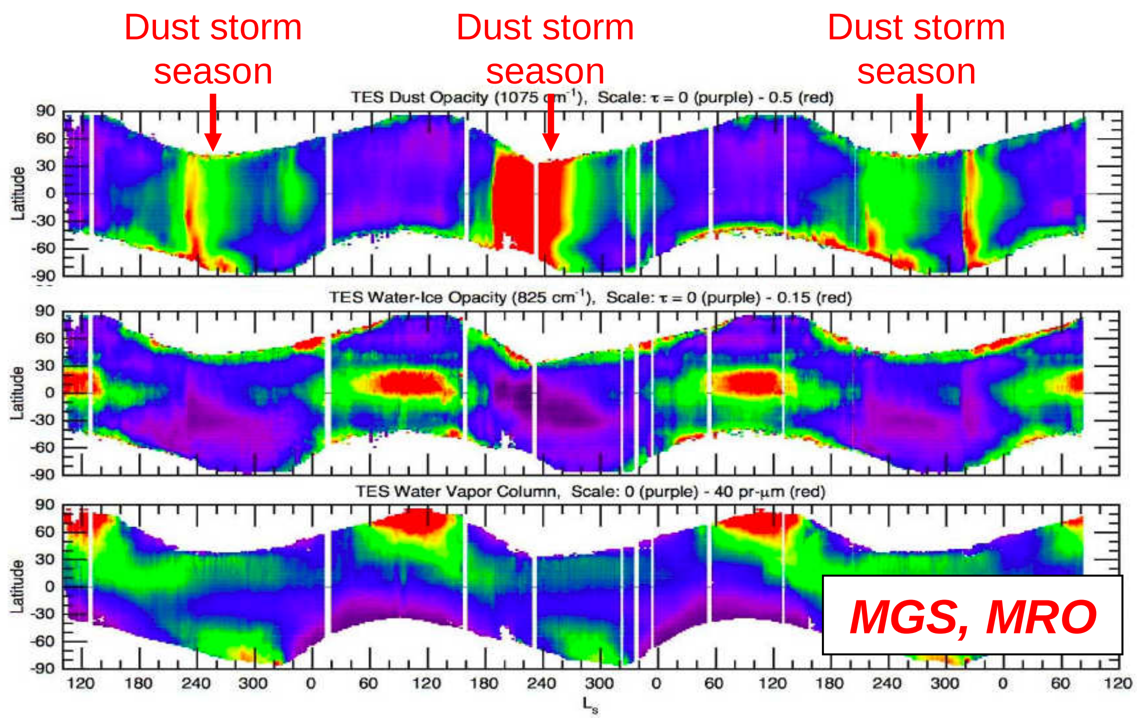
Mid-latitude mantes and gullies



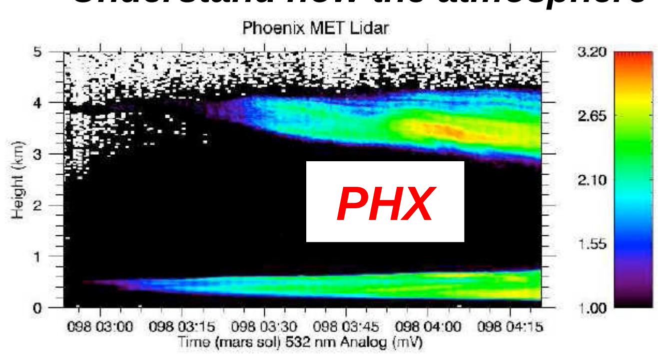


New Impact Craters

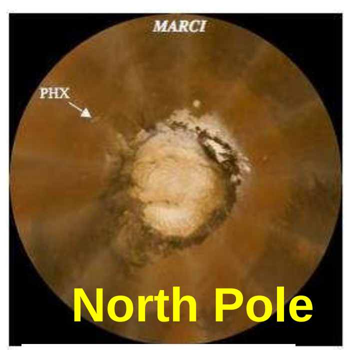
Past Decadal Results:
Atmosphere and Climate Results



