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Terrestrial Analogs to Mars

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Abstract. It is well recognized that interpretations of Mars must begin with the Earth as a reference. The most successful comparisons have focused on understanding geologic processes on the Earth well enough to extrapolate to Mars' environment. Several facets of terrestrial analog studies have been pursued and are continuing. These studies include field workshops, characterization of terrestrial analog sites, instrument tests, laboratory measurements (including analysis of Martian meteorites), and computer and laboratory modeling. The combination of all these activities allows scientists to constrain the processes operating in specific terrestrial environments and extrapolate how similar processes could affect Mars. The Terrestrial Analogs for Mars Community Panel has considered the following two key questions: (1) How do terrestrial analog studies tie in to the Mars Exploration Payload Assessment Group science questions about life, past climate, and geologic evolution of Mars, and (2) How can future instrumentation be used to address these questions. The panel has considered the issues of data collection, value of field workshops, data archiving, laboratory measurements and modeling, human exploration issues, association with other areas of solar system exploration, and education and public outreach activities.

EXECUTIVE SUMMARY

The overarching scientific goals of the Mars program have been documented by the Mars Exploration Payload Assessment Group. They include: a) detect life or its remnants, b) determine present and past climate and its drivers, c) determine the geologic processes that have created and modified Mars, and d) prepare for human exploration. Underlying this is the fact that we are entering a new phase of Mars study: the era of global mapping is ending and studies will begin to focus on detailed analysis at the regional to outcrop level. Analog studies will play a crucial role in this transition.

Prediction of capabilities and interpretation of data from future instruments is also a critical need. By optimizing the choice of instruments and their operating parameters through tests in analog environments on Earth, we maximize our chances for success. Instruments in need of such study include low-frequency airborne or orbital radar sounders; low-frequency airborne or orbital imaging radar;

surface ground penetrating radar and EM sounders; drills; rovers; high resolution stereo imagers from orbit, lander, or microscope; high resolution topography; hyperspectral visible, near-IR, thermal IR; Raman; Mössbauer; SEM/EDAX, Laser-Induced Breakdown Spectroscopy. Accurate georeferencing or geocoding of these data needs to be developed operationally. In addition, Mars surface operations, both robotic and human, need to be developed and tested in analog settings.

Much Mars analog research has been accomplished and a great deal of activity is currently ongoing. However, more coordination among the many current individual projects could yield additional benefits. Focusing the community on a few field sites will also help build the diverse remote sensing data sets and supporting data needed to interpret their equivalents from Mars. This should particularly benefit the technology and operations development community as new instruments and techniques need testing. Laboratory measurements are another area in which ongoing efforts could be enhanced through appropriate funding.

Coordinated deployment of airborne, spaceborne, field instrumentation, and personnel to several sites to test instruments, technology, and exploration strategies intended for Mars and to provide data for ongoing studies of terrestrial geologic processes relevant to Mars is the most important area for support. The support will be used to leverage current investments by NASA codes S (Space Science), Y (Earth Science), and M (Human Exploration); NSF; US Army CRREL; and international agencies by acquiring additional data sets at important analog sites which are being studied for a variety of reasons. These activities should begin as soon as possible in order to benefit current and upcoming Mars missions.

Places where activities should commence as soon as possible include desert sites in the western US, central Australia, the Sahara Desert in Egypt, and the Dead Sea. High-priority cold regions to be studied include Antarctica as well as sites in Alaska, Canada, and Iceland. Volcanic areas of high priority include Hawaii, the Snake River Plain in Idaho, Kamchatka, Iceland, Mt Pinatubo in the Philippines, and the East Africa Rift in the eastern horn of Africa. Young impact craters such as Meteor Crater, Arizona; Zhamanshin, Kazakhstan; Roter Kamm, Namibia; and several in Australia should also be given priority. These are all areas where significant activities are already underway, so that this program would be enhancing the data collection to improve applications to the study of Mars.

Costs for this part of the program will be modest for small enhancements to ongoing work in easily accessed areas, but high for coordinated multi-aircraft and field campaigns to places like Antarctica. These costs should be shared across agencies and it will require significant cross-agency and international coordination to make the larger projects happen.

Data archives are an important facet of this program. They would collect, document, and make available via the Web existing terrestrial data relevant to Mars studies. These could include various remote sensing and radar sounder data of important sites, laboratory data, and a comprehensive bibliography including actual articles and data files. The existing NASA Planetary Data System

could host these archives. A working group is needed to identify data sets and appropriate formats for inclusion.

Field workshops should be continued and expanded to include a wider range of researchers, with guidebooks published on paper as well as Web-based for wider community access. These field workshops could also include operation of field instruments similar to those intended for Mars, modeled after the Marsokhod field tests at Silver Lake (Stoker et al. 2001). The Lunar and Planetary Institute is prepared to assist in workshop organization as it did for the Martian Highlands/Mojave Desert Workshop (Howard et al. 2001).

Laboratory measurements are ongoing, however this panel identified several areas that should be given a high priority. There is a critical need to characterize more fully various Mars analog materials, such as clathrates, palagonites, and rock coatings. Electromagnetic characterization of Martian analogs, such as ices, evaporites, clays and magnetic minerals needs to continue in support of the definition of future subsurface radar sounders.

Mars analog studies and geological field training exercises will be crucial in the human exploration of Mars because of its rich and complex geological history (perhaps even biological history). At analog sites, astronauts will be able to carry out the proper field investigations for correct geological context of the landing site as well as the surrounding environs, conduct precision landings, maximize surface mobility, and also perform intelligent sample acquisition and interpretation.

In the area of education and public outreach, the more accessible Mars analog sites especially could become "standard" sets for filmed news stories and documentaries. Demonstrations of rovers are always popular- more so in a Mars-like setting. The public can be encouraged to visit some of the sites, yielding an opportunity to describe how the site is like Mars. National Monuments and Parks such as Death Valley, Mojave Desert, and Hawaii Volcanoes may be interested in helping to support this.

REPORT

1. Introduction

It is well recognized that interpretations of Mars must begin with the Earth as a reference. The most successful comparisons have focused on understanding geologic processes on the Earth well enough to extrapolate to Mars' environment.

Several facets of terrestrial analog studies have been pursued and are continuing. These studies include field workshops, process studies at terrestrial analog sites, instrument and operations tests, laboratory measurements, and computer and laboratory modeling. The combination of all these activities allows scientists to constrain the processes operating in specific terrestrial environments and extrapolate how similar processes could affect Mars.

We attempt to summarize some of the past and current activities in these areas to set the stage for a set of Recommendations.

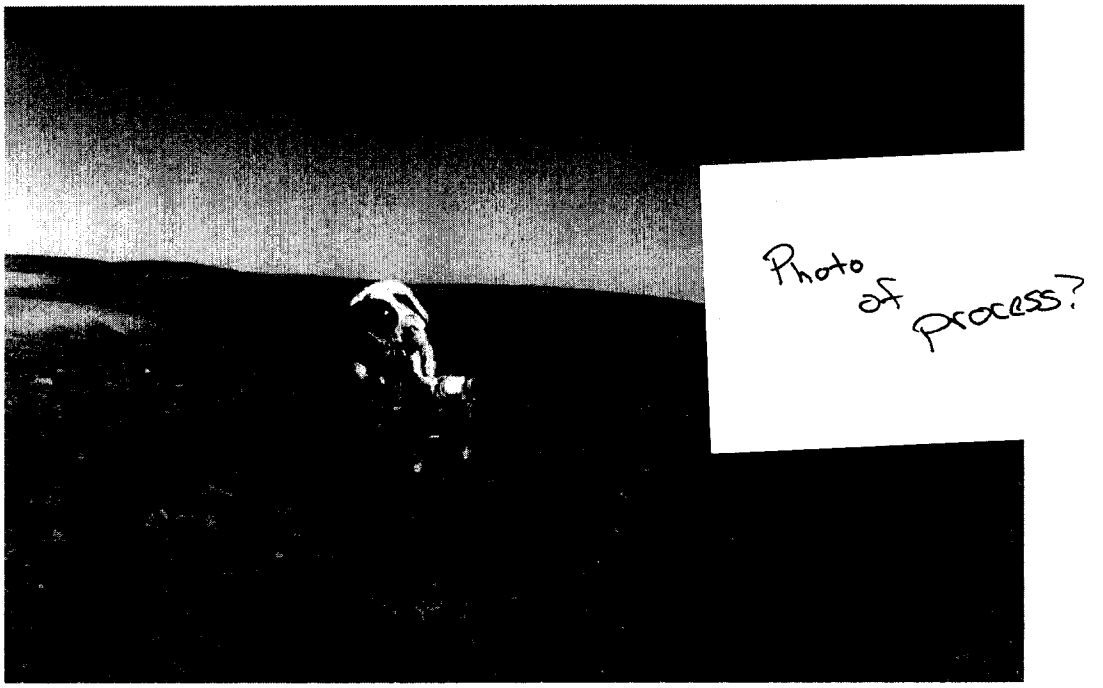

Figure 1. Testing Mars field operations at Haughton Impact Crater test site in the Canadian Arctic. (Courtesy, Haughton Mars Project, http://www.marsonearth.org/)

2. Field Workshops

Field workshops have been recognized as a very important aspect of comparative planetology training since before the Apollo missions to the Moon. The Apollo astronauts underwent field training under the supervision of planetary and terrestrial geologists in order to better recognize and return lunar rocks of particular importance to our understanding of the geologic processes that have operated on the Moon. At present, astronaut candidate classes receive a week of field geological training in the Rio Grande rift, including geophysical data acquisition. As we continue our exploration of Mars with robotic landers and rovers and prepare for a future that likely will include human exploration, we again find that the terrestrial experience is invaluable in interpreting the remote sensing data being returned by the various Mars missions (e.g., Figure 1). Planetary geologists have organized a number of field workshops in order to train each other in the interpretation of Mars mission data. Terrestrial analog sites are identified based on their similarity to specific environments on Mars (Table 1).

