

GOAL II: UNDERSTAND THE PROCESSES AND HISTORY OF CLIMATE ON MARS

Objectives	Sub-objectives
A. Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under the current orbital configuration.	A1. Constrain the processes that control the present distributions of dust, water, and carbon dioxide in the lower atmosphere, at daily, seasonal and multi-annual timescales.
	A2. Constrain the processes that control the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment.
	A3. Constrain the processes that control the chemical composition of the atmosphere and surrounding plasma environment.
	A4. Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.
B. Characterize the history of Mars' climate in the recent past, and the underlying processes, under different orbital configurations.	B1. Determine how the chemical composition and mass of the atmosphere has changed in the recent past.
	B2. Determine the climate record of the recent past that is expressed in geological, glaciological , and mineralogical features of the polar regions.
	B3. Determine the record of the climate of the recent past that is expressed in geological and mineralogical features of low- and mid-latitudes.
C. Characterize Mars' ancient climate and underlying processes.	C1. Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present.
	C2. Find physical and chemical records of past climates and factors that affect climate.
	C3. Determine present escape rates of key species and constrain the processes that control them.

The fundamental scientific questions that underlie the Mars Climate Goal concern how the climate of Mars has evolved over time to reach its current state, and the processes that have operated to produce this evolution. There is also considerable interest in understanding how Mars' climate fits into the context of other planetary atmospheres, including Earth's.

Mars' climate can be defined as the mean state and variability of its atmosphere and exchangeable volatile **and aerosol** reservoirs, evaluated from diurnal to geologic time scales. The climate history of Mars can be divided into three different states: (i) Present climate, operating under the current obliquity and observable today; (ii) Past climate operating under similar pressures, temperatures, and composition, but over a range of orbital variations (primarily obliquity) that change the pattern of solar radiation on the planet and whose effects are evident in the geologically recent physical record; and (iii) Ancient climate, when the pressure and temperature may have been substantially higher than at present, the atmospheric composition may have been different, and liquid water **was likely episodically or continuously stable on the surface**.

Prioritization

On Mars, the present holds the key to the past: a comprehensive understanding of the fundamental processes at work in the present climate is necessary to have confidence in conclusions reached about the recent past and ancient climate, when Mars may have been more habitable than today. Because many of the processes that governed the climate of the recent past are likely similar to those that are important today, an understanding of the present climate must be firmly established before an understanding of the climate of the recent past can be developed. **Furthermore, since not all climate processes leave a distinctive record, it is also necessary to determine which climate processes will have left detectable signatures in the climate archives of the recent past.** Numerical models play a critical role in interpreting the recent past and ancient climate, and it is imperative that they be validated against **observations** of the present climate in order to provide confidence in results for more ancient climates that are no longer directly observable.

Based on this philosophy, the Climate Goal is organized around three Objectives, each pertaining to the different climate epochs. Investigations within a Sub-objective are assigned a prioritization of high, medium, or low. This prioritization is based on subjective weighting that includes consideration of existing measurements with respect to needed measurements, relative impact of an Investigation towards achieving an Objective, and identification of Investigations with logical prerequisites. Importantly, the Investigation prioritization is only with respect to the Investigations within the parent Sub-objective. Thus, it is possible that a high priority Investigation within lower priority Objective C could be on par with or more important than a lower priority Investigation within the higher priority Objective B.

Objective A: Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under the current orbital configuration.

Our understanding of the chemistry, dynamics, and energetics of the present Martian atmosphere forms the basis for understanding the recent past and ancient climate. The atmosphere system consists of many coupled subsystems, including surface and near-surface reservoirs of CO₂, H₂O and dust; the lower atmosphere; the upper atmosphere; and the surrounding plasma environment. Each of these regions is an integral part of the interconnected atmospheric system, yet different processes dominate in different regions. Well-planned measurements of all of these regions enable characterization of the physical processes that maintain and drive the present climate of Mars. The boundary between the lower and upper atmosphere is an imprecise concept. The mesopause, around 90 km, provides a convenient choice. Below it, chemical composition is relatively stable and visible and infrared (IR) wavelengths dominate radiative heating. Above it, and particularly above the homopause around 110 km, chemical composition is more variable and ultraviolet (UV) and shorter wavelengths dominate radiative heating.

This Objective will not be achieved by observations alone. Numerical modeling of the atmosphere provides an additional, critical element to understanding atmospheric and climate processes. Models provide full dimensional and temporal context to necessarily sparse and disparate observational datasets, particularly when combined with data assimilation techniques, and models provide a virtual laboratory for testing whether observed or inferred conditions are

consistent with proposed processes. Proper consideration of this essential modeling element should be given to any proposed experiment.

Sub-Objective A1: Constrain the processes that control the present distributions of dust, water, and carbon dioxide in the lower atmosphere, at daily, seasonal and multi-annual timescales.

Knowledge of the processes controlling distributions of dust, water, and CO₂ may be arrived at by direct measurement of these substances, and by measurement of atmospheric state, circulation and forcings in the atmosphere. Although tremendous advances have been made towards characterizing and quantifying the atmosphere, existing measurements of the spatial and temporal distributions of dust, water and carbon dioxide, and the atmospheric state in the lower atmosphere are inadequate to achieve this Sub-objective; better diurnal coverage and better 3-D distributions are needed. A comprehensive and consistent picture of the relevant atmospheric processes will be achieved primarily through direct measurement of atmospheric forcing (e.g., radiation, turbulent fluxes), the quantities that feed into that forcing (e.g., dust and clouds), and the response of the atmosphere (e.g., temperature, pressure, winds, and volatile phase changes) to the forcing over daily, seasonal, and multi-annual timescales. As such, characterization of the thermal and dynamical state of the lower atmosphere (temperatures and winds) is a necessary, but not a sufficient, element of this Sub-Objective.

Obtaining a high quality data set from a properly accommodated weather station (i.e., one in which thermal and mechanical contamination from the spacecraft is minimal) is of highest priority. In nearly half a decade of attempts, there has yet to be an in situ weather station investigation that has successfully and simultaneously measured, without substantial spacecraft contamination or operational issues, the basic meteorological parameters of pressure, temperature, and wind. Any proposed measurement of in situ meteorological parameters should demonstrate the impact of accommodation on the fidelity of the measurements. Once high quality surface measurements of basic meteorological parameters have been acquired, measurements of quantities that have been poorly or never measured generally should be given higher priority.

In addition to a single surface station, in situ measurements can be obtained by networked landed observatories or aerial platforms (e.g., balloons, airplanes). Each of these platforms provides unique measurements helpful to a complete understanding of the climate system. Regardless of platform, in situ measurements also provide calibration and validation for complementary measurements retrieved from orbit, and provide data critical to the validation of climate and weather models. The importance of data for these purposes should be appropriately recognized and valued in any proposed experiment.

Substantial progress on this Sub-objective has been made via remote sensing, particularly from orbit. Retrievals of atmospheric temperature profiles from orbital missions have provided a good climatological record of global scale column dust, water, and ice opacity. Mars exhibits a vertical dust structure more complex than originally thought. The bulk, global thermal structure also has been captured over multiple years. Nonetheless, these orbital measurements are substantially limited in their local time coverage and over the ~~earth~~ poles. Due to these limitations, diurnal variations and atmospheric behavior in polar regions are poorly constrained. Moreover, nadir measurements generally have been limited to vertical resolutions of about a scale height, and off-

nadir or limb sounding measurements generally have been limited to horizontal resolutions on the order of 200 km. Future progress will be made by acquiring greater coverage over the full diurnal cycle, and by improving the vertical resolution of temperature, dust, water vapor, and dust profiles. New measurements, such as remotely-derived winds **velocity** would also advance the Sub-objective. Therefore, future orbital measurements that are motivated by this Sub-objective should provide new measurements (e.g., wind) or significantly improve spatial and temporal coverage and resolution beyond the existing data and ideally should span multiple Mars years. Further, the vertical resolution of profiles must be demonstrably matched to the processes or region of interest. For example, if the focus is on the daytime convective boundary layer, a profiler must provide sufficient vertical resolution to accurately quantify the very steep superadiabatic (convectively unstable) temperature gradient.