Understand how the atmosphere works



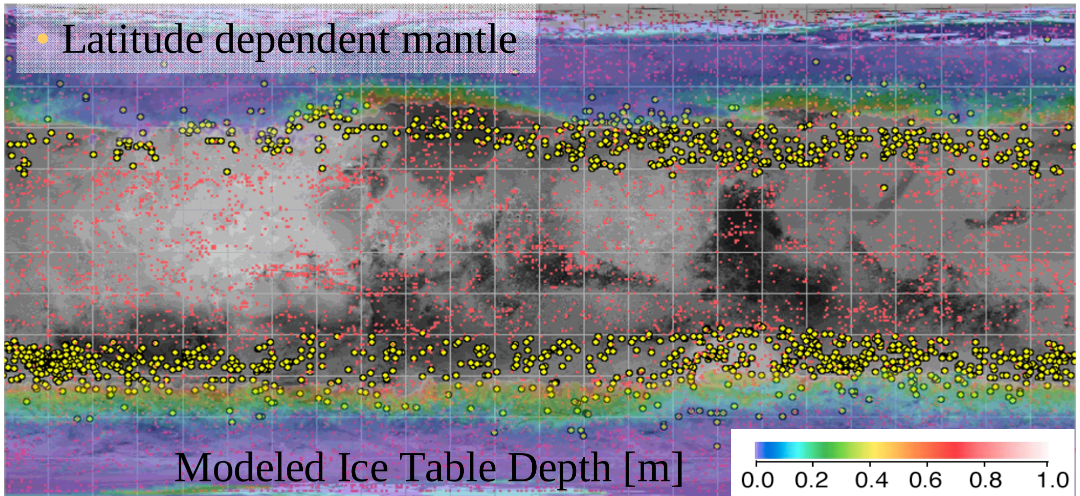
Cloud, fog and storm dynamics

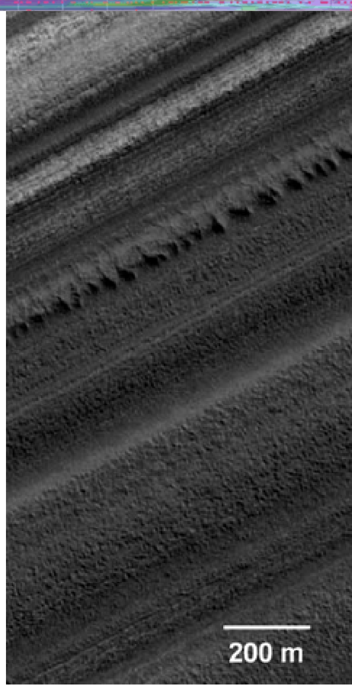


MEX MRO

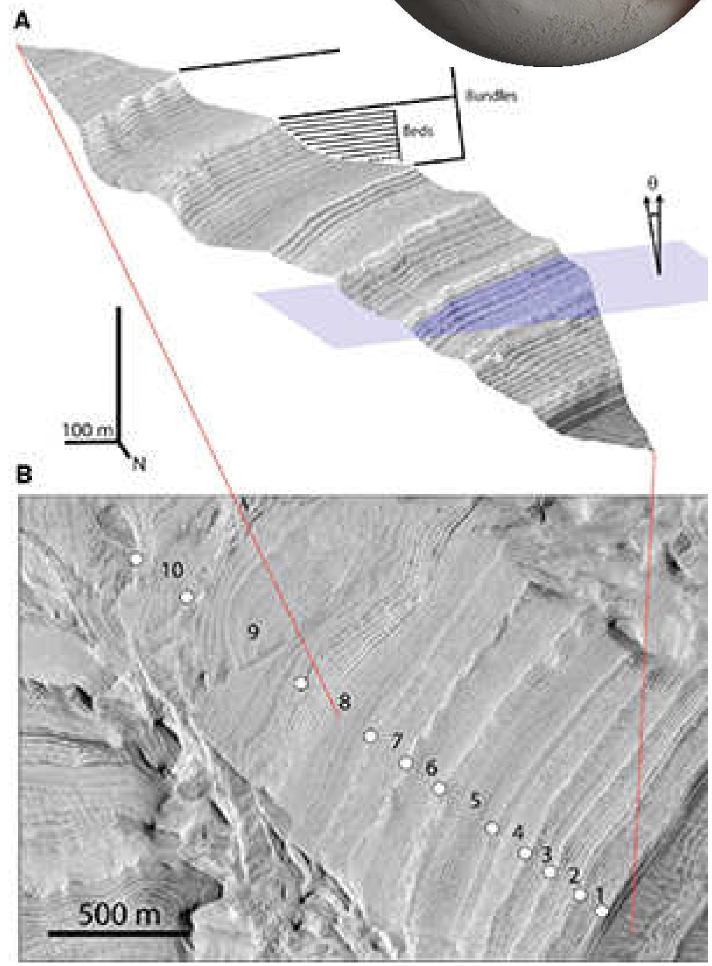
- ❑ **Climate change -- Past, recent and past: Understanding the process**
  - **Early wet (warm?) Mars (Noachian) has evolved to cold, dry Mars (Hesperian +)**
  - **Periodic change in last several million years**
- ❑ **Recent multi-year record of CO_2/water/dust; atmospheric dynamics [MGS, ODY, MEX, MRO]**
  - **Seasonal cycles and interannual variability**
- ❑ **SO_2, Argon, CH4, CO, etc.: Tracers of transport, chemistry, and surface-atmosphere interactions**

Past Decadal Results:
Periodic Climate Change





- **Volatile-rich, latitude dependent deposits (mantle, glaciers, gullies, viscous flow) coupled to orbitally-forced climate change**
- **Periodicity of layering in the north polar cap deposits as well as sedimentary deposits**

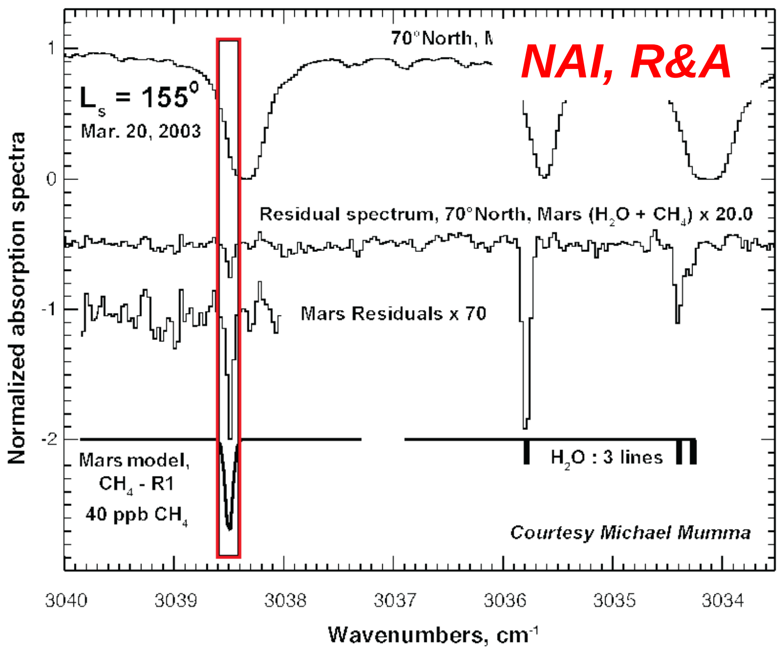


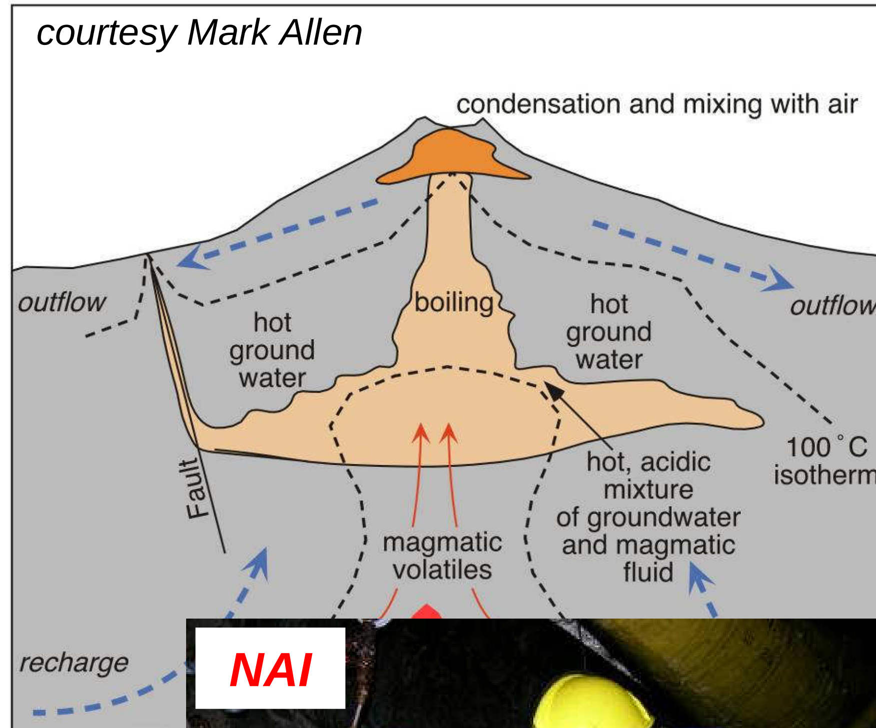
MGS, ODY, MEX MRO

Past Decadal Results:

Modern Methane

Courtesy Mike Mumma





Detection of Methane on Mars

MEX NAI R&A

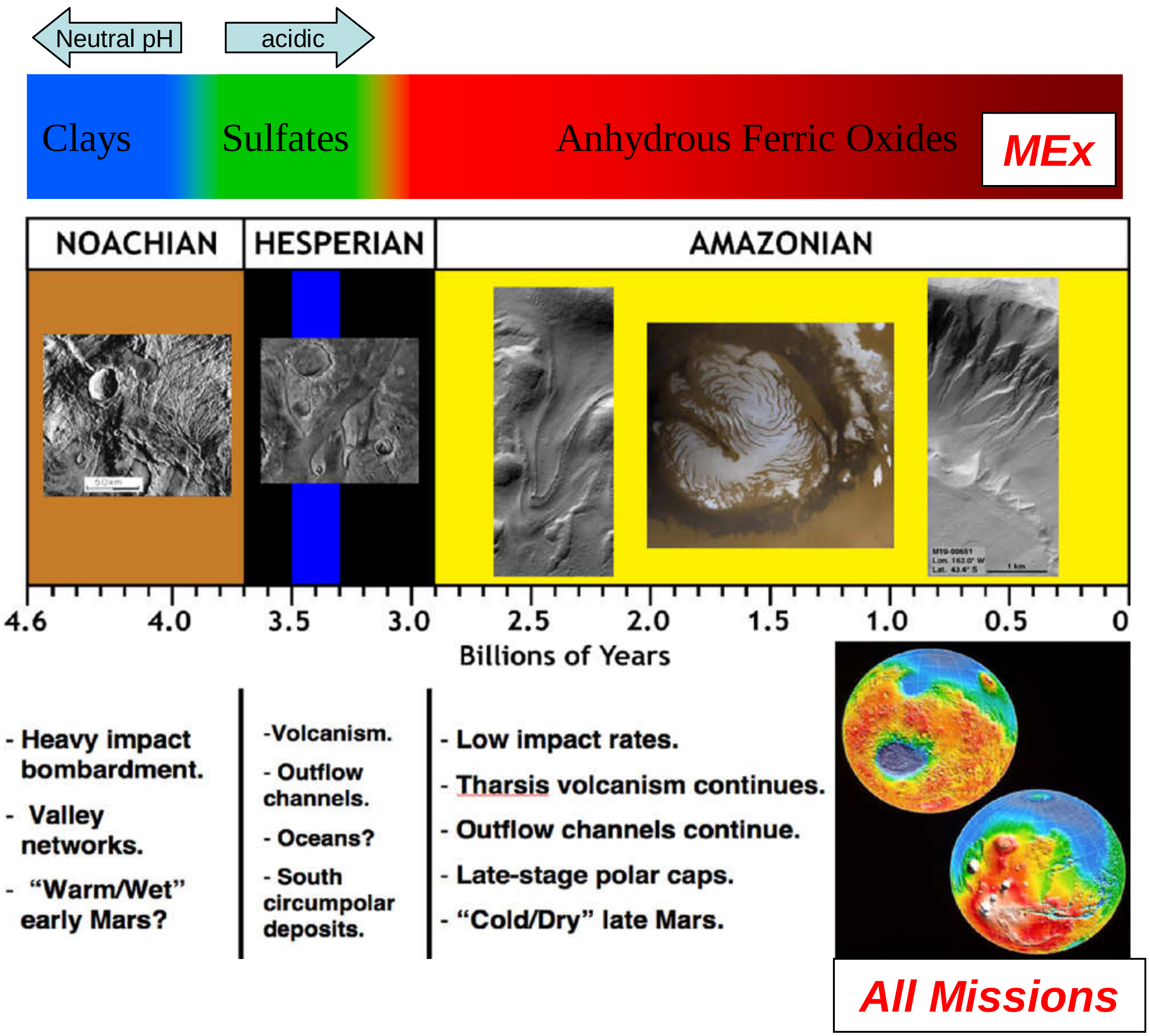
Evidence of an active subsurface?

Abiotic?

Biotic?

Past Decadal Results:

Mars Planetary Evolution



Hydrous Mineralogy Changed Over Time

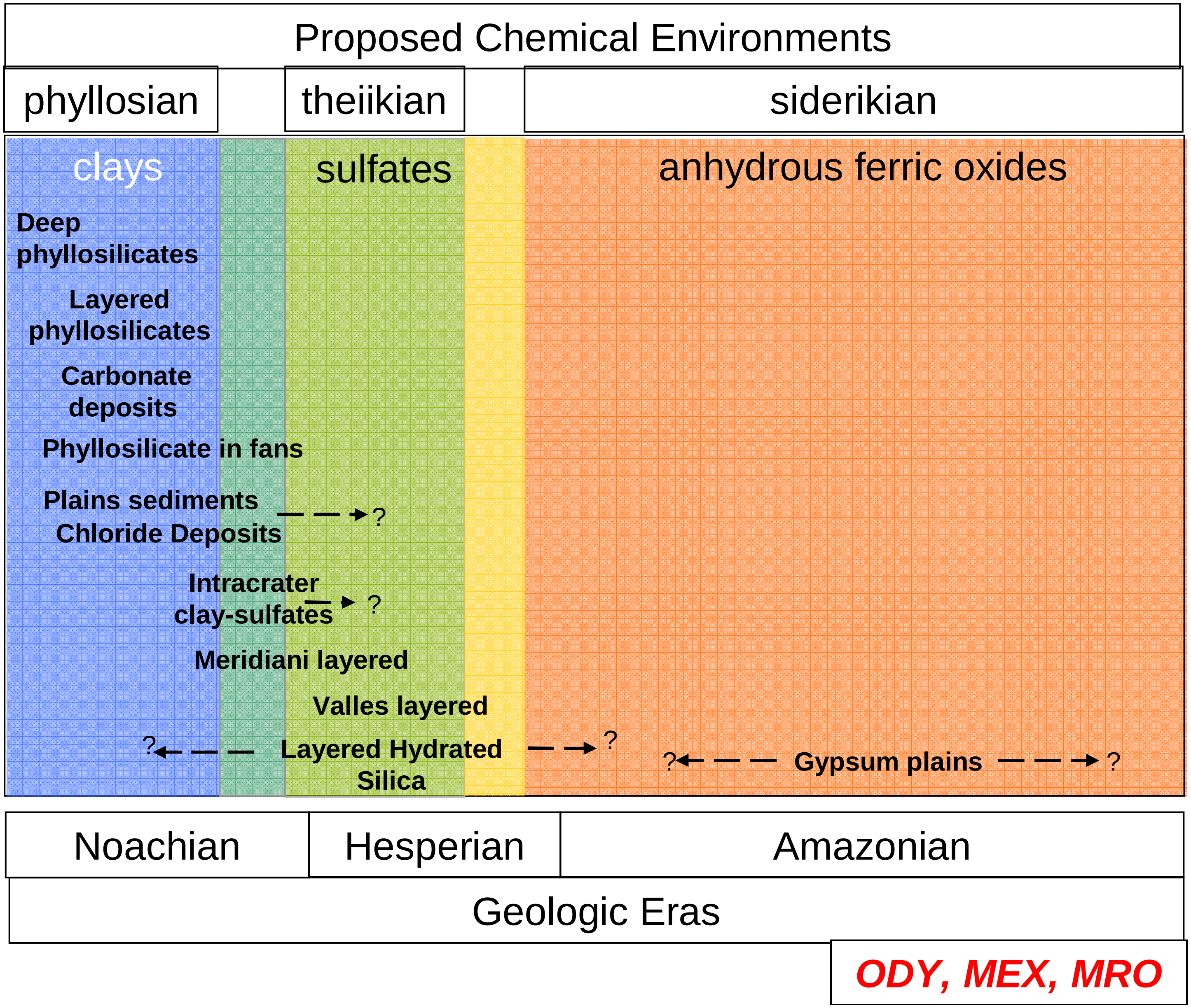
- Phyllosilicate minerals (smectite clay, chlorite, kaolinite…) formed early
- Evaporates dominated by sulfate formed later with opal/hydrated silica
- Few hydrated mineral deposits since

Evolution of Aqueous, Fluvial and Glacial, Morphology with Time

- Valley networks, lake systems
- Gullies
- Viscous flow, glaciers, latitude dependant mantle

Past Decadal Results:

Mars Planetary Evolution



Coupled mineralogy and morphology define aqueous environments

Their character has evolved indicating changing environments

Data support the hypotheses but indicate greater complexity in local environments

Given What We Have Learned, Mars is an Even More Compelling Exploration Target

Compelling Reasons to Explore Mars (1 of 2)

- **Conditions on early Mars, as interpreted from morphology and diverse aqueous mineralogy were conducive to pre-biotic chemistry and potentially to the origination and evolution of life.**
- **Mars retains this early history of an Earth-like planet that has largely been erased from Earth**
- **Mars has preserved physical records of its early environment and of climate change throughout its history, providing a means to understand Mars as a planetary system and planetary evolution as a process.**
- **Mars is accessible: It can be visited frequently and its atmosphere, surface and interior can be explored in detail from orbit and on its surface. The time-scale to implement a mission allows new findings to drive future exploration on approximately a decadal time scale (e.g. MOC gully paper 1996 to MRO observations of gullies 2006).**
- **This combination means that exploration of Mars is most likely in the foreseeable future to make substantial progress on the fundamental question of how and where life has arisen in the solar system.**

Compelling Reasons to Explore Mars (2 of 2)

- **Mars is unique in solar-system exploration in terms of breadth and depth of science goals, relative ease of implementing missions, feed forward of findings into future exploration and its importance to the highest-priority science objectives such as life.**
- **These objectives engage the public.**
- **The continuation of a Mars program is justified in that it has the best ability to achieve high-priority planetary science goals**
  - While other Solar System objects are compelling destinations, the effort, time, and expense required to investigate them at comparable levels of detail is greater than for Mars;
  - For a NASA Mars Program to continue, it must address goals which are both scientifically compelling and technically challenging.
- **To the extent that resources permit, including possibilities resulting from international cooperation, a broad program of Mars exploration should continue to be pursued to understand a complex, diverse planet.**
  - No one mission approach can address the full range of high-priority outstanding questions.

The Life Question: Program has Brought Us Much Closer to an Answer

- **Ancient life—potential has increased**
  - Lots of ancient liquid water in diverse environments
  - Past geological environments that have reasonable potential to have preserved the evidence of life, had it existed.
  - Understanding variations in habitability potential is proving to be an effective search strategy
  - **SUMMARY**: We have a means to prioritize candidate sites, and reason to believe that the evidence we are seeking is within reach of our exploration systems.
- **Modern life—potential still exists**
  - Evidence of modern liquid water at surface is equivocal—probable liquid water in deep subsurface
  - Methane may be a critically important clue to subsurface biosphere
  - SUMMARY: We have not yet identified high-potential surface sites, and the deep subsurface is not yet within our reach.

Plans and Strategies for the Future

External Factors & Constraints

- **Budget**. The budgets for NASA's Science Mission Directorate and its Mars Exploration Program have each been reduced in recent years.
  - Makes it more difficult to achieve major scientific progress frequently requires multiple complex, advanced missions (e.g., sample return) which are inherently more expensive
    - Reduced budgets are less resilient to costs overruns when they occur
  - International collaboration can enable the missions required to the extent that there are common goals and acceptable approaches
- **Engineering**
  - Major scientific progress will require significant technology developments
  - Critical mission support (telecom for data relay; critical event coverage; landing site certification) requires multiple missions
- Political. There has been, and will continue to be, a desire to conduct Mars exploration on a multi-national basis. This introduces multiple political drivers.