Field workshops have been a common addition to the Planetary Geology Mappers meetings supported by NASA. Examples of some of the field trips that have been held in association with these meetings are shoreline analogs at the Great Salt Lake and Lake Bonneville, Utah (1992), glacial features in northwestern New York (1999), and volcanic features near Flagstaff, AZ, (1998) and

Albuquerque, NM (2001). Several workshops have also been run by the University of Hawaii for graduate students, post-docs, and junior faculty. The workshops have focused on comparisons between Kilauea and Mauna Loa volcanoes and Mars. Remote sensing data from visible, near infrared, thermal infrared, and radar sensors over lava flows, cones, and calderas are used to help interpret Viking, Mars Global Surveyor, and Earth-based data for Mars. A comprehensive field guide and set of remote sensing examples are provided to the workshop participants. The next workshop is planned for summer 2003. Discussions are underway for a possible summer workshop in the Canadian High Arctic in the future which will include opportunities for field visits to several sites of interest (P. Lee and W. Pollard, personal communication).

Table 1. Terrestrial analogs to Mars

Mars Feature/ Environment	Terrestrial Analog Site	References
Low viscosity volcanism	Hawaii Snake River, Idaho	Greeley 1974 Greeley and King 1977
Wrinkle Ridges	Columbia River Plateau	Watters and Golombek 1989
Outflow Channels	Channeled Scablands	Baker and Nummedal 1978
Valley Networks	Colorado Plateau Devon Island	Howard et al. 1988 Lee and Rice 1999 Rice 1993
Gullies	Devon Island Greenland	Lee et al. 2001 Costard et al. 2001
Paleo-lakes	Bonneville, Utah Devon Island	Rice 1992 Lee et al. 1998
Aeolian Features	Southern California Southwest Egypt	Greeley et al. 1978 El-Baz and Maxwell 1982
Glacial/Permafrost Features	Alaska Devon Island Canada	Kargel et al. 1993 Lee et al. 1998, Lee 2000
Mars Polar Science	Iceland	
Volcano-Ice Interactions	Iceland	Gulick and Gudmundsson 2000
Spectral Analogs	Hawaii	
Fluvial, Aeolian Features	Death Valley, Mojave	Howard et al. 2001
Banded Iron Formations	Canada	Allen et al. 2001

3. Process Studies

Study of potential geologic processes operating on Mars through study of similar processes at analog field sites on Earth makes the results easier to extrapolate and less site-specific. Processes of interest include those that form and modify surfaces in arid and polar regions (e.g., aeolian, flood, periglacial, mass-wasting, glacial, rock weathering, lacustrine/marine, evaporites), ice and glaciers, volcanic processes (e.g., explosive, effusive, lahars, hydrothermal), tectonic (faulting, folding), magmatic/rock-forming processes, impacts, and radiation. A number of sites have been studied or are currently being studied for their application to understanding geologic processes on Mars. The following list attempts to summarize sites at which significant work has been done or is ongoing. Future work is proposed in the Recommendations Section.

3.1. Surficial processes (aeolian, floods, mass-wasting, rock weathering, lacustrine/marine, evaporite)

Mojave/Death Valley: The Mojave Desert/Death Valley region of southeastern California is currently a dry environment but climatic conditions in the past favored wetter conditions. Many examples of dry lake beds (playas) are found in this region and serve as excellent terrestrial analogs to Martian basins proposed to contain paleolake deposits and evaporites (Baldridge et al. 2001). As the evidence continues to mount that Mars has experienced warmer and wetter periods throughout its history, areas such as the Mojave Desert and Death Valley become increasingly important as terrestrial analog sites. In addition to the playa deposits, many other geologic processes have affected this region, including aeolian (sand dunes, sand sheets, and dust devil activity), tectonism and volcanism which also have implications for the development of the Martian highlands. The importance of the southeastern California desert region to understanding Mars is demonstrated by the early field guide developed for this region (Greeley et al. 1978) and the October 2001 workshop on its applicability as a terrestrial analog to the Martian highlands (Howard et al. 2001).

Arizona: This past summer, the MATADOR team put together a field expedition to Eloy, Arizona, to pursue dust devils with about a dozen instruments. MATADOR is an atmospheric dust payload developed in response to an AO released two years ago by the HEDS organization for the planned 2003 Mars Lander. The lander has since been cancelled, and the small amount of funding was used to explore measurement strategies in this Earth analog location, chosen for the frequent appearance of vortices. MATADOR is a combination of meteorological instruments (wind, temperature, pressure), dust impact devices (triboelectric and momentum), electrostatic sensors (total E-field and radio noise, or spherics), a camera, an oxidant sensor, and lidar.

Colorado River Plateau: The small valley network systems seen throughout the Martian highlands and on the flanks of some volcanoes have been argued to result from rainfall and surficial runoff and by groundwater sapping. Many of the morphologic features of the valley networks are characteristic of sapping valleys seen on the Earth. One example of sapping valleys on Earth that is commonly used as a terrestrial analog for the valley networks of Mars are the channels

found along the Colorado River Plateau in the southwestern United States. The sapping valleys are particularly well developed in southeastern Utah (Laity and Pieri 1980), where headwater retreat and hanging valleys characterize the morphology. The debate between a rainfall versus sapping origin for the Martian valley networks continues as higher resolution imagery becomes available, so such terrestrial analogs are expected to continue to play a role in the interpretation of the Martian data.

Channeled Scablands of the northwestern United States: The huge outflow channels found on Mars have a terrestrial analog in the Channeled Scablands of the northwestern United States. This area, although smaller than the Martian channels, displays the scour marks, "tadpole"-shaped islands, and other features characteristic of erosion by catastrophic floods. The Channeled Scablands were created by several episodes of catastrophic flooding associated with failures of ice dams during the Quaternary period. The last major episode of flooding extended from about 18,000 to 13,000 years ago when floodwaters from Lake Missoula spilled out over eastern Washington and down the Columbia River basin to the Pacific Ocean. Baker and Nummedal (1978) describe the similarities between the Channeled Scablands and the Martian outflow channels. The Channeled Scablands have been used as a terrestrial analog for outflow channels on many field workshops, including a pre-landing workshop to characterize the Mars Pathfinder landing site.

Central Australia: Next to Antarctica, Australia is the driest continent on Earth. Aridity began $\sim$ 5 million years ago, but a number of climatic oscillations have occurred through the Quaternary. This climatic evolution has created many landforms that are unique to Australia, including low relief deserts with extensive duricrust plains, stony deserts, a continental-scale whorl of longitudinal dunes, drainage-aligned playas and clay pans, and a network of disorganized internal drainage systems. Although the usefulness of any of these features as potential Martian analogs is obvious, little work has been done in this regards. Bourke and Zimbelman (2001) present a compelling case that rivers in central Australia share morphologic characteristics with many Martian valley networks. This implies that many fluvial deposits on Mars may have resulted from unconfined flow, and thus should be easier to identify in orbital images.

Because of the great age of its basement rocks, central Australia contains numerous impact structures that have become type examples for understanding cratering as a geologic process. Gosses Bluff, for example established the importance of shatter cones as one of the features diagnostic of impact cratering (Milton et al. 1972).

It is also worth noting that Earth's earliest biologic record is recorded in a variety of outcrops located in central Australia. Notable examples include microfossils found in the Bitter Springs formation and stromatolites common in the Warrawoona group (Westall and Walsh 2002).

Sahara Desert: The Eastern Sahara, including Egypt's Western Desert and neighboring parts of Sudan and Libya, is the site of late Quaternary river networks buried by several meters of sand and recently revealed by Shuttle Imaging Radar (Schaber et al. 1986, 1997, McCauley et al. 1986, Abdelsalam and Stern

1996, Stern and Abdelsalam 1996). In February 2000, at a test site located in the Southern Egyptian Desert, at the Bir Safsaf oasis, these paleo-channels were mapped by French scientists using 500-900 MHz ground penetrating radar. Additional tests are planned for the coming years (see Recommendations Section).

Tunisia: The Playa deposits of Chott el Jerid and el Gharsa in Tunisia have been studied as a Mars lacustrine analog. The area is located on the southern front of the Atlas thrust and fold belt. Chott el Jerid and Chott el Gharsa are environments undergoing dramatic changes at different scales and show a combination of aeolian, fluvial and lacustrine processes (Ori et al. 2001). This combination of geological environments is very similar to what has been observed on the surface of Mars. The chotts are underlain by a thick accumulation of Cretaceous and Tertiary (Mio-Pliocene) sediments that also contain gypsum-rich ancient marine evaporites. The lacustrine evaporite formation is an ongoing process and a large quantity of new evaporite minerals are formed after major flooding events. This pulsating hydrological cycle with episodic discharge and basin filling could be a good comparison with the Martian lacustrine system. Detailed analysis of the chott area is underway using multispectral and radar data, supported by fieldwork.

Dead Sea: Evaporites have been collected recently for study of microbial populations and fossilization in this environment.

3.2. Polar processes (aeolian, permafrost, periglacial, mass-wasting, glacial)

Antarctic dry valleys: The ice free desert regions of Antarctica are no doubt the best Mars analogs in terms of mean annual temperature, aridity, winds, and remoteness. These regions also contain relevant Martian analogs such as ancient lake deposits (e.g., Rice 1992, 1994), deltas, sand dunes, cinder cones, and periglacial processes and landforms. Glacial landforms have been postulated for Mars and these regions obviously contain glacial landforms. The field investigation of Antarctic microbial life habitats (i.e., endoliths, crypto-endoliths, chasmaliths) would also provide useful training for Mars missions.

Antarctic sub-ice lakes: With the emergence of a new field of exobiology to study plausible extraterrestrial life, there has been an increasing interest in Antarctic sub-ice lakes. About 77 lakes have been identified in Antarctica under the kilometers-thick ice cover from airborne radio-echo-sounding data of the early 1970's (Oswald and Robin 1973, Siegert et al. 1996). Radio altimeter data of the ice above Lake Vostok by the European satellite ERS-1 in 1993 coincided with the revised interpretation of seismic data obtained by Russian scientists in 1964 (Kapitsa et al. 1996). These data are complemented by the more recent radar imaging of the ice surface by the Canadian Radarsat satellite (September-October 1997) and the aerial geophysical survey of Lake Vostok in 2000-2001 by the University of Texas Institute for Geophysics (UTIG) including ice-penetrating radar, laser altimetry, gravity, and magnetics (Holt 2001).