The scientific results of this Sub-objective have substantial relevance to engineering aspects of the robotic exploration of Mars. Landing spacecraft safely on the surface of Mars requires the ability to adequately predict the structure and dynamics of the atmosphere, as well as its natural variability, at the time and place of landing. Because this atmospheric knowledge must be established well in advance of landing (usually years), models that are validated and constrained by previous observations are the only tool available. Presently, the atmospheric models used to make these predictions are poorly constrained by observations, especially at the local- and lander scale. An efficient mechanism for reducing risk would be to reduce large uncertainties in atmospheric predictions by acquiring suitable observations as constraints, which would correspondingly reduce engineering margins in spacecraft design. Generally, achieving this Sub-objective will significantly fill Strategic Knowledge Gaps (SKG) (P-SAG 2012) for entry, descent and landing (EDL) operations, which benefits the entire MEP, and facilitates achievement of every MEPAG Goal.

Investigation A1.1: Measure the state and variability of the lower atmosphere from turbulent scales to global scales (High Priority).

This Investigation focuses on the state or response of the atmosphere to forcing. Dust, water, and CO₂ distributions vary on daily, seasonal, inter-annual, and **perhaps** longer timescales and on all spatial scales from turbulent to global. This range of scales necessitates a range of investigational approaches:

- *Turbulent (microscale) scale: Basic measurements of pressure (p), temperature (T), wind (V), and water (RH), together with the measurement of turbulent fluxes of heat, momentum at a variety of sites at different seasons.*
- *Mesoscale: Measurement of atmospheric properties (p , T , V , RH), to quantify the role of physiographic forcing in local/regional circulations, gravity waves and tracer transport; Quantify mesoscale circulations, including slope flows, katabatic winds and convergence boundaries.*
- *Global scale: Measurement of atmospheric properties to quantify the mean, wave and instantaneous global circulation patterns, and the role of these circulations in tracer (e.g., dust/water) transport; quantify CO₂ cycle and global climate change (e.g., secular pressure changes).*

Previous experiments have provided some, but not all, of the data central to this Investigation, with varying degrees of success and fidelity. Wind measurements have been particularly

troublesome, and high quality wind measurements at the surface, made simultaneously with temperature and pressure, remain a high priority. New and novel measurements generally are considered to be of higher priority than those that would duplicate or refine existing data. For example, a landed meteorological payload that measures only temperature and pressure is helpful, but the additional measurement of winds and turbulent fluxes, would be new and more likely to result in a substantial rather than incremental advance in knowledge.

Regional (mesoscale) circulations forced most strongly by topography are thought to strongly control the atmosphere near the surface and may play an important role in the transport of dust, water, and other species. Topography is also likely to trigger large amplitude gravity waves that can redistribute momentum in the vertical and produce regions that are favorable for cloud condensation. Experiments that measure fundamental parameters (e.g., p, T, V, RH) and connect these parameters to distributions of dust and water, both at the surface and in the vertical, are necessary to characterize the nature of the atmosphere at the mesoscale. Because the mesoscale environment is so strongly coupled to topography, measurements at locations that represent the full diversity of Martian geography and topography are required (e.g., plains vs. craters vs. valleys).

Meteorological observations gathered on daily- to decade-long timescales establish the magnitude of inter-annual variability, characterize larger-scale circulations (e.g., baroclinic eddies and the thermal tide), and aid in the determination of the magnitude of any long-term trends in the present climate system. Specifically, these measurements provide a means to characterize the annual variations and cycling of volatiles, condensates, and dust. **The annual polar condensation and sublimation cycle causes ~1/3 of the current atmospheric mass to transfer between the surface and the atmosphere. This annual cycle drives both global and regional transport processes.** Measurement of noncondensable **tracers** (e.g., N₂, Ar, CO) can also provide important information on the global transport and cycling of mass. These observations of the present climate would also assist in identifying the causes of the north/south asymmetry in the nature of the polar caps, and the physical characteristics of the layered deposits, which are important for studies of the climate of the recent past.

At all scales, better diurnal coverage is needed in order to capture ephemeral phenomena, as well as systems (such as dust storms) that evolve over timescales of less than a day.

Investigation A1.2: Characterize dust **and other aerosols**, water vapor **and carbon dioxide** and **their** clouds in the lower atmosphere (High Priority).

Dust and clouds (H₂O and CO₂) are strong, radiatively active constituents of the atmosphere, and their distribution is tied directly to transport processes. Previous and ongoing measurements from orbit have provided a multi-year climatology of column dust, water vapor and clouds, although the record is problematic over the poles and is based on a narrow window of local times. Spatial and temporal variations in the vertical distribution are less well characterized. Orbital observations demonstrate that the vertical distribution of dust can be complex in space and time and the processes leading to the complex distributions are uncertain. Vertical water vapor distributions are relatively unknown, but probably exhibit similar complex structures. **Moreover, the radiative forcing from dust, ices, and water vapor depends not only on their vertical distributions, but also their optical properties. ~~Knowing the distribution of aerosols (H₂O and CO₂) and vapor is still not enough. The radiative forcing is a function of the optical properties in~~**

~~addition to the distribution.~~ Characterization of dust, water vapor, and clouds may be decomposed into four areas:

- *Vertical structure*
- *Physical and optical properties*
- *Spatial and temporal variations in column abundance*
- *Electrical properties of dust*

Although additional column abundance information is welcome, significantly ~~greater~~ knowledge gaps remain about the vertical distribution of dust and water, and how these distributions are connected to the atmospheric circulation. Similarly, the properties of atmospheric aerosols, which are critical to understanding the radiative processes, are poorly constrained. The electrical properties of dust have never been measured. This measurement has particular importance for exploration hazards (see Goal IV). It is also potentially relevant for electrochemical processes. Vertical structure and physical properties are the highest priority in this list.

Important sources and sinks for these materials exist in surface reservoirs, including polar caps and polar layered deposits. The fluxes of these materials into and out of these regions are important.

Investigation A1.3: Measure the forcings that control the dynamics and thermal structure of the lower atmosphere (High Priority).

Measurement of the forcing mechanisms of the atmosphere are largely absent from the observational record. Yet, these mechanisms are crucial to understanding atmospheric processes. The forcing mechanisms are partially determined by the state of the atmosphere (e.g., the distribution of dust), but they also simultaneously act to produce the observed state of the atmosphere. The forcing mechanisms may be investigated in three ways:

- *Surface energy balance*
- *Momentum budget*
- *Atmospheric energy budget*

Quantification of the distribution of energy inputs and outputs at the surface **and into the lower atmosphere** is essential to interpreting the observed behavior of the atmosphere near the surface and in the planetary boundary layer (PBL). The surface budget is ~~comprised~~ **composed** of insolation, reflected light, incoming and outgoing infrared radiation, turbulent fluxes, energy conducted to/from the surface, and possibly condensational processes. The surface energy balance is a high priority within this Investigation.

Wind/momentum measurements in the atmosphere other than at the surface are completely absent. This is a major hindrance to achieving this Investigation and the Sub-objective. **To date**, the atmospheric momentum fields have been diagnosed from the thermal structure assuming dynamical balance. However, the diagnostics are extremely sensitive to the temperature field, and the technique completely fails in the tropics. Numerical models attempt to characterize the momentum fields, but the errors in the model thermal fields compared to existing observations raise concerns about the fidelity of the model results. Measurement of winds (momentum) is a high priority within this Investigation.

The magnitude and partitioning of energy in the free atmosphere (above the PBL) is the major driver of atmospheric circulations. Knowledge of the spatial variability of deposition of solar radiation and absorption/emission of IR radiation ties the radiative forcing processes to the observed thermal and kinematic state of the atmosphere. Although this information is important, it is of lesser priority than the other two areas in this Investigation.

Sub-objective A2: Constrain the processes that control the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment.

Knowledge of spatial and temporal variations in the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment is not yet sufficient to determine how momentum and energy are distributed throughout the atmosphere system.

