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Introduction

PETER T. DORAN, W. BERRY LYONS, AND DIANE M. McKNIGHT

The dry valleys of East Antarctica are at first glance a barren landscape. This was certainly Robert Falcon Scott's impression when he was the first to visit the dry valleys in 1903. As his expedition marched down what is now called Taylor Valley, he commented in his journal "we have seen no living thing, not even a moss or lichen" and "It is certainly the valley of the dead; even the great glaciers which once pushed through it have withered away" (Scott, 1905). A party from Scott's second expedition, led by senior geologist Griffith Taylor, also visited the valleys in 1911 (Taylor, 1922). Another 45 years elapsed before other visitors came to the valleys when Operation High Jump established logistics bases at nearby McMurdo Station and Scott Base in 1956. These bases provided relatively easy access to the valleys by tracked vehicles and helicopters across the McMurdo Sound to these previously hard-to-get-to areas. Afterwards, the New Zealand national program carried out all kinds of natural science research in the valleys, largely based out of the busy Lake Vanda station which supported three manned over-winter investigations (Harrowfield, 1999). Early biological work in the dry valleys was also carried out by the U.S. program in the 1960s by now well-known ecologists Gene Likens, Charles Goldman, and John Hobbie who founded long-term monitoring programs at Hubbard Brook, Lake Tahoe, and Toolik Lake in Alaska (respectively). The National Science Foundation established a Long Term Ecological Research (LTER) site in the dry valleys in 1993 which has become one of the main sources of biological data and ecological understanding from the dry valleys. The McMurdo LTER has enhanced the connections to extreme environment research and also astrobiology, the development of

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which is outlined below. Today, hundreds of people a year visit the dry valleys, mostly for science, but some for tourism as well.

An early chronology of the dry valleys as a Mars analog

Some of the earliest field research performed in the dry valleys was a direct result of the Mariner 4 space probe which orbited Mars in July 1965. Images returned from this mission for the first time showed Mars to be a cratered, cold, and dry planet. The revelations from Mariner 4 drove Norm Horowitz from the Jet Propulsion Laboratory to be perhaps the first to consider the dry valley soils as suitable models for what the surface of Mars may be like. Horowitz, with colleagues Roy Cameron and Jerry Hubbard, initiated a study of soil microbiology in the dry valleys. They collected about 500 bags of soil from around the valleys which are still held today in cold storage at the National Aeronautics and Space Administration (NASA) Ames Research Center by Chris McKay. They wrote a series of high-profile papers (Horowitz et al., 1969, 1972) which started the myth of sterile soils in the dry valleys. Of the samples they analyzed, about 14% were reported to be lifeless. One sample (726, which is now depleted) did not show organic matter but did show signs of life. Gil Levin (an instrument principal investigator on the Viking Biology mission to Mars) latter asked John Cronin at Arizona State University to do a state of the art organic analysis on this sample and still found no organic matter.

The first grantee of NASA's exobiology program was Wolf Visniac of Yale Medical School. Visniac developed a device named the "Wolf trap" that could detect microorganisms living in the soil of another planet. Vishniac used his device on some of the "sterile" samples of Horowitz et al., and showed that at least some of them contained viable microbes. Vishniac also traveled to the dry valleys to test concepts for the Wolf trap. Although his device was initially selected to be included on the Viking mission to Mars, budget constraints forced it to be cut from the project before the landers were finished. Vishniac continued his interest in the dry valley soils and fell to his death while on a sample-collecting expedition on December 10, 1973, in Tyrol Valley, Upper Wright Valley (Dick and Strick, 2004).

Prior to Vishniac's death, he met Imre Friedmann, a microbiologist from Florida State University. Friedmann had been unsuccessful in acquiring research money to go to the dry valleys to look for endolithic bacteria similar to those he was investigating in hot deserts. Reviewers were skeptical that he would find any microbes at all. In frustration, Friedmann asked Wolf Vishniac to collect sandstone samples for him and send them back for analysis. When Vishniac was found dead, there was a bag in his pack labeled "samples for Imre Friedmann." Vishniac's wife Helen was mailed all of the personal effects and she forwarded the samples to Friedmann, who discovered endoliths in some samples and wrote a paper which was published in *Science*. Friedmann became a prominent figure in exobiological research in the dry valleys and elsewhere until his death on June 11, 2007.