A modeling study by Duxbury et al. (2001) concluded that Lake Vostok could have survived the Antarctic glaciation without freezing completely, supporting an alternative to a basal geothermal melting origin. The numerical

experiments of Duxbury et al. (2001), in combination with the recent Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA) data, also support the existence of subpolar water on Mars, even though the Martian ice caps are not thick enough to generate geothermal melting. Their model for the lake's origin relaxes the condition on the thickness of Mars's polar caps, i.e., potential subglacial lakes can exist on Mars under much thinner ice than it was thought before. As with Lake Vostok on Earth, the Duxbury et al. (2001) model has interesting implications for the search for life (either extant or extinct) on Mars: If there are lakes under the Martian polar caps, they might be the oldest preserved aquifers on Mars, and perhaps the most accessible sources of liquid water and extant or extinct life.

Antarctic ice sheets: Reliable detection and characterization of any sub-ice lakes or smaller scale water systems beneath the Mars polar caps will depend on a foundation of analogous interpretations for the Antarctic ice sheet. Most importantly, identification of any sub-ice water systems on Mars using radar sounding techniques will require detailed knowledge of the physical properties of the intervening ice. This is because attenuation of radar waves is a function of the temperature as well as the impurity content of the overlying ice column. New orbital observations of the surface elevation of Mars' northern polar cap (Zuber et al. 1998) have allowed detailed thermo-mechanical modeling of its internal properties (e.g., Larsen and Dahl-Jensen 2000). This has set the stage for calculations required to interpret future orbital radar sounding data collected over the ice caps. The process of interpreting sub-ice water from airborne radar sounding data is well established for the Antarctic ice sheet (Oswald and Robin 1973, Bentley et al. 1998). Similarly, new approaches are beginning to be used in attempts to more fully characterize sub-ice water systems in both West and East Antarctica using phase-coherent airborne radar sounding (e.g., Peters et al. 2002). Phase coherent radar surveys have recently been completed by UTIG over Lake Vostok in East Antarctica and Ice Stream D in West Antarctica.

A number of expeditions have been carried out to melt or otherwise penetrate ice sheets, a precursor to a Mars polar subsurface expedition. A group just returned from the Svalbard glacier off the coast of Norway after penetrating over 20 meters with a prototype of a Mars cryobot (Anderson et al. 2001).

Alaska/Canada: A number of regions, environments, and landforms in Alaska and Canada have potential for use in Mars analog research. A large proportion of the region is at present within the discontinuous and continuous permafrost zones, offering many opportunities for understanding the influence of permafrost processes on geological materials and features. The modern periglacial environment in the Canadian High Arctic is extensive, and surface exposure of bedrock and associated weathered materials within this polar desert is very good. Much of the region is far more accessible than similar terrain found in Antarctica. The entire landmass of Alaska and Canada has been repeatedly subjected to glacial and cold-climate conditions during the Quaternary, providing researchers today with a natural laboratory for understanding surface processes and features related to ice sheet properties and dynamics, glacio-isostacy, proglacial lakes and associated drainage systems. In addition, numerous impact features have been recognized, both on the Canadian Shield, and on geological units of the

Phanerozoic (World Crater Inventory 2002, Grieve et al. 1988). A field workshop was held in Alaska in 1993 to show the similarities of terrestrial eskers, pingos, polygonal terrain, and maars to features seen on Mars (Kargel et al. 1993). Future workshops in this area are planned to address the issues of impacts into ice-rich environments. The exceptionally well-exposed and preserved Haughton impact structure on Devon Island (Robertson 1988) has been the site of rover mission simulations and simulation activities regarding human crews. The presence of both impact processes and periglacial processes makes it an especially good analog for continuing work.

Devon Island: Devon Island is located in the Canadian High Arctic Archipelago in Nunavut Territory. It bears one of the highest-latitude terrestrial impact structures known on Earth, Haughton Crater. Located at 75° N, 89° W, it is the only impact structure known to be set in a polar desert, albeit one that is less extreme than Mars. Ongoing research conducted since 1997 under the auspices of the NASA Haughton-Mars Project (HMP) has revealed a wide variety of possible parallels between features on Devon Island and possible counterparts on Mars (e.g., Lee 1997, Lee et al. 1998, Lee 2000). At Haughton Crater, analog studies may focus on impact processes, their broad range of resulting features, and the post-impact modification of an impact structure under a climate that has been predominantly cold and relatively dry since the structure's formation. Studies of how an impact record (including intracrater paleolacustrine features) may be preserved and exposed under the present polar desert setting is of unique value, in particular for helping plan the exploration of similar sites on Mars (e.g., Lee 1993, Glass and Lee 2001, Osinski et al. 2001). More generally across Devon Island (including at Haughton), a wide variety of periglacial, niveal, glacial, fluvial, eolian, lacustrine, mass-wasting, and polar weathering features and processes can be investigated. Analog studies on Devon Island conducted by the HMP team are beginning to point to the possible key role played by cold climate niveal and glacial processes, including meltwater processes, in the formation of a variety of classically-called "fluvial" features on Mars (Lee and Rice 1999, Lee et al. 1999, Lee 2000, Lee et al. 2001). Microbiology studies on Devon Island also offer the opportunity to investigate the possibilities, adaptations and limits of life in the relatively extreme environment of the High Arctic, in particular in the context of an impact structure (Cockell and Lee 2002, Cockell et al. 2001, www.marsonearth.org).

Iceland floods: The most voluminous and catastrophic floods known to occur on Earth in historic times are the Icelandic jkulhlaups, the largest of which can have peak discharges on the order of 106 m^3/s and depths of 60-70 m. Jkulhlaups are caused by the abrupt drainage of ice dammed lakes or subglacial volcanic eruptions. The probable causes of Martian floods are massive releases of subsurface water/ice due to possible subsurface volcanic activity, mechanisms very similar to the release of jkulhlaups in Iceland. Another important aspect of jkulhlaups is that channel systems begin as point sources, at glacier termini or lacustrine breakout points, and flow is then directed along one or two primary incised channels until it emerges as unconfined outwash. This is analogous to Martian outflow channels, which also begin at point sources (chaotic terrain and box canyons), and then flow unconfined into a basin region. Erosional landforms

associated with jkulhlaups include streamlined hills, extensive washed/ stripped lava flows, and cataracts. Depositional landforms consist of pendant bars, boulder bars, imbricated boulder trains, transverse ribs, and giant current ripples. Many of these landforms are also found on Mars (Rice 2000b, 2001, Rice and Edgett 1997, Rice et al. 2000).

3.3. Volcanic

Hawaii: Hawaii has been used extensively for (a) developing ideas on the eruption and emplacement of lava flows (e.g., Macdonald 1953, Peterson and Tilling 1980, Hon et al. 1994); (b) analysis of the structure of basaltic volcanoes on Earth and Mars, including rift zones, calderas, and regional slopes (e.g., Rhodes and Lockwood 1995); (c) weathering processes (Farr and Adams 1984); (d) trafficability studies for Mars rovers; (e) education and public outreach. Hawaii is especially useful for the understanding of volcanic processes because of the near-continuous activity at Kilauea Volcano. No other site on the planet provides this mix of active volcanic processes and easy access. In addition to Kilauea, Mauna Loa (last erupted in 1984) is the largest volcano on Earth, providing a structural and volcanological analog to the even larger shield volcanoes on Mars. Hualalai and Mauna Kea provide excellent examples of more evolved eruptive products, which may have some relation to the "andesites" reported from Mars. Coordination with the USGS Hawaii Volcano Observatory would greatly increase the science value of future workshops in this area. Coordination with the US National Park Service and the native Hawaiian groups is also required for expanded studies.

Snake River Plain: The Snake River Plain in Idaho consists of a variety of low-viscosity basaltic lava flows emplaced primarily by fissure eruptions. These extensive volcanic plains serve as a good terrestrial analog to the volcanic plains of Mars, including the ridged plains and lava flows extending outward from the Tharsis and Elysium volcanoes. The use of the Snake River Plain as a terrestrial analog for extensive sheet lavas not only on Mars but also on Venus and the Moon has resulted in their being the destination for several workshops (Greeley and King 1977), including a Planetary Geologic Mappers meeting in 1994. As high resolution imagery continues to be collected on the volcanic plains of Mars, this region will continue to serve as an excellent terrestrial analog for the study of lava channels, aa versus pahoehoe flows, and fissure vents which are associated with such flows.

East African Rift: Tectonic and volcanic processes have been studied extensively in the East Africa Rift. Recently French scientists analyzed the composition of the basalts and weathering products and found strong similarity to Mars' composition. In particular, many iron-bearing phases were found, including ferromagnetic materials (Paillou et al. 2001).

Iceland: Iceland is a land of fire and ice, with the inevitable catastrophic floods when mixed. The largest basaltic eruption recorded by humans was the 1783-1784 Laki eruption (e.g., Thordarson and Self 1993). This immense lava flow produced a lava morphology unlike any commonly seen in Hawaii, but apparently very similar to the flood lavas on Mars (Keszthelyi et al. 2000). Iceland is

the only place on Earth that eyewitness descriptions of lava flows approaching the scale of flood basalt eruptions can be examined. There are a number of other pre-historic Icelandic lava flows that are larger in size, and similar in morphology to the Laki flows (Self et al. 1998). Rootless cones, formed by the explosive interaction of wet sediments and liquid lava, were first recognized in Iceland because they are very common and easy to observe there (Thorarinsson 1953). Martian examples of rootless cones are of great interest because they are proof of water/ice within the shallow subsurface (e.g., Lanagan et al. 2001). Iceland is also the home of recent sub-glacial eruptions that produce catastrophic floods (the last major example was in 1996) as well as tuyas, km-scale mesa-like landforms (Gulick and Gudmundsson 2000). Iceland provides by far the most accessible location to study the interaction between volcanic, glacial, and fluvial processes (McEwen et al. 2001).