In the upper atmosphere, both neutral and ionized species are present. Both influence the behavior of the atmosphere system. The dynamics and energetics of neutrals and plasma in the upper atmosphere are influenced through coupling to the lower atmosphere and by interactions with the solar wind. Consequently, solar cycle variations are expected to be significant. The forcings and responses relevant to the dynamics and energetics of the upper atmosphere and surrounding plasma environment have not been well constrained by observations. Crustal magnetic fields are likely to lead to significant geographical variations in the dynamics and energetics of plasma, and potentially also the neutral thermosphere via ion-neutral interactions.

Achieving this Sub-objective requires measurements of the densities, velocities, and temperatures of neutral and ionized species in the upper atmosphere, as well as measurements of the dominant forcings (solar irradiance, coupling to the lower atmosphere, conditions in the solar wind and magnetosphere). The MAVEN mission is likely to produce substantial contributions towards this Sub-objective, and *the priority ratings of the Investigations reflect the expectation that MAVEN will successfully complete its prime mission objectives*. If those objectives should not be met, then Investigations A2.1, A2.2, and A2.3 would become high priority. Investigation A2.4 remains a relatively low priority within this Sub-objective, regardless of MAVEN results.

Investigation A2.1: Measure the spatial distribution of aerosols, neutral species, and ionized species in the upper atmosphere (Medium Priority).

The constituents of the upper atmosphere include aerosols, neutral species, and ionized species. Due to their radiative properties, aerosols can markedly affect temperatures, and hence density distributions. The atmosphere is predominantly neutral at the base of the upper atmosphere, but becomes increasingly ionized as altitude increases. Because ionized species in the upper atmosphere generally are derived from neutrals, the behaviors of neutrals and ions are tightly linked. Thus, the three major categories for investigation are:

- *Aerosols*
- *Densities of major neutral species*
- *Densities of electrons and major ions*

Orbital observations have established that aerosols, specifically CO₂ ice, can be present in the upper atmosphere. It is also possible that dust may be lofted towards the base of the upper

atmosphere. There are strong seasonal and spatial variations in the abundances of aerosols in the upper atmosphere. Variability with local time is not well-constrained.

Prior to the arrival of MAVEN, there have been few measurements of the densities of major neutral species in the upper atmosphere. The neutral density distribution in the upper atmosphere sets the stage for the production of the ionosphere and exosphere, both of which play crucial roles in atmospheric evolution, as well as in coupling to the magnetosphere/solar wind.

Electron densities in the upper atmosphere have been measured on numerous occasions by radio occultation instruments, yet these data cover only a limited range of local times. They also have been measured extensively by radar, albeit with less accuracy and lower vertical resolution than the radio occultation observations. Available electron density measurements over strongly magnetized regions suggest very complex spatial distributions of densities that have yet to be comprehensively explored.

Investigation A2.2: Measure temperatures of neutral and ionized species in the upper atmosphere (Medium Priority).

The Martian upper atmosphere thermal structure is poorly constrained due to a limited number of measurements at selected locations, seasons, and periods scattered throughout the solar cycle. Temperatures of ions and electrons have not been measured at a significant level. Yet temperatures are the primary expression of the heating and cooling processes by which energy passes through the upper atmosphere. In turn, temperature gradients drive atmospheric motions and affect ionospheric reaction rates. The measurements of concern are:

- *Neutral temperature*
- *Temperatures of electrons and major ions*

Temperatures vary greatly with altitude, increasing sharply from the cold mesopause as they asymptotically approach the hot exospheric value. Because temperatures are controlled by the solar extreme UV (EUV: 5-110 nm) input, they also vary seasonally due to orbital eccentricity and on longer timescales due to the solar cycle. Temperatures are affected by composition via the influence of the atomic oxygen abundance on CO₂ 15 μm cooling.

In the lower portions of the ionosphere, plasma and neutrals are in thermal equilibrium and electron and ion temperatures match the temperature of the much more abundant neutrals. As altitude increases, electron and ion temperatures become decoupled from, and much greater than, the neutral temperature. The electron temperatures influence the rates of many critical ionospheric reactions and gradients in both ion and electron temperatures produce pressure gradient forces that drive the transport of plasma.

Investigation A2.3: Measure the forcings that control the dynamics and thermal structure of the upper atmosphere (Medium Priority).

Measurements of the forcing mechanisms of the upper atmosphere are largely absent. Yet, these mechanisms are crucial to understanding upper atmospheric processes. The forcing mechanisms are primarily imposed from outside the upper atmosphere and are minimally affected by the state of the upper atmosphere itself. Relevant measurements are valuable only if they are acquired

simultaneously with measurements of the state of the upper atmosphere. These forcing mechanisms may be investigated in three ways:

- *Solar irradiance*
- *Conditions in the solar wind and magnetosphere*
- *Coupling between lower and upper atmosphere*

The amount of soft X-ray (0.1-5 nm) and EUV (5-110 nm) solar radiation most responsible for heating the upper atmosphere of Mars (and forming its ionosphere) varies significantly over time. These temporal variations result from the changing heliocentric distance (~1.38-1.67 AU), the planet's obliquity (determining the local season), and the changing solar radiation itself. Over both a solar rotation (~27-day periodic changes in the planet facing solar output) and solar cycle (~11-year periodic overall changes in solar output), variations of the solar X-ray and EUV fluxes can be significant (up to factors of ~2 to 10).

Investigation A2.4: Measure velocities of neutral and ionized species in the upper atmosphere
(Low Priority).

The dynamics of the upper atmosphere are essentially unobserved. Neutral winds influence the thermal structure of the upper atmosphere and the transport of plasma. The transport of plasma will essentially control plasma densities throughout much of the ionosphere. Differential motions of ions and electrons generate currents, which are an important factor in the exchange of momentum and energy between the thermosphere/ionosphere and the magnetosphere above. There are two measurements of concern:

- *Neutral wind*
- *Velocities of electrons and major ions*

Direct measurements of the velocities of neutral and ionized species in the upper atmosphere are needed. Some constraints on the neutral wind have been provided by nightside airglow observations of the recombination of species photo-produced on the dayside, but these have poor accuracy and spatial resolution. The upper atmospheric circulation is predicted to be integrated with the circulation of the lower atmosphere, which makes the upper atmospheric circulation a valuable diagnostic of how the lower and upper atmospheres are coupled.

There have been no direct or indirect measurements of the velocities of electrons or ions in the upper atmosphere. In certain regions, transport processes are exceedingly important for shaping the distribution of ionospheric densities. In others, they play a negligible role. Velocity measurements would enable determination of where transport matters. Velocities are also important via their influence on ionospheric currents and associated electrodynamics. Such velocity measurements should have a vertical resolution of one neutral scale height and a lateral resolution commensurate with the spatial scale of the crustal magnetic field.

Sub-Objective A3: Constrain the processes that control the chemical composition of the atmosphere and surrounding plasma environment.

Knowledge of spatial and temporal variations in the abundance, production rates, and loss rates of key photochemical species (e.g., O₃, H₂O, CO, CH₄, SO₂, the hydroxyl radical OH, the major

ionospheric species) is not yet sufficient to provide a detailed understanding of the atmospheric chemistry of Mars.

Observations of atmospheric composition are scarce, both from orbit and from the surface. ESA's Trace Gas Orbiter (TGO) mission would make progress in this regard. *Because TGO has yet to launch, the Investigations do not assume a successful prime mission.* If the MAVEN mission successfully completes its prime mission, it should make substantial contributions toward understanding the composition of the upper atmosphere and plasma environment. *The investigation priorities do assume that MAVEN will achieve its prime mission objectives.*

Current multi-dimensional photochemical models predict the global 3-dimensional composition of the atmosphere, but require validation of key reactions, rates, and the significance of dynamics for the transport of atmospheric constituents. It is likely that some important processes for atmospheric chemistry have yet to be identified. For example, in the lower atmosphere recent in situ measurements of O by MSL strongly suggest an unknown or unaccounted for process is operating. Also, the importance of electro-chemical effects, which may be notably significant for certain species (e.g., H₂O₂), and of chemical interactions between the surface and the atmosphere have yet to be established. There is considerable uncertainty in the surface fluxes of major species. The curious case of methane has yet to be fully resolved. In situ MSL measurements indicate background levels of ~1 ppb, but temporary excursions of up to ~7 ppb have been found. The MAVEN mission will make measurements of some key species in the upper atmosphere and its findings may also illuminate the chemistry of the lower atmosphere to some degree.