Advice and Analysis

- **<u>Mars science community</u>**
  - MEPAG has provided a role model for the rest of the planetary science community with regard to providing timely analysis and input to the NASA and NRC advisory structures
  - MEPAG has been very active in the latest Mars architecture discussions
    - Through Science Analysis Groups, etc.
- **<u>Formal Advisory Structure</u>**
  - Various organs of the NRC (COMPLEX, Space Studies Board, Decadal Survey)
  - NAC: Planetary Sciences Subcommittee
  - Both look to MEPAG for priorities within the Mars exploration options
- ***MEPAG and MEP have carefully evaluated science priorities and mission objectives for the next decade while faced with rising MSL costs and declining SMD and MEP budgets (next slides)***

MEPAG and MEP Planning 2007-2009

- The Mars community has risen to the challenge in developing numerous Science Analysis Groups (MSO-SAG, ND-SAG, MSS-SAG, etc.)
- The Mars Architecture Tiger Team (MATT) incorporated MEPAG reports, technology assessments and MEP guidance to assess possible and probably architectures beginning in 2016
- MATT has reported to MEPAG often and incorporated perspectives and discussions
- MATT: The Rationale for a MEP
  - Mars has a unique combination of characteristics that translate into high science priority for Planetary Science
  - Questions pertaining to past & present habitable environments and their geologic context should drive future exploration:
  - Both landed and orbital investigations are required to address these questions. Their sequential nature & the need for orbital assets to support landed science dictate a coherent program.
- MART: Mars Architecture Review Team
  - Reviewed NASA-only architectures (including MEPAG/MATT input)
  - Discussed principles of ESA-NASA collaboration

MATT-3 *Strategic Principles to Guide Mission Architecture Development*

- **Conduct a Mars Sample Return Mission (MSR) at the earliest opportunity, while recognizing that the timing of MSR is budget driven.**
- **MEP should proceed with a balanced scientific program while taking specific steps toward a MSR mission**
- **Conduct major surface landings no more than 4 launch opportunities apart (3 is preferred)**
- **Controlling costs and cost risk is vital and can be achieved in the near-term while still making progress on science objectives**
- **Require that landed missions leading to MSR demonstrate and/or develop the sample acquisition and caching technologies and provide scientific feed-forward to MSR**
- **Preparation of the actual cache could be triggered by earlier discovery at a landed site**
- **Provide long-lived orbiters to observe the atmosphere and seasonal surface change, and to provide telecom and critical event support**
- **Scout missions are included in the architecture**

Scientifically Compelling Scenarios - MATT-3

Option	2016	2018	2020	2022	2024	2026	Comments
	2014-2018 budget guideline precludes MSR before 2022						
M3.1 [2022b]	MSO-lite [#1]	MRR [#2]	NET	MSR-L	MSR-O	Scout	MPR occurs 2 periods before 2022 MSR, which will need additional funding for tech development
M3.2 [Swap in 2022b]	MSO-lite [#1]	MRR [#2]	NET	MSR-O	MSR-L	Scout	Gives chance for robust technology program preparing for MSR and time to respond to MRR tech demo
M3.3 [Trades in 2024a]	MSO-lite [#1]	NET	MRR	Scout	MSR-L	MSR-O	Lowest cost early, but 8 years between MSL & MRR; MRR just 2 periods before MSR; early NET

FOOTNOTES:

#1 MSO-lite affordable for $750M; preferable to MSO-min in order to map potential localized sources of key trace gases

#2 MRR may exceed the guideline ~$1.3B ($1.6B required?)

MSO = Mars Science Orbiter

MRR = Mars Mid-Range Rover (MER class [?] Rover with precision landing and sampling/caching capability)

MSR = Mars Sample Return Orbiter (MSR-O) and Lander/Rover/MAV (MSR-L)

NET = Mars Network mission (3-4 Landers)

Preferred Scenario

Scientific Questions for Mars that can be addressed in the Next Decade

- Are reduced carbon compounds preserved and what geologic environments have these compounds? (Goal I)
- What is the internal structure and activity? (Goal III)
- What is the diversity of aqueous geologic environments? (Goal I, II, III)
- How does the planet interact with the space environment, and how has that affected its evolution? (Goal II)
- What is the detailed mineralogy of the diverse suite of geologic units and what are their absolute ages? (Goal II, III)
- What is the record of climate change over the past 10, 100, and 1000 Myrs? (Goal II, III)
- What is the complement of trace gases in the atmosphere and what are the processes that govern their origin, evolution, and fate? (Goal I, II, III)

Specific Proposed Objectives for the Next Decadal Planning Period

- Explore the surface geology of at least one previously unvisited site for which there is orbital evidence of high habitability potential. At that site, evaluate past environmental conditions, the potential for preservation of the signs of life, and seek candidate biosignatures.
- Quantify current processes causing loss of volatiles to space
- Extend the current record of present climate variability
- Test hypotheses relating to the origin of trace gases in the atmosphere, and the processes that may cause their concentrations to vary in space and time.
- Establish at least one solid planet geophysical monitoring station with a primary purpose of measuring seismic activity.
- Take specific steps to achieve the return of a set of high-quality samples from Mars to Earth as early in the 2020’s as possible:
  - Well-funded MSR technology development program in the 2010’s
  - Establishment of a returnable cache of samples on Mars

An Integrated Strategy for the Future

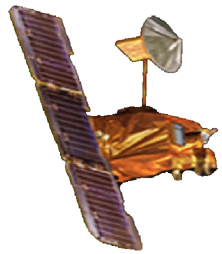
MEPAG's Program-Level Science Strategies

- **Introduced 2000: FOLLOW THE WATER**
- **Introduced 2004: UNDERSTAND MARS AS A SYSTEM**
- **Introduced 2008: SEEK HABITABLE ENVIRONMENTS**
- **Proposed for the period 2013-2023: SEEK THE SIGNS OF LIFE**
  - Suggested by MART, June, 2009
  - Reflects the need and opportunity to focus on the life question. Life is both "first among equals" for MEPAG, and a high-level NASA strategic goal.
  - This scientific strategy is well-aligned with the goals of multiple potential international partners.
  - Explicitly capitalizes on discoveries from prior missions. Seeking the signs of life is what we want to do in habitable environments, once we find them.