Peru: The objective of these studies are to improve understanding of the emplacement of thick, evolved lava flows by studying those at Sabancaya volcano in Southern Peru (Bulmer at al. 1999). Inferences have been made on the rheology and flow regime of the lava flows based on the dimensions, topography, morphology, petrology and geochemistry of the flows (Bulmer and Gregg 2000, Gregg et al. 2001). In addition, an examination has been made of the extent to which surface structure and roughness of different lava flow surfaces can be used as a diagnostic tool for accurate geologic interpretation of the emplacement styles and lava compositions from remotely sensed data on Earth and the terrestrial planets (Bulmer et al. 2001, Shepard et al. 2001).

Mt Pinatubo: Extensive data on the erosion of the lahars from the recent eruption have been collected by the University of Hawaii and the Philippine Volcano Observatory. Lahar movement on Pinatubo over the ten years since its most recent eruption has been mapped and quantified by Evans (2001) using detailed astronaut-acquired photographs.

Queensland, Australia: A workshop held in 1996 in Queensland, Australia, sponsored by AGU was convened to examine long lava flows. Young (< 2 ma) basalt flows are well preserved there due to the climate, and furthermore represent some of the longest subaerial flows on Earth. A single lava tube, emanating from Undara volcano, can be traced for $\sim$ 160 km. The excellent preservation and great lengths of these flows make them ideal analogs for long Martian lava flows.

3.4. Tectonic

Columbia Plateau: The Columbia Plateau in the northwestern United States has been used as a terrestrial analog site for the study of wrinkle ridges (Watters and Golombek 1989, Mege and Reidel 2001). Wrinkle ridges are seen not only on the lunar mare but also on the Venusian plains and the Martian ridged plains. They are believed to form from compressive stresses. An excellent terrestrial example of a wrinkle ridge is the Yakima Fold Belt, found in the Columbia River Plateau of central Washington. This feature is a series of anticlinal ridges and synclinal valleys composed of basalt flows from the Columbia River Basalt Group with interbedded sediments. The area was folded and faulted under north-south

directed compression, perhaps associated with the formation of the Cascade volcanic range to the west and the Rocky Mountains to the east, or with the Yellowstone hotspot in a manner possibly analogous to wrinkle ridge formation associated with Tharsis on Mars (Mege and Ernst 2001). The Yakima Fold Belt holds great promise for providing better information about the formation and characteristics of the wrinkle ridges seen in the ridged plains and intercrater plains regions of Mars.

3.5. Impact

Impact craters at a variety of sites around the Earth have been studied to learn more about the impact process itself as well as the processes that degrade the original morphology of craters. Sites that have been studied include young craters in arid regions (e.g., Meteor Crater, Arizona; Gosses Bluff and Henbury craters, Australia - Milton 1968); and in cold areas (e.g., Haughton, Devon Island; Zhamanshin, Kazakhstan; Popigai, Siberia; Elgygytgyn, Siberia).

Impacts into volatile-rich regions: There is increasing evidence that the near-surface substrate of Mars contains large quantities of ice into which the vast numbers of impact craters have excavated. The characteristics of impacts into ice-rich or water-rich targets are believed to be quite different from impacts into drier materials. Thus, there is increasing interest to identify and characterize terrestrial impact structures which formed in ice-rich or water-rich environments as well as impacts into targets containing evaporite platform sediments, such as carbonates (Agrinier et al. 2001). Impact structures such as Haughton on Devon Island (Glass and Lee 2001), Popigai and other impacts in northern Russia (Masaitis 1976), and a number of recently identified impact craters in Scandinavia are undergoing renewed study as terrestrial analogs for impacts on Mars.

Impact-induced hydrothermal activity: This may have important biological implications as hydrothermal systems in general may have provided suitable habitats where life may have originated/evolved on Earth and other planets such as Mars. For example, recent work on Devon Island has shown that impact-induced hydrothermal activity occurred following formation of the Haughton impact structure, generating a transient, warm, wet oasis (Osinski et al. 2001).

4. Instrument and Technology Tests

4.1. Remote sensing tests

Geologic remote sensing field experiment: The Geologic Remote Sensing Field Experiment (GRSFE) consisted of coordinated airborne remote sensing and field observations over geological targets in the Mojave Desert, California, and the Lunar Lake Volcanic Field, Nevada in 1989. GRSFE was funded by NASA's Planetary Geology and Geophysics Program, the Geology Program, the NASA Planetary Data System (PDS), the Pilot Land Data System, the Mars Observer Project, and the Magellan Project. The GRSFE archive is maintained and updated by the PDS Geosciences Node at Washington University. Release of

the GRSFE archive on a set of CD-ROMs provided a well documented data set for research and teaching. The primary GRSFE objectives were: (a) to acquire airborne remote sensing and field data in a coordinated campaign for key geological targets, e.g., alluvial fans, dunes, lava flows, volcanoes, etc.; (b) to reduce and document the data and deliver the archive to the PDS and the Pilot Land Data System (PLDS); (c) to take advantage of the multisensor approach, allowing cross-comparison of results acquired with different wavelengths; (d) to use results to test quantitative models for the extraction of surface property information from remote sensing data for Earth, Moon, Mars, and Venus; and (e) to use data in prototype terrestrial studies focused on the nature and ages of geological features and implications for regional climatic and tectonic histories. (Arvidson et al. 1993).

Volcanology data sets: Similar to GRSFE, several sets of CDs were compiled with remote sensing, field, and laboratory data for the volcanoes of Kilauea, Mauna Loa, and Kamchatka. Also, since the early 1990's, measurements have been acquired of the sub-meter topography of Surtsey, the small volcanic islet off the coast of Iceland that formed between 1963-67. Scanning airborne laser altimetry, aerial photos, and IKONOS images have been used. In 1991 the NASA DC-8 collected AIRSAR and AVIRIS data for the island.

ASTER: The capabilities of the Advanced Spaceborne Thermal Emission Radiometer (ASTER) instrument on the Earth Observing System platform Terra, for lithologic mapping based on spectral unmixing, thermal and slope models is being tested in the Mojave Desert (Galford et al. 2001). Familiarity with the types of data collected by ASTER will help the Mars community as we begin to analyze upcoming data returns from TES and THEMIS. Methods for analyzing ASTER data will be similar to THEMIS analysis methods and ASTER analysis provides an understanding of the strengths, weaknesses and various uses that may be possible for the THEMIS data. These tests are also examining the ability of investigators to "scale up" from lander images to a regional understanding by integrating orbital remote sensing with the landed data. An airborne instrument, MASTER, is also available for multispectral visible, near infrared, and thermal infrared data collection.

Hyperspectral: Guinness et al. (2001) are using Airborne Visible and InfraRed Imaging Spectrometer (AVIRIS) data, to identify and map alteration units at the summit of Mauna Kea. The intent is to understand the processes generating the alteration. In addition to the remote data sets, they are using field work and reflectance measurements of field samples to calibrate the remote spectra and to test the derived maps.

Mass movement monitoring: The University of Maryland UMBC, USGS, University of Durham, University of Leeds, CNR-IRPI, and University of Ferrara are studying the application of RADARSAT and ERS data under NASA Code Y to investigate potential precursory phenomena of landslides. The goal is to better integrate radar interferograms, field measurements, and ancillary remote sensing at four selected landslides to obtain "calibrated" interferograms, which

will provide useful geologic and geophysical information to the landslide monitoring community (Bulmer et al. 2001b, Petley et al. 2002). The results from this project have relevance to the design of techniques and methodologies to study landslides on Mars.

Exploration strategies and operations: A team of scientists and engineers from the NASA ARC, NASA JSC, University of Tennessee, Arizona State University, and the University of California at Berkeley have been testing operations strategies for scientific exploration of Mars on Devon Island. Target sites are selected prior to field deployment based on analysis of orbital images. Sites are then prioritized and further investigated using simulated autonomous aerial platforms and rovers, followed by more detailed simulated telerobotic investigation by field team members. The highest priority sites are then explored in simulated human EVA traverses, with significant interaction between the field team and the simulated Science Backroom at ARC.

4.2. Microtopography of desert surfaces

A helicopter-borne, fixed-baseline, dual-camera system for close-range stereophotography has been used in the southwest U.S. to image volcanic, alluvial fan, and playa surfaces. The resulting close-range stereo photographs and microtopographic data can provide input to geomorphic and volcanological studies and radar scattering models for the Earth, Venus, and Mars. (Farr 1992, Wall et al. 1991)

4.3. Antarctica and the Arctic

The University of Texas Institute for Geophysics (UTIG) is currently funded by NSF to develop airborne radar sounding techniques in Antarctica using a new testbed radar, funded in part by NASA. This is a chirped, coherent system that operates at a center frequency of 60 MHz, has 8 kW of peak power with variable PRF, pulse length and chirp bandwidth. Multiple acquisition systems provide different, simultaneous gain, detector and stacking options. Portions of this radar were developed by JPL in conjunction with the University of Kansas (KU) as a prototype for the Europa Radar Sounder. The remainder was developed by UTIG and the Technical University of Denmark (TUD) and has been used in Antarctica since the early 1970's (TUD) and 1994 (UTIG). The JPL/KU portion was operationally tested in Antarctica in 2000, and has since been integrated with the other components. The entire system is being operated in Antarctica during the 2001/02 austral summer by UTIG over both East and West Antarctic ice sheet targets. This testbed is being used to evaluate techniques for improved penetration, resolution, and interface characterization, and could form the basis for a new radar design for performing large-scale surveys in polar regions or adaptive surveys of specific targets. It is capable of penetrating over 4000 m of the more absorptive West Antarctic ice.

Dry valleys: The US Army Cold Regions Research and Engineering Laboratory (USACRREL) and the University of New Hampshire (UNH), in a joint NSF proposal, visited the Dry valleys in 1998 and 1999. The intent was a pilot study of the ability of ground Penetrating Radar (GPR) to penetrate the glacial

deposits there and reveal stratigraphy. The possible Martian analog is that the permafrost is very cold (-18 to -23 C), possibly volcanic, and variable ice content but not ice-rich. GPR frequencies of 50, 100 and 400 MHz showed 35-40 m penetration leading to the conclusion that electromagnetic loss processes are not significant. Most importantly, the presence of volcanic minerals was not an impediment, although the local rock and soil may not necessarily contain magnetic minerals.