Advances in this Sub-objective will require global orbital observations of neutral and ion species, temperatures, and winds in the lower and upper atmospheres, and the systematic monitoring of these atmospheric fields over multiple Mars years to capture inter-annual variability induced by the diurnal cycle, solar cycle, seasons, and dust storms. Temporal coverage must match the species and processes in question. Relatively well mixed and slow reacting species may only require sporadic measurements, commensurate with the expected chemical lifetime. Other highly reactive species may require sampling at greater than diurnal frequencies. It is anticipated that MAVEN will make substantial progress on this Sub-objective.

Investigation A3.1: Measure globally the vertical profiles of key chemical species (High Priority):

- *Neutral species including H₂O, CO₂, CO, O₂, O₃, CH₄, as well as isotopes of H, C and O.*
- *Ionized species including O⁺, O₂⁺, CO₂⁺, HCO⁺, NO⁺, CO⁺, N₂⁺, OH.*

Measurements of the vertical profile of species couples photochemistry with vertical diffusion and mixing. Photochemical models typically predict these profiles, and measurements provide one of the most direct ways to validate and test photochemical reaction rates and pathways, and to test assumptions about vertical mixing.

Investigation A3.2: Map spatial and temporal variations in the column abundances of species (listed) that play important roles in atmospheric chemistry or are transport tracers (Medium Priority):

- *Non-condensable species including N₂, Ar, and CO.*

- *Other species including H₂O, HDO, OH, CO₂, O, O₂, O₃, SO₂, CH₄, H₂CO, CH₃OH, C₂H₆.*

Non-condensable species provide information on atmospheric transport. Non-condensables are species that are stable or have very long photochemical lifetimes compared to the annual CO₂ condensation cycle and which have condensation temperatures below that found on Mars. Measuring the enrichment of non-condensables directly measures the mixing of the atmosphere.

Mapping of column abundances provides information on the horizontal spatial and temporal variability of sources and sinks. By tracking species with different photochemical lifetimes, information on atmospheric transport can also be extracted.

Investigation A3.3: Determine the significance of heterogeneous chemical reactions (i.e., those involving atmospheric gases and solid bodies such as aerosols or surface materials) for the chemical composition of the atmosphere (Medium Priority).

Heterogeneous chemistry occurs when chemical reactions are catalyzed by substrates. The substrates can be grains on the surface or aerosol in the atmosphere. The importance of heterogeneous chemistry in the Mars photochemical cycle is poorly constrained. Determining the importance is highly desirable, but better characterization of homogeneous photochemistry (Investigations A.3.1 and A.3.2) generally is considered a prerequisite to this Investigation.

Investigation A3.4: Measure key electrochemical species (Low Priority).

Electro-chemical effects may be important for production of certain species (e.g., H₂O₂) and promoting surface-atmosphere reactions, but confirmation is needed. This Investigation would require global orbiter observations of neutral and ion species, temperatures, and winds in the lower and upper atmospheres, and the systematic monitoring of these atmospheric fields over multiple Mars years to capture inter-annual variability induced by the solar cycle, seasons, and dust storms.

Sub-Objective A4: Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.

Knowledge of how volatiles and dust exchange between surface, sub-surface, and atmospheric reservoirs is not yet sufficient to explain the present state of the surface and sub-surface reservoirs of water, which include buried ice, the **seasonal** polar caps, and the Polar Layered Deposits (PLD), and how these reservoirs influence or record the present climate. **The seasonal polar caps play a major role in these exchanges.**

Knowledge of the processes that control the lifting of dust from the surface and into the atmosphere are also insufficient. The most fundamental process for dust lifting is thought to be the stress exerted by the wind, and subsequent saltation of sand-sized particles that kick smaller dust particles into the air. **However Furthermore**, rapid pressure changes associated with dust devils and electrostatic forces also may be important. **In polar regions, dust injection by seasonal CO₂ jets may be significant.**

Investigation A4.1: **Measure Characterize** the **turbulent** fluxes **and sources** of dust and volatiles between surface and atmospheric reservoirs (Medium Priority):

- *Turbulent fluxes as a function of surface and atmospheric properties.*
- *Dust lifting processes, including surface stress, roughness, lifting thresholds, and the distribution of sand dust.*

Wind stress is defined as the magnitude of the turbulent momentum flux in the atmospheric surface layer. Also, the intensity of dust devils has been linked to the magnitude of the turbulent heat flux. Thus, measurement of these turbulent fluxes provide a direct link to sand and dust lifting. Ideally, fluxes would be measured directly, but other methods, such as obtaining vertical profiles of winds in the surface layer, are possible.

Once the wind stress is known, there is still great uncertainty about the minimum value necessary to mobilize dust and sand, and the amount of sand/dust that is lifted once that minimum threshold value is exceeded. Simultaneous measurement of the turbulent fluxes along with the properties of sand/dust on the surface and lifted into the atmosphere, and the threshold and efficiency parameters associated with that lifting, are needed. **Other processes may lift dust in polar regions, including seasonal CO₂ jets and avalanches on margins of the polar layered deposits.**

Charging of dust and sand grains due to collisions and the resulting electric fields and currents are included in this Investigation. Grain charging is tied to the dust lifting and saltation process, and E-fields may play a role in dust lifting, particularly within dust devils.

Investigation A4.2: Determine how the **exchange-of processes exchanging** volatiles and dust between surface and atmospheric reservoirs **has have** affected the present **horizontal and vertical** distribution of surface and subsurface water and CO₂ ice (Low Priority).

Water ice has been detected at many locations and depths. At mid- and high-latitudes, water ice may be stored within pores or as bulk ice beneath a lag deposit. In the polar layered deposits, water ice may be stored directly on the surface. Co₂ ice is stored at and beneath the surface of the south polar layered deposit. The current distribution of these materials is not in equilibrium with the environment, which suggests that they were emplaced under different climatic conditions.

The current Martian seasonal cycle is dominated by condensation and evaporation of ~1/3 of the carbon dioxide atmosphere into the seasonal caps. Both dust and water ice are entrained in this seasonal wave and may be incorporated into more permanent icy deposits **after the CO₂ sublimates in spring**. Mechanisms of deposition (falling “snow” or direct condensation) as well as **evolution metamorphosis** and densification of deposits bear directly on the stability, evaporation, and venting of those deposits in spring.

Large-scale sub-surface water ice deposits exist at **mid- and high-latitudes** in both hemispheres and may buffer long-term surface-atmosphere exchange **because protective layers of water-ice (for the CO₂ units in the south polar layered deposit) or dust lags (for bulk ice at mid-latitudes) allow these units to persist through obliquity changes**. The **current** equilibrium state between the subsurface water ice and the atmosphere is unknown, **as is how that equilibrium state has changed over time**. Assessment of net accumulation or loss of the residual ice deposits and mass, density and volume of the seasonal ice as function of location and time are important

components of this Sub-objective. The transport of carbon dioxide may also be variable if CO₂ condensed in large-scale sub-surface reservoirs, such as the buried deposits discovered near the south pole, can exchange with the atmosphere.

Measurements that quantify the rate at which water vapor diffuses between subsurface water ice and the atmosphere would fall under this Investigation.

The transport of dust and water in and out of the polar regions, including the polar caps and PLD, are variable on seasonal, annual, and decadal timescales, and therefore require long-term monitoring. The PLD are thought to record primarily cyclical deposition regimes associated with changes in obliquity under the backdrop of the contemporary climate. However, the nature of these deposits at any time may also depend on the interaction of winds flowing over the ridges and troughs of the PLD. **The processes that shape the PLD, and their relative importances, are not well-known. That impedes efforts to infer the climate history from the records contained within the PLD.** Thus, better characterization of processes now operating on the formation, removal or change in layers is germane to this Investigation.

Investigation A4.3: ~~Determine how the exchange of volatiles and dust between surface and atmospheric reservoirs has affected the Polar Layered Deposits (PLD)~~ Determine the energy and mass balance of the surface volatile reservoir over relevant timescales, and characterize their fluxes (Low priority).