Measurement Strategy for the Decade

- **Seeking Signs of Life:**
  - Search for biosignatures in habitable Martian environments
    - Not in situ life detection per se
  - *Return carefully selected samples* from a high-priority site to understand the prebiotic history of Mars and with the potential to determine whether there is or has been life there
    - Definitive answers will require repeated analyses in which preliminary findings are tested by the most sophisticated tools available on Earth
  - Look for trace gas evidence that Mars is biochemically active today
- **Advancing our understanding of Mars as a Planetary System:**
  - Understand interior processes and their past contributions to climate change and possible evolution of life
  - Continue to characterize climate change processes in the Mars atmosphere
  - *Return carefully selected samples* from a high-priority site to make a major advance in our understanding of the climate and geologic history of Mars specifically, including the action of water, and of planetary evolution generally
    - Samples to be returned from a site whose geology/habitability is well-characterized
  - Look for trace gas evidence that Mars is geologically active today

Steps to Achieve the Science Goals



Trace Gas & Telecomm Orbiter (NASA)

- Detect a suite of trace gases with high sensitivity (ppt)
- Characterize their time/space variability & infer sources
- Replenish orbiter infrastructure support for Program

Rovers (NASA & ESA)

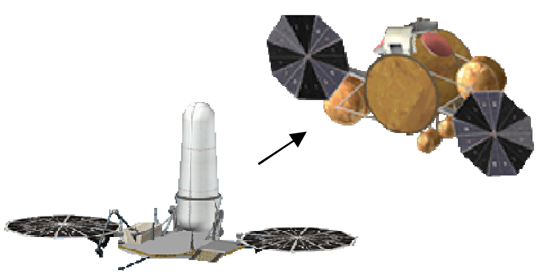
- Explore Mars habitability in the context of diverse aqueous environments provided by a new site
- Characterize sites suitable for sample return
- Select and prepare samples for return

Geophysical Surface Science (NASA & ESA)

- Determine the planet's internal structure and composition, including its core, crust and mantle
- Collect simultaneous network meteorological data on timescales ranging from minutes to days to seasons

Technology Development for MSR

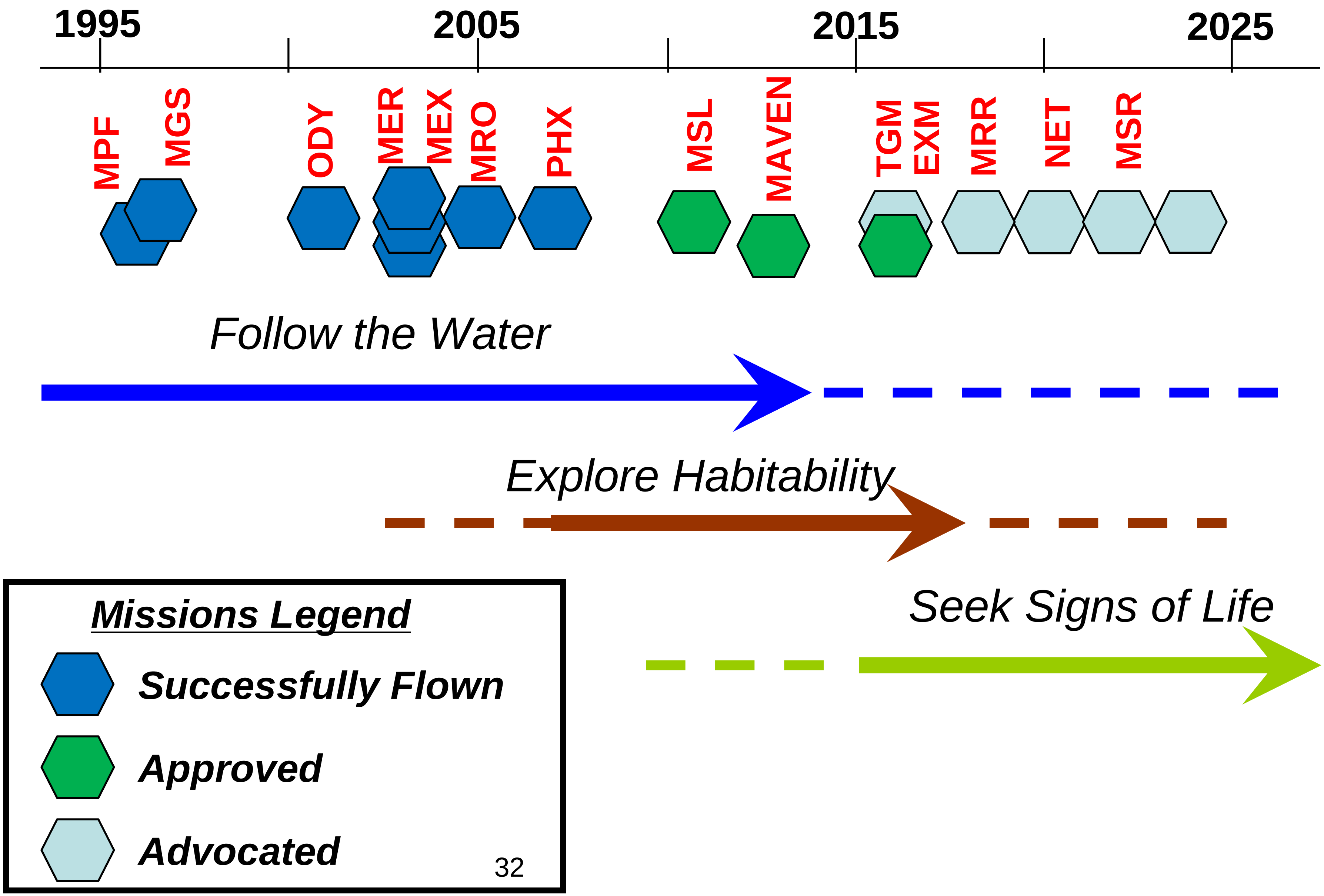
- Start work on long-lead technical issues (e.g., Mars Ascent Vehicle)



Mars Sample Return (NASA & ESA)

- Make a major advance in understanding Mars, from both geochemical and astrobiological perspectives, by the detailed analysis conducted on carefully selected samples of Mars returned to Earth