UTIG has operated its new testbed radar in the Dry Valleys in order to evaluate techniques for the detection of shallow subsurface water and ice. Targets included permafrost in Taylor Valley (including the USACRREL/UNH GPR sites described above), Beacon Valley (ice body beneath rock glacier), subglacial water below Taylor Glacier, and the grounding line of Ferrar Glacier. Wilson Piedmont Glacier, at the foot of the Dry Valleys, is also part of the regional targets.

West Antarctic ice cap: USACRREL and UMaine are collaborating on a proposal, funded by NSF, to determine historical accumulation rates and chemical climate records in West Antarctica. CRREL is acquiring high resolution radar stratigraphy using a very small antenna unit (400-MHz) and achieving penetration of more than 100 m in the dry snow and firn, which is about 10X greater than previously achieved by any other researcher at this frequency. The penetration is achieved by high rates of signal trace stacking; the output power is only 1.2 Watts peak, and milliwatts average.

High-resolution airborne radar studies of the ice sheet along the ice divide between the Ross Sea and the Amundsen Sea embayments have been accomplished by UTIG using an 8 kW, short pulse (60 ns) radar sounder operating at 60 MHz (Morse et al. 2002). This reveals internal layers whose thickness variations can be attributed to climatic changes (e.g., Morse et al. 1998) and complements previous large-scale West Antarctic regional surveys by UTIG of surface elevation, ice thickness, magnetics and gravity (Blankenship et al. 1993, 2001; Behrendt et al. 1994, 2002; Holt, 2001). During the 2001/02 season, UTIG is operating its new testbed radar in West Antarctica inorder to evaluate techniques for improved layer resolution, characterization of ice stream basal properties, and penetration of the deepest parts of the West Antarctic ice cap (i.e., the Bentley Subglacial Trench).

Devon Island: A number of studies have been conducted or are underway on Devon Island under the auspices of the NASA Haughton-Mars Project (HMP) to help develop some of the technologies, strategies and human factors experience needed to help plan the future exploration of Mars by robots and humans. In support of geological studies specifically, drilling was conducted in 1998 in collaboration with the U.S. Army CRREL to sample permafrosted intracrater paleolakebeds at Haughton Crater without using any liquid cooling or lubrication of the coring augers and drill bit. The collected core samples are curated at NASA Ames Research Center and are currently under study for paleoclimatic content. Ground-penetrating radar surveys were also conducted to study the distribution of ground-ice in impact-produced materials (breccia formation) and other potential Mars analog features (ice-cored mounds).

5. Laboratory Measurements and Modeling

5.1. Spectral analogs

Wyatt et al. (2001) and Hamilton et al. (2001) compared TES spectra (and mineral compositions via a deconvolution technique) of the Martian surface with terrestrial basalts and andesites, whose spectra were measured in the lab. This gave an interesting look at how well these rock types could actually be distinguished by seeing if rocks of known composition could be adequately distinguished.

A 3-year project funded by NASA's Exobiology program has begun to determine limits of detection (i.e., spatial and spectral resolutions needed) for aqueously-derived minerals in the thermal and near infrared using terrestrial analog sites. So far evaporite basins in Death Valley have been investigated using sensors MASTER (Modis/Aster airborne simulator), ASTER (Advanced Spaceborne Thermal Emission Radiometer on Terra), and AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) (Moersch et al. 2001). In order to make this work more relevant as a terrestrial analog study, plans are to expand to at least one or two more evaporite basins including Salar de Atacama in Chile, the salt pans of Australia, and the Chott el Jerid in Tunisia (in cooperation with G. Ori and G. Komatsu).

5.2. Physical properties of analogs (thermal, electrical, magnetic)

Ices: Water ice, CO_2 ice, and CO_2 clathrate hydrate are the principal ices expected to be present in the polar ice caps of Mars and in Martian soil. Laboratory experiments are now giving us well resolved information on the strength of these ices under ductile flow conditions, such as during the slow spreading of an ice sheet under the influence of gravitational forces. Recent results (Durham et al. 1999, 2000) have shown that the three pure phases have very distinct rheologies. The clathrate hydrate is extremely strong and can be considered almost undeformable in comparison with other ices. CO_2 in contrast is exceedingly weak and will dominate the behavior of icy mixtures of which it is a component. The strength of water ice is intermediate to that of the other two ices.

Electromagnetic properties: A number of radar experiments are in the planning stages to map the Martian subsurface down to several kilometers, searching for subsurface liquid water reservoirs, all based on the penetration property of radio frequency waves in arid soils. The penetration depth of low frequency radar is mainly related to the electromagnetic properties of the medium, emphasizing the importance of investigations of the electrical and magnetic properties of possible Martian surface and subsurface materials. One approach is to use measurements of the electric permittivity and magnetic permeability of laboratory analogs to then construct a dielectric profile representative of the Martian subsurface (Heggy et al. 2001). Laboratory experiments have also been conducted by Williams and Greeley (2001a,b) to quantify the ability of X-band through P-band radars to penetrate sand and Martian analog dust material. These laboratory experiments have been conducted and compared to field measurements and radar images to discuss near-surface penetration abilities of potential imaging radar missions to Mars.

5.3. Studies of Martian meteorites

Current investigations of Martian meteorites utilize a wide range of available analytical techniques including electron microprobe, SEM, TEM, SIMS, ICPMS, XRF, XRD, Raman and Mössbauer spectroscopy, and controlled crystallization experiments. The general goal of most of these studies is to measure compositions of the whole rock, major, minor, and trace elements and isotopes, both stable and radiogenic, all with the aim of understanding the conditions on Mars under which these rocks formed and what processes, if any, were involved in their later alteration. With the new focus in NASA on "Follow the water", several studies have focused on the involvement of water during formation (e.g., McSween et al. 2001, Dann et al. 2001, Lentz et al. 2001) as well as alteration (e.g., Gooding et al. 1991, Swindle et al. 1997) of the Martian meteorites, and what this may imply for the recent water budget, and current water location, for Mars (e.g., Leshin 2000, Wadhwa 2001). There have also been a few studies using terrestrial analogs for the Martian meteorites. The nakhlites were compared with Theo's Flow, an archean differentiated lava flow in Ontario, Canada (Treiman 1987, Lentz et al. 1999), in an attempt to elucidate their unusual formation. Terrestrial comparisons were also prominent in the discussions of ALH84001. Several of the observations purportedly serving as evidence of life in the rock were compared with terrestrial counterparts: organically and inorganically grown magnetites (e.g., Chang and Kirshvink 1989), carbonate rosettes (?), nanofossils (?), etc. While the jury is still out on the life in ALH84001 issue, these sorts of comparisons are critical for learning as much as possible from these small samples from Mars.

5.4. Microscopic observations of petrologic textures

Hawaiian basaltic lava flows are being frozen and sectioned at different points in their cooling history, providing information on the formation and modification of primary petrologic textures within real lava flows (Sharma et al. 2000).

5.5. Mass movement modeling

Evidence exists for various types of landsliding, including debris flows on Mars, however little is known about the slope-forming materials on Mars and the processes that govern their failure. By focusing on a terrestrial debris flow, ulmer et al. (2002) tested the application of Chezy-type modeling to provide more direct estimates of the dynamics of proposed debris flows on Mars. The model was applied to the General's slide debris flow in Madison County, Virginia. Topography along and across the debris flow was obtained using GPS equipment. Determinations of velocity were made from observations of superelevation, mudlines, clasts imbedded in trees, vegetation stripping, and H/L. Such an approach is also being used to study the Chaos Jumbles Rock Avalanche, California.

6. Key Science Questions

The overarching scientific goals of the Mars program have been documented by the Mars Exploration Payload Assessment Group (MEPAG; Greeley 2001). They include: 1) Detect life or its remnants, 2) Determine present and past

climate and its drivers, 3) Determine the geologic processes that have created and modified Mars, and 4) Prepare for human exploration. Underlying this is the fact that we are entering a new phase of Mars study: The era of global mapping is ending and studies will begin to focus on detailed analysis at the regional to outcrop level. This makes it all the more important for Mars geologists of the future to be fully cognizant of geologic processes that operate on Earth which may be analogous to those on Mars.

Prediction of capabilities and interpretation of data from future instruments is a critical need. By optimizing the choice of instruments and their operating parameters through tests in analog terrains, we maximize our chances for success. Possible instruments in need of such study include low-frequency airborne or orbital radar sounders; low-frequency airborne or orbital imaging radar; surface ground penetrating radar and EM sounders; seismic instruments; drills; rovers; high resolution stereo imagers from orbit, lander, or microscope; high resolution topography; hyperspectral visible, near-IR, thermal IR; Raman; Mössbauer; SEM/EDAX, Laser-Induced Breakdown Spectroscopy. Accurate georeferencing or geocoding of these data needs to be developed operationally. These instruments should be tested in a variety of sites, listed below. In addition, Mars surface operations, both robotic and human, need to be developed and tested in analog terrains.

7. Recommendations

As the previous sections indicate, much Mars analog research has been accomplished and a great deal of activity is currently ongoing. However, more coordination among the many current individual projects could yield additional benefits. In particular, the collection and wide dissemination of terrestrial analog data could be expanded. This could take the form of enhancing already-approved field projects so that additional remote sensing and field measurements are obtained. In addition, data from these campaigns could be archived and made available via CD or the Web to a wider community, allowing broad use of the data. Both additional data collection and its subsequent reduction, calibration, and archiving will require new funding to make it happen.

Focusing the community on a few field sites could also help build the diverse remote sensing data sets and supporting data needed to interpret their equivalents from Mars. This should particularly benefit the technology and operations development community as new instruments and techniques need testing. Laboratory measurements are another area in which ongoing efforts could be enhanced through appropriate funding. Detailed recommendations are given below.

Support for data collection and dissemination for specific Mars analog field sites, however should not preclude science proposals seeking to investigate other field sites, as it is impossible to capture all features and processes of Mars in a small set of sites.

7.1. Data collection and field observations (DCFO) at terrestrial analog sites - General

Coordinated deployment of airborne, spaceborne, field instrumentation, and personnel to several sites should be undertaken to test instruments and technology intended for Mars and to provide data for ongoing studies of terrestrial geologic processes relevant to Mars. Selected scientist-astronauts could participate in field data acquisition to complement their experience in spaceborne observations; they would contribute to the research and develop capabilities for Mars exploration (http://geoinfo.nmt.edu/penguins/home.html).