~~The annual cycling of atmospheric CO₂ into and out of the seasonal caps is a primary driving force of the martian climate. The seasonal caps are primarily CO₂ ice with the addition of small amounts of water ice and dust that act as condensation nuclei and persist after the CO₂ sublimates.~~

~~The seasonal caps may reach a maximum depth of 1 to 2 m, but spatial and seasonal variability in thickness and density (or column abundance) is only partially constrained. Observations of seasonal and diurnal deposition of volatiles bears directly on the surface-atmosphere interface, exchange of energy and mass between the surface and atmosphere, and the thermal state of atmosphere. The amount, rate, and distribution of deposition and sublimation is determined by the balance of several energy sources and sinks, including insolation, net radiative loss to space, the latent heat of fusion, summertime heat storage in the regolith, and atmospheric storage and transport of energy.~~

~~The seasonal cap persists for many months during the polar night, but at its lowest latitudes the cap experiences diurnal forcings that cause its margin to be highly variable, even dissipating during the day to return at night. Similar processes occur throughout the year at high elevations on the volcanoes. Due to poor local time coverage in existing observations, a result of sun-synchronous orbits, existing observations have not been able to measure this variability.~~

~~To satisfy this investigation fully, it is necessary to determine the distribution of h₂o and co₂ frost deposition and loss on diurnal, seasonal, and multi-annual timescales via precipitation, direct deposition, and sublimation, from within the seasonal cap down to the lowest latitudinal extent.~~

~~In terms of the permanent caps and the PLD, knowledge about the rates of energy flux and mass accumulation on diurnal and seasonal time scales is very limited. Debates continue on whether the PLD are gaining or losing mass. The energy-mass balance is intimately related to the~~

question of what happens at the surface with energy absorption/reflection and volatile phase changes, especially sublimation, direct deposition, and precipitation that reaches the surface. By constraining these properties, at best through in situ measurements, it will be possible to begin to answer bigger questions of how much ice is gained or lost each year and what the long-term trends are.

Objective B: Characterize the history of Mars' climate in the recent past, and the underlying processes, under different orbital configurations.

As Mars' obliquity varied in the geologically recent past, volatiles would have **transferred** between the atmosphere and reservoirs in the surface and sub-surface, thereby changing the mass of the atmosphere **and redistributing materials across the surface**. It is also possible that such changes could have occurred under the current orbital configuration if carbon dioxide was exchanged between the atmosphere and the condensed reservoir that has been discovered buried near the south pole. Changes in the atmospheric mass **due to partial atmospheric collapse of CO₂ onto the surface** would have affected the thermal structure and dynamics of the atmosphere in myriad ways. For instance, **CO₂ ice may cover large portions of the polar regions, and water-ice may be redistributed from the poles to the equator or mid-latitudes**. In those cases, the planetary albedo would have been different and the changed surface pressure would have altered the efficiency of dust lifting. Because CO₂ condenses under different conditions than other atmospheric species, even the atmospheric composition will have **differed varied through time**.

Many geological features that formed in the recent past are available for interpretation today. Their properties likely contain information about the climate under which they formed. This information about the climate of the recent past can be used to test predicted extrapolations from the current climate. Such tests against the recent past are essential validation for extrapolating further back in time, ~~understanding mars' climate in the recent past is necessary for interpreting many geological features from this period and for validating techniques and models used to infer the climate at even earlier times,~~ when Mars was likely more habitable than today. The most likely locations of ~~a preserved records~~ of recent Mars climate history ~~is are~~ contained within the north and south polar **layered** deposits (PLD) and circumpolar materials. The polar layered deposits and residual ice caps may reflect the last few hundred thousand to few **tens of millions of million** years, whereas terrain softening, periglacial features, and glacial deposits at mid- to equatorial-latitudes may reflect ~~recent~~ high obliquity cycles within the last few ~~million years~~ **tens to hundreds of millions of years**.

Understanding the climate and climate processes of Mars under orbital configurations of the geologically recent past will require interdisciplinary study of the Martian surface and atmosphere. It will also require the study of geologic materials to search for **climate archives corresponding to this period** ~~records of climates of the recent past~~. The Sub-objectives described below ~~focus on~~ **include** quantitative measurements of the concentrations and isotopic compositions of key gases in the atmosphere and trapped in surface materials.

Sub-objective B1: Determine how the chemical composition and mass of the atmosphere has changed in the recent past.

Knowledge of how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved over the geologically recent past to its present state is not yet sufficient to provide quantitative constraints on the evolution of atmospheric composition, on the sources and sinks of the major gas inventories, ~~and~~ or on how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes. **A discovery of volatile reservoirs changes assumptions about how much volatiles have been available and which processes need to be considered (e.g. different surface pressure conditions).**

The implications of this Sub-objective cannot be fully understood until an adequate understanding of how atmospheric composition varies temporally and spatially in the present climate is obtained. Results from mass spectrometers on MSL and MAVEN are important steps towards this prerequisite. The most accessible records of the chemical composition of the atmosphere in the geologically recent past are the polar layered deposits and other gas-preserving ices, which have not been sampled by past landed missions. Knowledge of the absolute ages of analyzed samples would ensure that the results were placed in their proper context.

This Sub-objective will require knowledge of the composition of the atmosphere at various times within the geologically recent past, which could be provided by high precision isotopic measurements, either in situ or on returned samples, of trapped gases in polar layered deposits or other gas-preserving ices.

Investigation B1.1: Measure isotopic composition of gases trapped in the Polar Layered Deposits (PLD) and near-surface ice (Medium Priority).

Terrestrial ice cores have provided invaluable information from isotopic measurements about the ages of terrestrial ice and about the climatic history of earth, including glacial and inter-glacial cycles. Similar information is present in ice deposits on mars. As on earth, volatiles on mars fractionate due to multiple factors. For gas species in the atmosphere, molecular weight and freezing point determine what is incorporated into the surface deposits. For isotopes, loss to space, sublimation from a surface deposit, and deposition onto the surface fractionate individual species. Thus, layers in the PLD will record compositional and isotopic variability. Measurements of isotopes within deposits of different ages, especially deuterium to hydrogen (D/H) will help to determine mass loss of water through time and the processes that are recorded during layer formation.

Investigation B1.2: Determine how and when the buried CO₂ ice reservoirs at the south pole formed (Medium priority)

Greater than one atmospheric mass of CO₂ is stored beneath the south polar residual cap. This ice accumulated in three periods, but the processes and timing that led to partial atmospheric collapse and sequestration are not known. Nor is it understood why only three periods are represented. No CO₂ reservoir currently exists at the north pole, but evidence of past CO₂ glaciation exists there. Determining the enabling processes and epochs under which these deposits formed will provide valuable information about recent changes in the martian climate.

Sub-objective B2: Determine the **climate record of the recent past that is expressed in geological, **glaciological**, and mineralogical features of the polar regions.**

Knowledge of how current geological features of the polar regions have been shaped by the climate of the recent past is not yet sufficient to establish how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes. **In particular, it is unclear how materials are sequestered and maintained through large-scale climatic changes.**

~~The presence of~~ Extensive layered deposits in the polar regions **composed primarily of water ice with measurable portions of dust and CO₂ ice are not in equilibrium with their surroundings. This suggests that these deposits were thermodynamically stable at some point in the climate of the recent past. However, interpreted records in the polar regions of mass lost and subsequently re-deposited indicate that frequent and significant changes in the stability of these deposits have occurred. Clues to the evolution and periodicities of the climate are recorded in the stratigraphy of the PLD, including its physical and chemical properties.** Specific examples of the type of information these deposits may preserve include a stratigraphic record of volatile mass balance; insolation; atmospheric composition, including isotopic composition; dust storm, volcanic and impact activity; cosmic dust influx; catastrophic floods; solar luminosity (extracted by comparisons with terrestrial ice cores); supernovae; and perhaps even a record of microbial life. Keys to understanding the climatic and geologic record preserved in these deposits are to determine the relative and absolute ages of the layers, their thickness, extent and continuity, and their petrological and geochemical characteristics (including both isotopic and chemical composition). ~~Also~~ **critically important is to understand the processes by which the PLD were produced and the processes recorded in the properties of the PLD.**

This Sub-objective will require in situ and remote sensing measurements of the stratigraphy and physical and chemical properties of the PLD.