Proposed Next Decade Missions



Priority within the Architecture

Make Progress toward Sample Return

- **Analysis of returned samples will revolutionize our understanding of Mars, both across multiple disciplines and as the integrated understanding of a complex planet and of Solar System processes. We need to go forward and achieve this challenging step.**
  - The Program is acquiring the data necessary to choose candidate sites
  - MSL is developing the EDL system needed for the MSR lander
  - An MRR can be designed to cache the samples for a future return vehicle
  - An MRR launched in 2018 or 2020 would have the benefit of MSL data to determine the site for future return of a collected data--it may be a new site or previously visited (e.g., MSL).
- **Sample return from a single site, no matter how carefully chosen, will not address all of the high-priority scientific objectives for Mars. The diversity of Martian environments, now and in the past, and the complexity of the processes at work will require a broader program of exploration.** ***However, the first sample return from a well-characterized site is the means to make the greatest progress at this point in the program.***

Back-Up

Rationale for Mars Sample Return (1 of 2)

- **Analysis of returned samples is required to advance our understanding of most Mars scientific disciplines**
  - Biogeochemistry, prebiotic and geochemical processes, geochronology, volatile evolution, regolith history
  - Only returned samples can be analyzed with full suite of analytic capabilities developed
  - Only returned samples permit the application of new analytic techniques and technologies, including response to discoveries
- **As with successful sample return and sample analysis (meteorites, Moon, Stardust), sample return is expected to revolutionize our understanding of Mars that cannot be done in situ or by remote sensing**
  - Sample return is a necessary step toward potential human Mars missions

Rationale for Mars Sample Return (2 of 2)

- **While sample sites must be characterized in situ, could return to previous site or examine new site and cache**
  - *Precursor missions can "buy down" risk but are not required*
- **Detection of complex organics is not required**
  - Reasonable possibility of biosignatures is sufficient
  - Approach to life questions and other disciplines much broader than single litmus test of detecting complex organics
  - Complex organics may not be accessible at the surface even if life had developed in the past

We Are Already Implementing a Sample Return Program: Technology

- **The Mars Exploration Program has made great strides in developing the technologies needed:**
  - MPF and MER have demonstrated the surface mobility and much of the basic instrumentation needed to acquire high-priority samples;
  - MER and PHX have provided valuable experience in sample handling and surface preparations; MSL will do more;
  - The MSL EDL system design can accommodate a MSR Lander / Rover with a Mars Ascent Vehicle (MAV);
  - The assets for certifying site safety (e.g., MRO HiRISE) continue to operate and have already scrutinized a number of scientifically exciting sites;
  - Orbital relay assets to support routine operations by landed craft and for critical events continue to be emplaced.
- **This productive interplay of missions has resulted from the Program approach.**

Remaining Steps for Mars Sample Return

- ❑ **Sample return requires more than one mission to Mars**
  - ❑ Preliminary steps have been taken by previous missions
- ❑ **MSL is the next mission in a sample return program**
  - ❑ Most sophisticated instrumentation brought to Mars to explore site with high potential habitabilty, including biosignatures
- ❑ **After MSL, next landed mission is to prepare sample cache at MSL site or newly selected site based on orbiter data**
- ❑ **Technology for Mars Sample Return must be started in parallel, particularly for the Mars Ascent Vehicle and accommodation of planetary protection/contamination requirements**

DRAFT Top Ten MGS Discoveries

1	MAGNETIC FIELDŃLarge remnant magnetic anomalies in the oldest Martian rocks are evidence of an early molten interior with a vigorous core dynamo. No global field is present currently.
2	GRAVITY AND FIGURE ŃThe ellipsoidal shape of Mars is flattened by ~ 20 km due to rotation and the center of figure is offset by nearly 3 km, indicating that the north pole is about 6 km lower than the
3	TOPOGRAPHYŃA global topographic model, the best produced for any planet including earth, shows a 30-km range of topography, a pole-to-pole slope that controlled the transport of water in early Martian
4	BASALT AND WEATHERINGŃThermal emission spectra show wide-spread occurrence of basaltic composition in the south and andesitic composition in the north. Identification of widespread
5	depositional environment (lacustrine, aeolian, crater ejecta, or volcanic airfall) and erosional environment (fluvial and cratering) over an extended period during
6	and possibly indicative of deposition in a surface hydrothermal environment, has become a prime landing site. No similar areas of carbonate, sulfate, or quartz have bee
7	channels and valley networks seem to originate by both sapping and precipitation-- and possible evidence for recent liquid water seeps in numerous spatially isola
8	AEOLIAN PROCESSESŃCurrent aeolian processes are evidenced by widespread dust mantles, dust devils, dust storms, streaks, dunes, and sand sheets. Evidence for a complex and extended depositional
9	POLAR CAPSŃA reliable estimate of water volume in the present polar caps and evidence for distinctively different evolution of the north and south polar caps. Summer time sublimation of carbon
10	ATMOSPHERIC DYNAMICSŃSignificantly improved understanding of atmospheric dynamics and interannual variation from more than two Martian years of continued monitoring of temperature,

DRAFT 'Top Ten' ODY Discoveries

1	Highest resolution global maps of Mars: 100 m/pixel day and night IR. [THEMIS]
2	Detection and mapping of ground ice poleward of ~60 latitude. [GRS]
3	Detection of H-rich minerals in mid latitudes. [GRS]
4	Mineralogical mapping showing a wide diversity in surface composition, from low-silica basalts to high-silica dacite. [THEMIS]
5	Discovery of heterogeneous thermophysical properties at scales down to 100 m. Utilized to make new discoveries about drainage networks, secondary impact crater abundance, Phoenix landing site safety, etc. [THEMIS]
6	Measurement of mass of surface CO2 as a function of season in polar regions for 3.5 Mars years. Highly repeatable pattern is observed. [GRS]
7	Discovered large lateral heterogeneity in elemental composition of near-surface materials; e.g., Cl-rich zones associated with Tharsis volcanoes, Fe-rich northen plains and depleted southern highlands, K and Th enrichment in northern plains volcanic terrains. [GRS]
8	Discovered chloride salt outcrops at numerous southern hemisphere locations. [GRS]
9	K/Th indicates that SNC meteorites are not representative of Mars crust. [GRS]
10	First robust detection of water ice on south polar surfaces. [THEMIS]
11	Detection of large seasonal variations in atmospheric Ar due to CO2 cycle. [GRS]
12	Evidence for catastrophic release of CO2 ice as spring time geysers. [THEMIS]
13	Strong evidence that modern near-surface geothermal activity is negligible. [THEMIS]
14	Radiation levels in cruise and in Mars orbit are 2-3 times that in low-earth orbit. [MARIE]