This is the most important area for support. The support will be used to leverage current investments by NASA codes S (Space Science), Y (Earth Science), and M (Human Exploration); NSF; US Army CRREL; and international agencies by acquiring additional data sets at important analog sites which are being studied for a variety of reasons. These activities should begin as soon as possible in order to benefit current and upcoming Mars missions. An important aspect of these campaigns is the rapid and wide dissemination of data, which should be an explicit part of any data collection under this program.

Costs for this part of the program will probably range from less than $100K for sites requiring only a few field measurements, up to as much as $1M for a coordinated multi-aircraft, spacecraft, and field campaign to Antarctica. These costs should be shared across agencies and it will require significant cross-agency and international coordination to make the larger projects happen.

Desirable field site characteristics include easy access, good infrastructure (power, communication, roads, accommodations, etc.), easy aircraft overflight access, little to no vegetation, cold and/or dry, dominance of a few processes thought to be important on Mars, good documentation (e.g., surficial maps, geologic maps, drill logs, etc.). This work must be accompanied by field mapping and determination of the types, rates, and magnitudes of processes to couple with the interpretation of the instrumental data. Terrestrial geologists familiar with the area should be included in these studies and deployments.

Field sites proposed for initial activities under the Mars analog program are detailed in the following sections.

7.2. DCFO - Arid regions

Mojave/ Death Valley: The Mojave Desert/Death Valley region of southeastern California is currently a dry environment but climatic conditions in the past favored wetter conditions. Many examples of dry lake beds (playas) are found in this region which serve as excellent terrestrial analogs to Martian basins proposed to contain paleolake deposits and evaporites (Baldridge et al. 2001). As the evidence continues to mount that Mars has experienced warmer and wetter periods throughout its history, areas such as the Mojave Desert and Death Valley become increasingly important as terrestrial analog sites. In addition to the playa deposits, many other geologic processes have affected this region, including tectonism and volcanism which also have implications for the development of the Martian highlands. The importance of the southeastern California desert region to understanding Mars is demonstrated by the early field guide developed for this region (Greeley et al. 1978) and the October 2001 workshop on its applicability as a terrestrial analog to the Martian highlands (Howard et

al. 2001). The close proximity of NASA's base of remote sensing aircraft such as AVIRIS, MASTER, and AIRSAR, make data collection even easier.

Central Australia: Wasson et al. (1988) estimate that the dune fields in Australia represent more than 38% of the world's aeolian landscape. Although the dune fields are contained in seven interconnected deserts, most dunes are longitudinal, up to 300 km long, 10-35 m high, and spaced 160-200 m apart (Croke 1997). Twidale (1972) suggests that these dunes originated downwind from debris mounds associated with playas and alluvial plains. Although the dune sand ranges in color from white to dark red, there is an ongoing debate as to whether this is a function of age or sediment source. Understanding sediment sources, transport distances, and ages of dune fields in Australia has implications for understanding similar features on Mars.

A majority of rivers in Australia are ephemeral. Because they are storm-fed, appreciable runoff typically occurs in localized areas within the much larger drainage basin. This results in only portions of the channel or tributaries containing flow at any one time. Streamflow is infrequent, has a rapid onset, and is short-lived (Mabbutt 1977, Graf 1988, Bourke and Pickup 1999). To date, most terrestrial analog studies have focused on the morphologic characteristics associated with perennial rivers or catastrophic floods. However, if Martian fluvial systems had abundant sediment supply, were subjected to oscillating climates or base levels, or were formed in an arid environment with high transmission losses, then ephemeral rivers may make better analogs. At the very least, ephemeral rivers represent an end member to the range of potential fluvial processes that may have occurred on Mars.

Australian deserts also contain vast plains of duricrust materials, particularly silcrete. The formation of these materials may have occurred as silica-rich groundwater met saline waters contained in paleolakes. They are often interpreted to represent wetter climates. Given the evidence for paleolakes on Mars and earlier, wetter conditions, formation of silcrete may be possible. Ancient (3.45 Ga) microbial mats - possible analogues for Martian biota - are available for sampling as well (Westall and Walsh 2002).

Outside of North America, Australia probably offers the best infrastructure for supporting fieldwork for Americans. The local facilities are excellent, the language is English, the climate is usually bearable, yet the area is remote enough so that land use does not create problems with interpreting deposits the way it can in the southwestern United States (e.g., Cooke and Reeves 1976). NASA aircraft instruments have already visited and there are sophisticated airborne remote sensing instruments available locally as well.

Sahara Desert: The Eastern Sahara, including Egypt's Western Desert and neighboring parts of Sudan and Libya, is floored mainly by quartzitic sandstones, interbedded shales, and conglomerates of the "Nubia Sandstone" with scattered outcrops of granite and granitic gneiss. Much of the region is surfaced by thin sheets of windblown quartz sand and a sediment blanket, centimeter to meters thick, that completely obscure the underlying geologic units, in particular late Quaternary river networks. These hidden structures, mainly composed of alluvial deposits containing calcium carbonate and gypsum, were revealed by Shuttle Imaging Radar images. Such buried geological structures could be very

relevant analogs to the past history of Mars, since MOC images indicate that much of the surface of Mars has been intensely reworked by aeolian processes, and key evidence about the history of the Martian environment seems to be hidden beneath a widespread layer of sand and dust.

The French NetLander mission, to be sent to Mars in 2007, offers a unique opportunity to explore simultaneously the deep interior of the planet and the first layers of the subsurface in 4 landing sites displaying different geophysical morphologies. To take advantage of this opportunity, a ground penetrating radar (GPR) has been proposed on the 4 landers. This experiment aims at characterizing geological structures in the vicinity of the landers and at detecting possible water reservoirs in the form of ground ice or even of liquid water down to one kilometer depth. The GPR will operate at a frequency of 2 MHz (Berthelier et al. 2000).

The Siwa, Egypt site was selected to test the NetLander GPR since it presents deep groundwater (between 500 and 600 m depth) covered by homogeneous limestone layers. Good geological maps and drilling logs are available. The site can be easily accessed by road, and the Siwa oasis offers all accommodation facilities. Another site is also being considered for testing the NetLander GPR is a kind of "hematite desert" in the region of Aswan. This work is done in cooperation with the University of Cairo.

A third test site is located in the Southern Egyptian Desert, at the Bir Safsaf oasis. Previous data collection will be supplemented by dense GPR mapping (2D grid of GPR profiles over large areas) and P-band (70 cm wavelength) airborne SAR (RAMSES French facility) planned for February 2003. It may be possible to add experiments relevant to Mars: ground-based geologists for paleo-hydrology, drilling facilities, other EM sounding techniques, GPR on-board rovers, etc. The Italian Space Agency is also planning airborne experiments in Africa with a low-frequency radar.

These measurements will also support other planned radar sounder efforts such as the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), planned for Mars Express in 2003 and other possible orbital and surface ground penetrating radars being considered for 2005 and beyond.

Italy: A workshop in Sept. 2002 in Italy is currently being planned to replace the cancelled Tunisia Workshop originally scheduled for September 2001. The associated field trip will be focused on exobiology and volcanism.

Tunisia: A field workshop is also being discussed for Tunisia in 2004 and would include the first data provided by Mars Express.

Dead Sea: An evaporite basin located within the Jordan Rift Valley, it is 400 m below sea level and dry. The dominant cations (in descending order) are Mg, Na, Ca, K. In the southern end of the Dead Sea there are excellent salt deposits that are readily accessible from the road. There are excellent hotel and restaurant facilities on the Israeli side of the Dead Sea. The area is barren and relatively easy to reach. A short distance from the Dead Sea, there are solar ponds, and closer to Eilat, sabkhas. All would be excellent for evaporite analogs.

Chaos Jumbles avalanche, California: The Chaos Jumbles rock avalanche deposit in Lassen Volcanic National Park was emplaced as three separate events. These are distinguishable on the basis of morphology, size variation of large dacitic clasts, and by the matrix of the entrained blocks. The deposits have well defined margins and surface structures such as folds. The avalanche appears to have been dry when emplaced and most likely triggered by a seismic event. The avalanches traveled NW from the Chaos Crags until deflected by topography, most notably Table Mountain, where the deposit is 100 m above the valley floor. The deposit covers an area of 6.8 km^2 and traveled $\sim$ 4.5 km from the base of the Chaos Crags. The characteristics of the Jumbles make them morphologically similar to those of landslides on Mars identified in Viking and MOC images and offer insight into their triggering, movement, and emplacement.

7.3. DCFO - Antarctica

Ongoing research in Antarctica presents an opportunity to bring additional resources to the area such as airborne radar sounders, imaging radars, GPR, drills, etc. These opportunities will probably continue for many years, especially for the ice cap and ice-covered lakes. An important aspect of this program will be to collect data from past studies and archive them for easier access to raw or processed data for future workers.

Dry valleys: USACRREL and the University of Kansas have collaborated on a NASA Planetary Instrument Definition and Development Project with JPL to develop a prototype of a miniature ground-based GPR. This was recently tried out at a permafrost site in Alaska. The same radar technology will be applied to an NSF funded information technology proposal to develop robotic Synthetic Aperture ground based radar for polar ice studies. There will be trials in Antarctica and possibly Greenland.

Ice sheets and subglacial lakes: Ice sheets and glaciers of Earth can contribute to the preparation for future Mars investigations. The development of robotic systems, for both surface and subsurface operations in and on ice sheets of Earth is a direct benefit to Mars exploration. Instrumentation development and the evolution of scientific strategy for in situ investigations in Earth ice will greatly aid studies on Mars. One way to develop insight into subglacial scientific approaches is through Earth analog studies of the deep subsurface glacial environment. Such studies could address basal ice dynamics, ice sheet-bed interactions, subglacial biota, subglacial lakes and similar investigations. A systematic program to detect Antarctic sub-ice water systems including subglacial lakes, using both airborne and ground level radar sounders, is needed. Accurate detection and characterization of these water bodies will require that this program utilize modern phase-coherent radar sounders. In addition, these radar sounding data will need to be interpreted through tightly coupled thermomechanical modeling of the overlying ice column. This systematic radar study should be followed by a similarly rigorous program to model and sample sub-ice water systems. This program can be leveraged by the existing scientific ice drilling expertise developed for studies of terrestrial paleo-climate and ice stream dynamics in Antarctica.