~~Investigation B2.1: Map the ice and dust layers of the PLD and determine the absolute ages of the layers (Medium Priority). Split into two investigations: B2.1 and B2.2 below.~~

~~Investigation B2.2: Obtain compositional and isotopic measurements of gases trapped within the PLD (Medium Priority). Absorbed into B1.1.~~

Investigation B2.1: Determine the vertical and horizontal variations of composition and physical properties of the materials forming the polar layered deposits (Medium Priority).

The stratigraphy of the PLD contains a long record of accumulation of dust, water ice, and salts. These materials vary horizontally across the PLD likely due to local variations in conditions and latitudinal variations in insolation and dynamics. They vary vertically due to temporal variations in their rates of accumulation and removal. Each process of accumulation may have left a stamp that can be measured by examining exposed outcrops from orbit with optical and radar instruments and in situ by sampling the subsurface with instruments that measure composition.

Unconformities indicate local or cap-wide removal of ice, likely due to transport to other locations. This may be indicative of regional or global climate change. Trapped gases in each layer should provide information about the composition of the atmosphere at the times of layer

formation and any subsequent modification. Salts in the ice as portions of the crystalline structure may provide additional information about atmospheric aerosol re-distribution and mineral sources.

Investigation B2.42: Determine the absolute ages of the layers of the polar layered deposits (Medium priority).

Knowledge of the ages of individual layers of the PLD, including the important lowermost layers, will provide firm constraints for climate models and for the recent history of martian climate. Techniques that can determine the ages include isotopic measurements and interpretation of stratigraphy. Additionally, determination of the rates of relevant processes may provide independent constraints on layer ages.

Investigation B2.3: Determine which atmospheric and surface processes are recorded during layer formation (Medium priority).

The extent to which physical, chemical, and isotopic properties of the PLD are influenced by specific processes that occur at the PLD are poorly understood. For instance, the abundance of dust in a particular layer indicates the deposition rate of dust at the time of layer formation, but is also influenced by the acceptance of dust into the crystalline ice structure. In order to constrain climate history from in situ PLD measurements, it is necessary to understand more fully how layers are formed in the PLD. Direct extended observations of accumulation and loss of materials at the surface of the PLD are required.

Investigation B2.4: Constrain Mars' polar and global climate history by characterizing and interpreting the relationships between orbitally forced climate parameters and the layer properties of the PLD (Medium priority).

Once the processes that influence the PLD are well understood, fundamental atmospheric properties in climate models, such as atmospheric mass, can be varied such that predicted PLD properties best reproduce observations. Agreement between observations and predictions will constrain the absolute ages of specific layers in the PLD.

However, current models do not reproduce a long-lived south PLD or mid-latitude ice. Until models can reproduce key features seen in the current climate, efforts to use such models to infer climate history will face substantial obstacles.

Sub-objective B3: Determine the record of the climate of the recent past that is expressed in geological and mineralogical features of low- and mid-latitudes.

Knowledge of how current geological features of low- and mid-latitudes have been shaped by the climate of the recent past is not yet sufficient to establish how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes.

High-resolution orbital imaging has shown numerous examples of terrain softening and flow-like features on the slopes of the Tharsis volcanoes and in other lower-latitude regions. **Moreover, recent orbital radar observations have found substantial ice deposits at mid-latitudes.** These

features, interpreted to be glacial and peri-glacial in origin, may be related to ground ice accumulation in past obliquity extremes. The ages of these features and the conditions under which they formed provide constraints for the climate of the geologically recent past. These features are also relevant for the present climate as indicators of potential reservoirs of ice **and for determining what climate processes influenced the geologic record.**

An unanswered but important question is how those materials remain quasi-stable under the current orbital configuration. Current climate models cannot sustain mid-latitude ice, instead predicting that it rapidly transfers to the poles.

This Sub-objective will require the identification of the ages of these features and, via modelling, determination of the range of climatic conditions in which they could have formed **and persisted.**

Investigation B3.1: ~~Identify and map the location, age, and extent of glacial and peri-glacial features and quantify the depth to any remnant glacial ice~~ Characterize the locations, composition, and structure of low and mid-latitude ice and volatile reservoirs at the surface and near-surface (Medium Priority).

Recent neutron spectroscopy and radar observations have indicated that sub-surface ice deposits exist at low and mid-latitudes. This is supported by geomorphological evidence from orbital images. However, the locations, composition, and structure of these volatile reservoirs have not been determined. It is not clear whether these reservoirs are localized or were once part of a larger-scale glacial feature. Since these volatiles are potentially available for exchange with the atmosphere on geologically short timescales, these reservoirs are an important part of the atmosphere system.

Investigation B3.2: Determine the conditions under which the low- and mid-latitude volatile reservoirs accumulated and persisted until the present day, and ascertain their relative and absolute ages (Medium priority).

Current models predict that the low and mid-latitude volatile reservoirs are unstable on geologically short timescales. Hence the presence and persistence of these features requires explanation.

Changes in orbital obliquity are likely to influence the stability of these reservoirs. As obliquity changes, ice deposits may shift between polar regions, mid-latitudes, and the tropics. This will affect global climate as planetary albedo and volatile availability also change. Therefore determination of the ages of known ice deposits will constrain the recent history of Mars' climate.

GOAL III: UNDERSTAND THE ORIGIN AND EVOLUTION OF MARS AS A GEOLOGICAL SYSTEM

Objectives	Sub-objectives
A. Document the geologic record preserved in the crust and interpret investigate the processes that have created and modified that record.	A1: Identify and characterize past and present geologic environments and processes relevant to the crust.
	A2: Determine the absolute and relative ages of geologic units and events through Martian history.
	A3: Identify and characterize processes that are actively shaping the present-day surface of Mars.
	A4: Constrain the magnitude, nature, timing and origin of past planet-wide climate change.
B. Determine the structure, composition, and dynamics of the Martian interior and how it has evolved.	B1: Identify and evaluate manifestations of crust-mantle interactions.
	B2: Quantitatively constrain the age and processes of accretion, differentiation and thermal evolution of Mars.
C. Determine the manifestations of Mars' evolution as recorded by its moons.	C1: Constrain the planetesimal density and type within the Mars neighborhood during Mars formation, as implied by the origin of the Mars moons.
	C2: Determine the material and impactor flux within the Mars neighborhood, throughout Mars' history, as recorded on the Mars moons.

Insight into the composition, structure, and history of Mars is fundamental to understanding the Solar System as a whole, as well as providing insight into the history and processes of our own planet. There are compelling scientific motivations for the study of the surface and interior of the planet in its own right. Earth-like (or nearly Earth-like) environments— that is, environments similar to those on modern Earth — are rare in the history of the Solar System, and Mars represents a planet where such an environment once may have existed. **Additionally, as we explore the outer solar system, environments dominated by volatile cycles have been found that may share more similarities in surface-atmosphere interactions and resultant surface changes with Mars than with the Earth, and thus studies of Mars geology may contribute towards new types of comparative planetology investigations focused on the ways in which Mars is distinctly not like the Earth.** The geology of Mars sheds light on virtually every aspect of the study of conditions potentially conducive to the origin and persistence of life on that planet, and the study of the interior provides important clues about a wide range of topics, such as geothermal energy, the early environment, and sources of volatiles.

Prioritization

Within Objectives A and B, individual Objectives, Sub-objectives and Investigations were examined through the lens of understanding Earth-like environments (**which includes understanding how Mars is not Earth-like**), and prioritized based on how and at what level each would increase accuracy, be unique or game-changing, or be most likely to yield results in the context of geoscience. As this document is meant to encompass planning over a timeline of a few decades, also taken into account was whether the work needed for major advances in an

Investigation would constitute a long-term investment (complex, requiring many missions to achieve) or could be achieved rapidly (e.g., substantial advances within the scope of one or two missions). In some cases, a high science-value Investigation may be prioritized lower than another Investigation because its accomplishment is less likely within the timeframe given the state of knowledge/technology. Where Investigations were considered equal with respect to other criteria, those supporting other Goals were given a higher priority within their Sub-objective than those that did not.