DRAFT Top Ten MER Discoveries

1	At both Meridiani Planum and the Columbia Hills, conclusive physical and chemical evidence was found for persistent surface and subsurface water in the distant past.
2	The sedimentary rocks at Meridian record an ancient environment of wind-blown sulfate sands that were intermittently wet at the surface, similar to a salt flat or playa dominated by acidic sulfate chemistry.
3	The Columbia hills are formed of layered volcanic rocks, many of which were heavily altered by liquid water early in their history. The alteration is very variable, with adjoining outcrops having different levels of alteration.
4	Deposits of silica-rich soils and coatings on rocks provide strong evidence for hydrothermal or fumarolic processes altering the rocks after the "Home Plate" deposits were emplaced.
5	Hematite concretions precipitated when groundwater entered the sediments of Meridiani Planum. These concretions accumulate on the surface as the softer sandstone containing them is eroded away. Variations in the ancient groundwater table accounts for differences between concretion rich layers and layers without concretions.
6	Iron sulfate salts have been found in the soil at a number of locations in Gusev. These salts contain bound water and were likely brought to the surface in aqueous solution or by volcanic vapors that mobilized elements from local rocks. The fact that these salts are found in the loose soil rather than rocks allows for the possibility that this activity could be relatively recent.
7	Spirit's investigation of "Home Plate" and surroundings find that explosive volcanic deposits once covered a large region. Water was present when these rocks were deposited. "Home Plate" is an erosional remnant of this larger deposit.
8	Liquid water in Meridiani was not a one-time event. At the bottom of Endurance crater there is evidence for a later episode of water, after the formation of the crater in the original sediments.
9	The Meridiani sediments are extensive. The sediments at Meridiani extend to depth. Opportunity has yet to see the contact between the sediments and the base rock. The surface water needed to form the sulfates extended laterally from the landing site at Eagle Crater to Victoria Crater. It likely extends across all of Meridiani.
10	Rocks on the plains of Gusev crater are olivine-rich basalt lava which extend the known range of compositions of igneous magmas on Mars. The rocks indicate that since the emplacement of these rocks, little weathering has occurred with only small amounts of water. This means that the alteration in the Columbia hills pre-dates the plains basalts.

DRAFT Important MEX Discoveries

1	The relative abundance of liquid water on the Martian surface through time, as well as its climate history, have been derived from alteration minerals [OMEGA].
2	The presence of methane has been confirmed from orbit and its spatial and vertical distribution are being mapped [PFS].
3	Tropical and equatorial glacial landforms have been identified, as well as possible glaciers active just a few hundred thousand years ago [HRSC].
4	The North and South Polar Layered Deposits consist of nearly pure water ice [MARSIS]. Maps of H_2O ice and CO_2 ice in the polar regions have been produced [OMEGA].
5	Volcanism on Mars may have persisted until recent times (Olympus Mons caldera being only 100 Ma old) and could still be active near the North pole. Several outbursts of volcanism may have occurred throughout Martian history [HRSC].
6	The solar wind penetrates deeper into the Martian atmosphere (down to 250 km) than previously thought. The current rate of escape of energetic ions is relatively low [ASPERA].
7	The existence of auroras over mid-latitude regions with paleomagnetic signatures, as well as the presence of airglow in the night-side, have been documented [SPICAM].
8	The existence of a third transient ionospheric layer, due to meteors burning in the atmosphere, has been identified through occultations [MaRS].
9	The most accurate estimate so far for the mass of Phobos has been derived from radio science data [MaRS]. Also, the sharpest images of Phobos (4 m/pixel and in 3D) were acquired [HRSC].
10	The first unambiguous detection of very high-altitude (80 km) CO_2 clouds was reported [OMEGA] and corroborated by further results [SPICAM and HRSC].

DRAFT Top Ten MRO Discoveries

	Ancient Mars
1	Morphologic and mineralogical evidence (phyllosilicates, opaline silica, carbonates, sulfates) reveal episodic or diverse alteration of surface materials by water early in Mars history. This is exposed beneath unaltered materials in hundreds of "windows" in the ancient Noachian crust
2	Sedimentary rocks covering many regions of Mars show indurated fractures that imply groundwater movement, cementation and alteration
3	Evidence that the Tharsis plateau is underlain by a large elliptical basin suggests an impact origin of the hemispheric dichotomy
4	Inverted stream-beds suggest wetter conditions with extended (rainfall driven?) run-off
	Recent Mars
5	Indications of geologically young gullies shaped by water (possibly modified even today)
6	North polar layered terrains may be as young as ~10 Myr in age
7	Ice cap base flatness implies chrondritic internal heat production & a cooler, more rigid crust
8	Internal layering in the northern ice cap and exposed layering elsewhere suggest two dominant time scales in their formation, possibly driven by obliquity and orbital cycles
9	Thick (> 100 m) subsurface ice deposits in mid-latitudes preserved beneath debris blankets; these may be the physical remnants of the last "ice age" cycle (discussed above)
	Present Mars
10	Ongoing change: New impact craters, surface avalanches, year-to-year variations in atmospheric and surface processes. A fourth Mars year added to long-term climatology of temperature, dust & water vapor
11	A "leaky" atmospheric trap for water vapor transport and evidence of complex dynamics

DRAFT Top Five PHX Discoveries

1	Perchlorate. Deliquescent ClO4 identified in soils. Eutectic is at approximately the Mars frost point. May play a part in control of atmospheric water vapor concentration. May contribute to low-latitude hydrated mineral discovery from ODY. Possible nutrients for microbes but also combusts organics during pyrolysis.
2	Snow. Precipitating clouds may confine presence of water to the boundary layer (up to 4 km). Cloud formation, height, precipitation may be the control on the seasonal abundance of water. Particle sizes are much large than expected (~20-40 micron radii vs. several micron radii)
3	Carbonate. 3-5% Ca-Carbonate detected in soils.pH values confirm carbonate: pH is 7.8-8.0. Converting that value to partial pressure of CO2 on Earth gives you a value of 8.3. Formed by action of liquid water (small amounts are enough).
4	Water. Two different expressions: pore ice and "segregated" or "pure" ice. Suggests two different mechanisms of formation, at least vapor diffusion. Segregated ice was unexpected. TEGA confirmed H2O rather than hydrated minterals, etc.
5	Boundary layer determined to be 4 km high during northern summer daytime.