A valuable technology development for Mars polar cap subsurface studies is thus a probe such as the thermal probe, or Cryobot, which melts its way into an ice cap. One such probe is in development and has recently been deployed for the first time in glacial ice. In-situ instruments for subsurface probes have technology issues as well. While miniaturization is underway for almost all instruments, the problems of sample handling are great for a high-pressure subsurface environment and small sample volumes.

There is a scientific benefit to undertaking parallel studies for the East and West Antarctic ice sheets. East Antarctica has a thick and comparatively stable ice column giving rise to numerous subglacial lakes, and is therefore a natural laboratory for studying lake formation and interconnections as well as the implication of analogous processes for Martian exobiology. In addition the smaller scale sub-ice water systems beneath the warmer and more ephemeral West Antarctic ice sheet are more likely a result of enhanced geothermal flux and active subglacial volcanism (e.g., Blankenship et al. 1993, 2001, Behrendt et al. 1994, 1998). In the absence of organized subglacial lakes, sub-ice water on Mars due to enhanced geothermal flux would give rise to exobiological communities that have encountered analogous selective processes.

The Italian Space Agency is also planning airborne experiments in Antarctica with a low-frequency radar to support MARSIS data interpretation.

7.4. DCFO - Other cold areas

Besides ongoing work in Alaska, Canada, and Iceland, much of which has already been discussed, there are other projects in the planning stages that should be supported.

Drill tests: A proposal has been made to the NASA Astrobiology program to field-test a Mars drill in Axel Heiberg Island, north of Devon Island in the Canadian arctic (Briggs, pers. comm.). Test objectives include: Core sampling in ice and permafrost with minimal alteration, Asceptic drilling, Autonomous operations, and Low mass and power. The work is proposed for July 2002, 2003, and 2004. Axel Heiberg provides many options for relevant Mars analog sites and sites that are of astrobiology significance including Arctic tundra polygonal ground, permafrost, ground ice in marine sediments, ground ice in diamicton, weathered bedrock, pingo, gypsum dome, and floodplain. Further, we know from previous studies that there are ice-covered lakes and subsurface hydrothermal systems in the area that are active (Pollard et al. 1999, Anderson et al. 2001). Perennial springs located on Axel Heiberg Island provide useful analogs to liquid water habitats that may have existed on Mars. The springs occur in a region with a mean annual air temperature of -17 C and thick, continuous permafrost reaching depths of 400-600 meters.

Devon Island: The ongoing Haughton-Mars project is in place to investigate the unique Polar Desert of Devon Island and to capitalize on the well preserved geologic features of the Haughton Impact feature and surrounding area.

Proposed work by University Alaska Fairbanks (Yoshikawa, pers. comm.) will involve collecting data from air- and helicopter- borne radar and coring of ground materials. Terrestrial data and drill-core data will be collected in the

following permafrost and/or groundwater related sites: a saline brine layer (Barrow, Copper River basin, Alaska), a rock glacier (Wrangell mountain, Alaska), a thermokarst (Copper River basin, Alaska), an open system pingo (Tanana River basin, Alaska), closed system pingo (North Slope, Alaska), polygons (North Slope, Alaska), debris deposits (aprons) (Brooks range, Alaska), ice cap (Greenland), surging glacier (Alaska range, Alaska and Disko Island, Greenland), hot springs (Seward Peninsula, Alaska), lava field (Seward Peninsula, Alaska), and mountain permafrost (Mauna Kea, Hawaii). Studies have shown that perennial groundwater in these areas has three different sources (Yoshikawa, pers. comm.): 1) near-surface permafrost free flow, 2) deep bedrock sub-permafrost flow, and 3) intra-permafrost (mainly between sediment and weathered bedrock) flow. The intra-permafrost aquifer affects refreezing depending on the temperature and thickness of the permafrost. The deep sub-permafrost water infiltrates from permafrost-free south facing slopes.

Finally, the Canadian Space Agency is considering an initiative for Mars analog sites around the Canadian Arctic (http://www.csedi.ca/CJSEv1n1.pdf).

If these proposals are accepted, they may be a good opportunity to add other resources to some of the sites, including ground-based geologists. It may also be possible to add some sites, if resources are made available. In any case, it should also be explored whether data from the proposed studies and any other ancillary data could be archived for easier access to raw or processed data for future workers.

7.5. DCFO - Volcanic areas

Hawaii: Kilauea and Mauna Loa are active volcanoes, allowing effusive eruption processes to be studied first-hand. The rain shadow of the Kau Desert and the higher slopes of Mauna Loa and Mauna Kea provide dry areas to study surficial processes operating on lava flows of varying age.

Snake River Plain: Greeley and King (1977) proposed the term "plains volcanism" to describe the style observed at the Snake River Plains: overlapping small basaltic shields separated by lava flows commonly fed by channels or tubes. MOLA data have revealed numerous small shields within the northern plains of Mars, as well as within the Tharsis and Elysium regions. It may well be that plains volcanism is among the most common of volcanic expressions on Mars. A proposal has been made for a thorough topographic analysis of regions within the Snake River Plains to provide a quantitative basis for comparison with Mars (Sakimoto, pers. comm.).

Kamchatka: Kamchatka contains some of the world's most active explosive volcanoes. Shiveluch is in nearly constant activity with the production of an active dome and small pyroclastic flows. The 1964 debris avalanche deposit is excellently preserved and the overlying pyroclastic flows preserve many of their pristine textures. This site is accessible by helicopter or rugged military vehicles.

The Kliuchevskoi group of volcanoes, a few tens of kilometers to the south of Shiveluch contains several large explosive centers including Kliuchevskoi, Bezymianny, and Tolbachik. Kliuchevskoi is the highest volcano in Kamchatka. It is a perfect conical stratovolcano that has erupted 68 times since its first observed activity in 1697. Bezymianny is best known for its classic horizontal blast

of 1956. Since then it has produced several huge explosions with their attendant pyroclastic deposits. Tolbachik is a basaltic shield volcano that has erupted 31 times since 1730. It is best known for the giant fissure eruption of 1975, the largest eruption of this type in an arc setting this century.

In the southern part of Kamchatka is the Ksudach complex of calderas and domes. The eruption of the Stubel volcano within this caldera in 1907 was one of the largest explosive plinian events of the 20th century. The blast deposits of this volcano are well preserved as the uppermost horizon in the complex. The nested calderas and surrounding welded tuffs are also fine examples.

Mt Pinatubo: Field analysis of Mt. Pinatubo lahar deposits provides many striking comparisons with Utopia Planitia deposits. Erosion within deep canyon systems, braided valley systems, and broad shallow fans of material at the distal ends of the channels are all seen at both Mt. Pinatubo and Utopia. Observations by PHIVOLCS and the University of Hawaii has shown the speed at which the Mt. Pinatubo lahars can evolve, and the physical characteristics of the resultant deposits bear a good similarity to the Viking Lander 2 site. Detailed grain-size analyses and field mapping, as well as the collection of a comprehensive remote sensing data set over the last decade, make it relatively easy to place the Mt. Pinatubo lahars into the context of data collected by Mars Global Surveyor.

Iceland: The recently formed island of Surtsey is important for several reasons: first, it is a closed sub-arctic landscape system composed entirely of effusive lavas, hydrothermally altered (palagonitized) basaltic tephra, and was devoid of a biological record at its time of birth. Erosional gullies from subsurface release of interlayer water has produced features geometrically similar to ones observed on Mars. Future efforts should include testing models for flood dynamics against observed floods and the identification of different fluvial features (especially at the "rover-scale") as a function of bedrock and flow regime. Spectroscopically, the palagonite resembles some of the Martian spectra and multispectral surface imaging data. While Surtsey is certainly wet and in that sense not very Mars like, it offers some unique opportunities. Other analogues in Iceland are well known and relevant to aspects of the preserved geomorphology on Mars, including the Skeidararsandur (site of the 1996 jkulhlaups), recent activity at Hekla, the mixed magmatism in the Krafla area, rootless cones, maar craters. Low lava shields in Reykjanesskagi and larger ones such as Skjaldbreidur, as well as tuyas, are also germane. The degradation of rootless cones via eolian and fluvial processes needs to be better characterized. The characteristics of mafic pyroclastic deposits, and their facies changes away from vents, is best studied in Iceland. Iceland also provides excellent locations to test rover mobility and the trafficability of various scientifically important terrains.

East Africa Rift: The Republic of Djibouti in East Africa appears to be a good analog to the volcanic surface of Mars. It is located in the Afar depression, a triple junction between the Somalia, Arabia and Africa plates, and presents a unique emerged rift with active basaltic volcanism. Results of the analysis of basaltic rocks indicate a mineral content similar to Martian basalts analyzed by Viking and Mars Pathfinder instruments. Basalts collected in Djibouti originate from layered lavas flows (the Afar Stratoid Series) that look remarkably similar

to the stratigraphy of the upper crust of Mars as revealed by high resolution MOC imagery. Sediments produced by alteration and weathering of these basalts have strong magnetic properties and contain a high concentration of iron bearing materials. This composition is also quite similar to the Martian soil, and results of X-ray analysis of the samples show the presence of ferromagnetic materials, in particular maghemite, ilmenite and pyrite. Calcareous lacustrine deposits were also observed in several places. Moreover, the Djibouti region shows strong hydrothermal activity which produces large quantities of evaporites (halite) and gypsum. Finally, the whole region is covered with fine basaltic dust transported by wind and dust devils, as also observed on Mars. (Paillou et al. 2001).

Pyroclastic deposits: Good examples of terrestrial ash-flow sheets exist as analogs for suspected regions of Mars. The Bishop Tuff of California contains many features that are characteristic of such deposits, as does the Bandellier Tuff in New Mexico. Erosion of variably welded tuffs could provide insight into similar processes on other planets. Surface characteristics of these examples easily could be measured and compared with data from similar features on Mars. It is generally assumed that Martian volcanic products are dominantly mafic. However, the Martian paterae are most likely composed of pyroclastic deposits. To understand this important class of Martian volcanoes, we need to investigate large-scale basaltic pyroclastic deposits on Earth. Masaya Caldera, Nicaragua, experienced a large-scale Plinian eruption that generated a wide-spread, basaltic pyroclastic deposit (Gregg and Williams 1996). This deposit and the way it has eroded through time needs to be examined as a likely terrestrial analog for the deposits comprising Martian paterae.