Objective C focuses on the Mars moons, Phobos and Deimos, and aims to identify science investigations of these components of the Mars system that would yield important insights about the formation and evolution of Mars. Prioritization within this Objective reflects the high value of information regarding Mars' formation environment that could be interpreted from knowing the origin of these moons, and the information most needed to answer that question (in light of existing information and understanding).

Within each hierarchy level (Objective, Sub-objective, Investigation), the list order corresponds to the prioritization: e.g., A is of higher priority than B, A1 is of higher priority than A2, and A1.1 is of higher priority than A1.2. However, prioritization is less obvious when moving between hierarchy levels; e.g., it is possible that a high priority Investigation within lower priority Objective B could be on par with or more important than a lower priority Investigation within the higher priority Objective A.

Objective A: Document the geologic record preserved in the crust and investigate the processes that have created and modified that record.

The Martian crust contains the record of processes that shaped it, from initial differentiation and volcanism, to modification by impact, wind, ice, water, and other processes. Understanding that record provides clues to reconstructing past and present environments (as reflected, for example, in the alteration mineralogy); the total inventory and role of water, ~~ice~~ CO₂, and other volatiles in all their forms; regions likely to have been habitable; processes involved in surface-atmosphere interactions; and the planet's thermal history. **To understand that record requires interpretation of both present-day changes and observed (sometimes evolving, sometimes relict) landforms and structures, within a context of assumed environmental conditions and processes.** Many of the listed Investigations are interrelated and could be addressed by common data sets and/or methodologies. In many cases, the reasons for separating some subjects into different Investigations have to do with issues of scale (vertical and lateral) or geologic/geophysical process. For the purposes of Goal III, we use the traditional definition of "crust," as the outermost solid shell of Mars, compositionally distinct from deeper layers **and including bedrock, regolith, and icy deposits.**

Sub-objective A1: Identify and characterize past and present geologic environments and processes relevant to the crust.

Investigation A1.1: Determine the role of water and other processes in the sediment cycle.

Mars is now recognized as a world with an abundance of sedimentary rocks. Moreover, liquid water was once stable there, and was part of the sedimentary process, making it an extremely

rare geologic environment within the Solar System. Sediments and sedimentary rocks formed in and near fluvial, lacustrine, or other deposition regimes, record the history of aqueous processes, and are the most likely materials to preserve traces of prebiotic compounds and evidence of life. Aeolian sediments record a combination of globally averaged and locally derived, fine-grained sediments and weathering products that feed into the overall sediment budget. Thus, understanding these sedimentary processes would provide a powerful second datapoint, alongside Earth, in understanding the origin and evolution of Earthlike environments. This Investigation is meant to be inclusive of processes that are less well-understood, where the mechanism of modification is transient or unclear (e.g., Recurring Slope Lineae/RSL). This Investigation requires knowledge of the ages (see Sub-objective A2), sequences, and mineralogies of sedimentary rocks; as well as the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport. The resolution at which such measurements must be taken would be location- and process-specific, but recent advances have demonstrated the value of combining orbital remote sensing data at nested resolutions, and in situ observations at a range of judiciously-chosen scales from meters to microns, to produce detailed reconstructions of past aqueous sedimentary environments.

Investigation A1.2: Identify the geochemical and mineralogic constituents of crustal materials and the processes that have altered them.

Understanding Mars' geologic/environmental history requires quantitative measurement of mineralogy and chemistry. Identification of alteration processes and their rates requires characterization of both unaltered and altered rock. Hydrothermal environments in particular provide a potentially unique environmental niche in which life may presently exist, or in which life may have existed in the past. Hydrothermal systems also may play an important role in the chemical and isotopic evolution of the atmosphere. There have been considerable advances in the understanding of surface mineralogy based on remote sensing and limited in situ observations. Orbital remote sensing with high spatial and spectral resolution has demonstrated the ability to correlate mineralogy with specific geologic units and such measurements should continue so as to cover more of the Martian surface. Furthermore, orbital data are critically enhanced by in situ determination of mineralogy, which ensures that the interpretations based on orbital data are correct and facilitates identification of species that either have limited spatial extent or concentration, or which cannot be detected in remote observations.

Investigation A1.3: Characterize the textural and morphologic features of rocks and outcrops.

Observations of rocks and outcrops at resolutions of meters to centimeters can identify a range of important attributes such as sedimentary structures, stratigraphic relationships, and volcanic flow features. Lithological features involving grains and grain relationships 0.5-10 mm in scale (hand lens scale) provide key indicators of rock-forming and -altering environments, including evidence for past Earth-like environments (e.g., deciphering depositional mechanisms, habitability and characterization of the potential for biosignature preservation). At the microscopic scale (tens of microns or less), grain size and mineralogy can provide clues to the cooling history for igneous deposits or the temperature under which certain minerals formed during water-rock reactions. High-resolution imaging across a range of scales, ideally in color

and stereo, is required. Imaging in stereo or from multiple perspectives is particularly desirable to yield three-dimensional characteristics.

Investigation A1.4: Identify ice-related processes and characterize when and how they have modified the Martian surface.

~~Although many planetary bodies have water ice,~~ Water and carbon dioxide frosts and ices on Mars (and the geologic evidence they leaves behind) may be studied as an important indicator of changes in the Martian climate because they drive surface-modifying processes (such as frost heave, gully formation, CO₂ jets, loading on slopes). Additionally, ~~ice (water and otherwise) has been, and continues to be, a surface-modifying process on Mars and a~~ they serve as reservoirs for volatiles, so recognizing the extent of ice at the poles and other surface and near surface locations (e.g., permafrost, pore filling ice, and massive ice at mid-latitudes) is key to evaluating the volatile budget. Understanding the processes and environmental conditions under which ice deposits form is important for evaluating how that volatile distribution may have changed throughout Martian history. A range of techniques can be applied to this Investigation, for example, active sub-surface radar or seismic sounding, neutron and other spectroscopies, radar, and thermal and visible imaging. This Investigation has significant overlap with Investigations in Goal II, Objective B because of the geological and climatic nature of volatile deposits.

Investigation A1.5: Document the surface manifestations of igneous processes and their evolution through time.

The Martian crust was formed initially through igneous processes. Subsequent volcanic activity dominated the additions to the crust. The surface is overwhelmingly basaltic in composition, and has been shaped dramatically by volcanism. Understanding volcanic and other igneous processes through the record exposed at the surface is crucial for placing other observations in context. This Investigation spans the full range of igneous processes and includes the study of the mineralogy and petrology of igneous rocks. Understanding primary igneous lithologies also is a key to interpreting alteration processes that have produced secondary mineralogies. The study of igneous processes requires orbital and surface measurements of composition, morphology, and other aspects across a range of resolutions.

Investigation A1.6 Determine the processes that create dust and distribute it around the planet, identify its sources, and fully characterize its composition and properties.

Dust is a ubiquitous feature of the surface and atmosphere of Mars and an important window into the weathering and alteration history of the planet. However the genesis and fate of dust are poorly constrained, and questions remain about its composition. This investigation aims to understand the physical and chemical processes that make and alter dust. Also important is to identify the sites of dust creation and the mechanisms of transport and distribution across the planet. Critical open questions relate to the dust size distribution and if any process cements dust to form new geologic units. Additionally, knowing the average dust composition on the planet, may aid in measuring the ages of layers in the polar layered deposits.

Investigation A1.76: Evaluate the effect of large- and small-scale impacts on the nature and evolution of the Martian crust and establish their production rates.

Impacts are one of the global processes shaping the crust and surface of Mars. Ubiquitous throughout most of the Solar System, some impact structures on Mars have unique characteristics that reveal clues regarding the nature and composition of the surface and 3-dimensional crust. Additionally, a detailed understanding of effects of impact events (e.g., those producing quasi-circular depressions and basins) on Mars' crust, structure, topography and thermal history, is a prerequisite for any broad understanding of the history of the crust and lithosphere. Understanding impact effects would require geologic mapping using global topographic data combined with high-resolution images and remote sensing data.

Sub-objective A2: Determine the absolute and relative ages of geologic units and events through Martian history.

Investigation A2.1: Quantitatively constrain the absolute ages of the surface and accessible crustal layers.

The evolution of the surface, as well as the evolution of an Earthlike environment, must be placed in an absolute timescale, which is presently lacking for Mars. Currently, the ages of various terrain units on Mars are constrained using crater size-frequency distribution models that are linked to a quasi-absolute timescale from the Moon. But there are major sources of uncertainty with this approach. Developing an accurate chronology requires determining the absolute ages of crystallization or impact metamorphism of individual units with known crater frequencies. This would allow calibration of Martian cratering rates and interpretations of absolute ages of geologic units. Additionally, such calibration could help to constrain the timing of various events throughout the Solar System. This Investigation could be approached with in situ and/or returned sample isotopic analysis.

Investigation A2.2: Assess the characteristics of Martian craters and document their distribution.

For decades, impact craters have been used as an indicator of relative age, to describe how a surface, and the environment of which it retains a record, has changed over time. Craters are a crucial tool in understanding the relative ages of geologic units. However, assessing the Martian cratering record in this light presents difficulties peculiar to Mars. An active erosional and depositional cycle has modified craters throughout Martian history, and variations in composition and mechanical structure in surface and sub-surface layers affect the morphology of resulting craters, so that direct comparison with crater assessments from small, airless, rocky bodies can be problematic. This Investigation will require studies of both individual craters (to assess morphologic characteristics as they relate to crater degradation over time) and crater populations, using topographic data combined with high-resolution images and remote sensing data.

Investigation A2.3: Identify and characterize the distribution, nature, and age relationships of rocks, faults, strata, and other geologic features via comprehensive and topical geologic mapping.

Comprehensive geologic mapping is an investigative process that organizes disparate datasets into geologic units with the goal of revealing the underlying geologic processes and placing those processes into a global, contextual framework. A geologic map is a visual representation of the distribution and sequence of rock types and other geologic information. It allows observations to be organized and represented in an intuitive format, unifies observations of heterogeneous surfaces made at different localities into a comprehensive whole, and provides a framework for science questions to be answered. This information can then be used to analyze relationships between these characteristics; this, in turn, can inform models of thermal and structural evolution. Special purpose or topical geologic maps (e.g., for landing site characterization) are produced in advance of more comprehensive mapping, typically when time critical information is required. Many areas of Mars are mapped at high resolution and are well-understood, whereas for others this is less true – the benefits of mapping are highly dependent on the global, regional or local issues being addressed. In general, however, the data required includes correlated high-resolution topographic, compositional and morphologic data and data products. These various datasets must be linked by common cartographic standards to enable accurate correlation.

Sub-objective A3: Identify and characterize processes that are actively shaping the present-day surface of Mars.

Investigation A3.1: Identify present-day changes within the rocky or icy surfaces of Mars, and estimate past and present rates of change.

Over the past decade, many new examples of contemporary large- and small-scale changes have been identified within the coherent and granular rocky surfaces and polar ice surfaces of Mars – including, but not limited to:

- Mass-wasting (e.g., gullies on rocky and sandy slopes, linear gullies on sandy slopes, boulder tracks, avalanches at the PLD margins)
- Decadal-timescale or faster creation/evolution of erosional landforms (e.g., spiders)
- Migration and evolution of aeolian landforms (e.g., ripples and dunes),
- Changes within the polar cap surface features (e.g., Swiss-cheese terrain, PLD texture, and other polar cap pit features)
- New impact craters
- Rapid, localized changes in surface albedo that then fade over a season or multiple Mars years (e.g., RSL, slope streaks, and large-scale albedo changes in response to dust storms).

The many observed present-day surface changes have altered thinking about dominant Martian surface processes within at least the present Martian climate, and in some cases, observations have enabled a more robust test of hypothesized surface processes that have occurred in the past. Continued investigations are needed to identify additional types of present-day changes, measure their rates, and constrain the timing and environment associated with these changes. Additionally, measuring the rate of activity and the variations in these rates between seasons or

Martian years is important for extrapolating the effect of these surface changes over longer timescales (see Investigations A3.3 and A4.2). This investigation generally relies upon having overlapping spatial coverage in images and a sufficient temporal baseline and coverage for identifying whether an observed change occurs only within a particular season or Mars year.

Investigation A3.2: Determine relevant surface and atmospheric environmental conditions and/or processes that cause observable surficial changes over diurnal, seasonal, and multi-annual timescales.

Within the present Martian climate, the main activities that are currently known to generate diurnal-to-seasonal-to-decadal observable landform changes on Mars are related to (1) impacts, (2) diurnal and seasonal frost (H₂O and CO₂), (3) wind, and (4) thermal stresses. The specific ways in which these drivers leave records on the Martian surface is becoming better understood as we identify yet more types of changes, connect them to specific environmental conditions, and also better understand and appreciate ways in which the Martian environment is not Earth-like. Independent observations of the present climate and environment, from multiple instruments or investigations, can constrain the relevant conditions for surface changes. This investigation relies upon the information (and related datasets) obtained from Investigation A3.1, coupled with observations of the conditions where the activity is occurring, and possibly coupled with modeling and laboratory investigations of potential processes.

Investigation A3.3: Extend the evolving knowledge of active surface processes to other locations on the planet and backward in time.

Evidence of active surface processes on Mars is, in many cases, limited because of incomplete coverage of key datasets (e.g., high resolution images). Thus, it becomes necessary to extrapolate existing knowledge of active surface processes to places where comparable conditions may be present (now or in the recent past). This can be done by determining where else a given process may act or by locating similar features in regions where the environment is less-well known. In that way, the related new and relict features can be used as markers of specific present-day or recent environmental conditions across a larger portion of the planet than can be observed with current exploration techniques. Furthermore, extrapolating present rates of activity backward in time can yield constraints on the interpretation of older terrains (i.e., *the present is the key to the past*). This investigation is about the broader application of evolving knowledge of active surfaces processes; Investigation A4.2 is related through its focus on interpreting the processes recorded within both geomorphic markers and the rock record. This investigation can encompass a wide range of spacecraft observations (including images) and generally will involve the integration of different analyses and overlapping datasets collected around the globe.

Sub-objective A43: Constrain the magnitude, nature, timing, and origin of past planet-wide climate change.

Investigation A43.1: Identify paleoclimate indicators in the geologic record and estimate the climate timing and duration.

Evidence for climate change on Mars is based on a variety of observations including ancient valley networks, heavily eroded craters, the presence of various minerals in the stratigraphic record, banded sedimentary deposits, and changes in the polar caps. The study of these and other paleoclimate indicators offers the potential to recognize variations in Martian climate over time.

Relative timing and duration of different climate regimes can be estimated in some cases from crater size-frequency modeling of appropriate terrain units and superposition relationships. Depending on the nature of a given indicator, a full range of measurements spanning composition, morphology, and subsurface characterization are needed for this Investigation.

[We note that investigations of more recent climate change are addressed within Goal II, Objective B, which are cross-linked with some Goal III A investigations.]

Investigation A43.2: Characterize surface-atmosphere interactions as recorded by aeolian, glacial/periglacial, fluvial, lacustrine, chemical and mechanical erosion, cratering and other processes.

The role of atmospheric processes in modifying the surface is most evident among features of the recent past. Dunes and other aeolian bedforms, ice-containing features (including the poles), various erosional features, and even recent impacts provide information on the interaction of the atmosphere with the surface. Studying surficial features resulting from recent atmospheric interactions informs interpretations of features formed in past climates. Orbital and surface-based imaging supplemented by compositional measurements are needed for this Investigation.

Investigation A43.3: Determine the present state, 3-dimensional distribution, and cycling of water on Mars, including the cryosphere and possible deep aquifers.

Water is an important agent for modifying and generating geologic units on Mars and is directly influenced by climatic conditions. Understanding the distribution of water in its various phases and different locations in the current climate provides a basis for interpreting water-related paleoclimate indicators. This Investigation encompasses many possible measurements across all scales, with impact excavated ice and recurrent slope lineae as recent examples of manifestations of water in the current environment.