Volcanic debris avalanche deposits: There are many good examples of well-preserved volcanic debris avalanche deposits. Many of these preserve original features and are easily accessible for study. Good sites for study include the 1964 Shiveluch deposit (Kamchatka), debris deposits from Colima Volcano (Mexico), and Socompa (Chile).

Volcanic blast deposits: Volcanic blasts are associated with many terrestrial volcanoes. Although these deposits are thin, they have textures and surface features that are distinctive. Good analog examples include the 1980 Mount St. Helens deposit, the 1956 Bezymianny beds, and the 1907 Stubel deposits, Kamchatka. Each deposit has some features in common, but other distinctive characteristics.

Peperites: MOC has revealed that the surface of Mars is replete with cycles of deposition and exhumation. Work proposed by Dr. Tracy Gregg (University at Buffalo) will examine locations within the Snake River Plains and elsewhere in the American west where lavas now on the surface were originally emplaced as shallow sills beneath wet sediments that have subsequently been eroded. These shallow sills, called peperites, have a unique morphology that can be quantified once they are exhumed. Identifying peperites on Mars would allow us to constrain deposition and erosion cycles through time.

7.6. Impact sites

Impact craters on the Earth and other solar system bodies are an important database for evaluating the mechanics of crater formation and degradation. Study of the varying morphology of pristine impact craters and their ejecta occurring in a wide range of planetary settings can yield information for use in relating the formation of certain characteristics to the influence of key environmental parameters. Interpreting possible mechanisms responsible for the evolution of pristine crater morphology can be complicated, however, by post-formation degradation. Examination of simple, unglaciated impact craters on the Earth helps to define characteristic degradation signatures for use in placing first-order limits on the number and intensity of processes that have been active. For example, Martian impact craters display a tremendous range in pristine and degraded morphology. Some degraded craters reveal evidence of extensive crater wall incision, rim breaching, and reduction of wall slopes below the angle of repose. Refinement of terrestrial crater degradation sequences may eventually permit more quantitative evaluation of Martian craters and help to confirm the possible role and source of running water in Martian crater degradation (Grant 1999, Grant et al. 1997). Finally, attention should also be focused on the search and characterization of post-impact hydrothermal sites within impact craters, especially bearing in mind the possible astrobiological implications.

Sites for continued study include young craters in arid regions (e.g., Meteor Crater, Arizona; Gosses Bluff, Henbury, Wolf Creek, and Connolly Basin, Australia (Milton 1968); Roter Kamm, Namibia; Lonar Crater, India); in cold areas (e.g., Haughton, Devon Island; Zhamanshin, Kazakhstan; Popigai, Siberia; Elgygytgyn, Siberia); and into carbonate-rich targets (e.g., Haughton, Devon Island - Martinez et al. 1994; Ries, Germany - Hørz 1982). There are some excellent field geophysics datasets for these features and orbital as well as airborne remote sensing data (e.g., McHone et al. 2002). However, additional airborne and spaceborne radar images as well as GPR and potentially seismic data need to be acquired for many of these sites. These data, as well as field photographs, need to be compiled into an accessible database.

7.7. Aqueous sites

Sites at Mid-ocean ridges, hot springs, and other aqueous environments on Earth have special significance for the search for life on Mars. Chemosynthetic communities at mid-ocean rifts and hydrocarbon seeps in the Gulf of Mexico and the supporting bacteria (both macro and micro) may be a potentially good modern day analog to early forms of life on Mars. At Sharks Bay, Australia, cyanobacteria exist as a modern analog to the nearby fossil sites of the Cambrian-Devonian, which may also mimic early, simple forms of life on Mars. Hot springs and geysers of Yellowstone National Park contain hyperthermophyllic organisms which may be even earlier in the evolutionary tree than the cyanobacteria.

7.8. Data archives

Collect, document, and make available via the Web existing archives of terrestrial data relevant to Mars studies. These could include GRSFE data, various remote sensing data of important sites, Devon Island results, Surtsey observations, Hawaii remote sensing and spectral analogs data, microtopographic data,

raw or processed GPR and sounder data of various sites, laboratory data, a comprehensive bibliography including actual articles scanned in as PDF files. The existing NASA Planetary Data System could be the host of these archives. It already has tools for users to submit data. The availability of an archive like this would increase the efficiency of investigations, eliminating redundant work, and allowing new proposals to be made, building on the archived work.

Only modest funding would be required to acquire, format, and send the highest priority data sets to the PDS. A working group may be needed to identify data sets for inclusion.

7.9. Field workshops

Continue support of a series of workshops for established scientists, graduate students, and scientist-astronauts. The workshops should be process-oriented. Suggested processes should include aeolian, volcanic, biologic, glacial/ice, fluvial/flood, rock weathering, periglacial, impact. The current Planetary Geology Mappers workshops could be expanded to include a wider range of researchers with guidebooks published on paper as well as web-based for wider community access. These field workshops could also include operation of field instruments similar to those intended for Mars, modeled after the Marsokhod field tests. The Lunar and Planetary Institute is prepared to assist in workshop organization as it did for the Martian Highlands/Mojave Desert Workshop (Howard et al. 2001).

Funding would be modest for publishing past guidebooks on CD or the web. Adding participants and activities to ongoing field workshop series may prove more costly. Support of new workshops would probably cost on the order of $100K per workshop, depending on location.

7.10. Laboratory measurements and modeling

A number of studies are ongoing, however this panel identified several areas of laboratory measurements that should be given a high priority. There is a critical need to characterize more fully various Mars analog materials, such as clathrates, palagonites, rock coatings. Additional effort needs to go into collecting and making available new Mars analog materials such as JSC-1. Rock and mineral analogs would also be useful for instrument tests. In particular, while pure clathrates are relatively easy to produce in the laboratory, soil-clathrates are more difficult, but potentially more relevant to Mars studies.

One strategy in understanding Mars ice better is to create analog ice in the laboratory; while this is a high-priority activity, it is complicated by uncertainty on the basic method of deposition of Mars water ice and frost. A useful Mars analog laboratory study would then be the modeling of the generation of polar frost and ice in simulations of the Mars atmosphere, a challenging experimental task. Other laboratory examinations could follow, e.g., the selective ablation and concentration of dust.

Remote sensing and electromagnetic characterization of Martian analogs, such as evaporites, clays and magnetic minerals, especially at low temperatures, needs to continue in support of the definition of future subsurface radar sounders.

As many of these activities are already funded and ongoing, only modest funding is foreseen to ensure high-priority areas such as clathrate characterization are covered.

7.11. Association with other areas of solar system exploration

Results of studies of terrestrial analogs to Mars will be applicable to many studies of the other terrestrial planets such as ice deposits on the Moon and Mercury, drilling on other planets, and remote sensing data analysis. Results from ice sheet and sub ice lakes will be applicable to Europa exploration and planning. Results from ice sheet and other cold regions may also be applicable to Titan exploration.

8. Maintaining Capabilities for the Future

- Continue expanded field workshops and support of projects such as the Haughton Mars Project. Change sites/processes as Mars results come in. Continue building human observational experience and insight by involving astronaut researchers.

- Continue coordinated deployments of bread-board instruments or instruments similar to those intended for Mars on aircraft, Earth-orbiting spacecraft, and the ground. Develop relationships between NASA offices and other national and international agencies for support of these multi- disciplinary activities. For example, NASA Earth Science may be interested in ice studies or sounding for deep soil moisture; NSF is interested in polar studies as is CRREL. International interest in Martian analogs (e.g., CNES, ESA, ASI, etc.) could help support non-US sites in, for example, Africa, Tibet, Atacama Desert, Australia, Iceland, Russia, Canada.

- Continue support of data archive of terrestrial analog data. Review periodically based on latest Mars results. As Mars materials become better understood, define new Mars analog materials for laboratory study.

- Establish a few prime sites for continuing study, human training, Education and Public Outreach, etc. (see below)

9. Human Exploration

Mars analog studies and geological field training exercises will be crucial in the manned exploration of Mars because of its rich and complex geological history (perhaps even biological history). This will present new and exciting challenges to the human exploration of both the surface and subsurface of Mars. At analog sites, astronauts will be able to carry out the proper field investigations for correct geological context of the landing site as well as the surrounding environs, conduct precision landings, maximize surface mobility, and also perform intelligent sample acquisition and interpretation (Rice 2000a).

At JSC, Shuttle crews are briefed in observing/documenting/interpreting features on Earth that may be analogues for those on Mars. As a result, a growing collection of astronaut-acquired photography is being built, focused on diagnostic attributes of terrestrial sites (e.g., Channeled Scablands) for rigorous comparison with MOC and future images of Mars. An outgrowth of early efforts

was an online education/outreach publication produced in collaboration with planetary scientists at JSC and LPI (Willis et al. 2000).

On Devon Island, a number of studies are currently underway under the auspices of the NASA Haughton-Mars Project to develop some of the technologies, strategies and human factors experience that will help plan the future exploration of Mars and other planets by robots and humans (www.marsonearth.org). The HMP is established as an international interdisciplinary field research project managed for NASA by the private SETI Institute, thus offering an opportunity at the same time to explore government-private partnerships in extracting the scientific and technological potential of Mars analog research.

10. Education and Public Outreach

For this application, the visual aspect of the analog site and the logistics and accessibility are the most important factors. The more accessible sites especially could become "standard" sets for filmed news stories and documentaries. Demonstrations of rovers are always popular- more so in a Mars-like setting. The public can be encouraged to visit some of the sites, yielding an opportunity to describe how the site is like Mars and how it isn't. National Monuments and Parks such as Death Valley and Mojave Desert, may be interested in helping to support this.Hawaii Volcanoes National Park already hosts annual workshops for teachers and school students who use the volcanic terrain as a planetary analog. Planning for manned and un-manned surface activities on the planets (including Mars) are included in the program.

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