Chris McKay, now of NASA Ames Research Center (an author on Chapters 4 and 9) was a scientist working with Imre Friedmann from 1980 to 1986. McKay had seen a talk by Mike Carr (author on Chapter 5) at Ames about the Viking mission imagery. Carr had speculated that some of the deposits on Mars were remnants of ancient lakes. McKay asked if the lakes had ice covers and Carr's answer was yes, they must have been frozen solid. During a trip to Antarctica with Friedmann, McKay met Robert Wharton from Virginia Tech. Wharton was conducting his Ph.D. research on the perennially ice-covered lakes in the dry valleys. McKay became interested in how the lakes could maintain liquid water in such a cold environment. This meeting started a collaboration which led to the publication of the first paper (McKay et al., 1985) making the connection between the dry valley lakes and purported lakes on Mars in the past. This connection continues to be made (e.g., Wharton et al., 1989, 1995; Doran et al., 1998), and the fact that these lakes harbor a viable ecosystem year round in this harsh climate makes them a frequently cited example of an extreme environment on Earth.

As mentioned above, the early 1990s saw the establishment of the McMurdo LTER, for which Robert Wharton was the first principal investigator. It is interesting to note that a number of studies begun in the dry valleys in relation to the exobiology research have been incorporated into the LTER. For instance, an important study (Squyres et al., 1991) on the ice-covered lake sediment dynamics was led by Steven Squyres, who later became the Science Lead for NASA's Mars Exploration Rovers. The Mars connection with the dry valleys intensified following the establishment of the Planetary Analog joint program between NASA and the U.S. National Science Foundation (NSF). Under this program, Wharton was awarded a grant to develop and test a remotely operated vehicle (ROV) which helped with operational aspects and algorithm development for subsequent Pathfinder/Opportunity missions to Mars. This project also involved Dale Andersen and Carol Stoker who are authors on Chapter 9. All of the meteorological records at the lakes in Taylor Valley, including the longest continuous meteorological record at Lake Hoare, were initiated as part of exobiological research to study the formation of the lake ice covers. In fact, the common concern for keeping these measurements running was part of the motivation for the scientists studying different aspects of the dry valleys to join forces and form the LTER.

As scientists with diverse backgrounds studying ecosystems in temperate regions have become involved in research in the dry valleys, their interest has been captured by the potential implications of their research results for understanding Mars. The chapters in this book represent a synthesis of our current understanding of the dry valleys from a martian analog perspective that also informs our overall understanding of life in extreme environments on Earth.

Summary of chapters in this book

In this book, Chapters 2 through 7 each discuss different environmental components of the dry valleys in relation to Mars. The last two chapters look at microbial diversity in general and other analog sites on Earth.

Chapter 2 by David Marchant and Jim Head, looks for geomorphic analogies between Mars and the McMurdo Dry Valleys. By using the dry valleys to "calibrate" the climatic significance of certain geomorphic features, they have been able to make conclusions about the climate that formed similar features on Mars, and also to speculate about past climate change on Mars. In the dry valleys, three microclimate zones (coastal thaw, inland mixed, and stable upland) are defined on the basis of atmospheric temperature, soil moisture, and relative humidity. These zones are sensitive to changing climate, which can impact distribution and morphology of features at the macroscale (e.g., slopes and gullies); mesoscale (e.g., polygons and debris-covered glaciers); and microscale (e.g., salt weathering and surface pitting). Marchant and Head conclude by stating that through examining the relationships between the climatic zones, geomorphic features, and soil organisms in the dry valleys, some inference may be gained on the habitat of potential martian biota of the past.

Chapter 3 by Barrett et al. describes the soils in the dry valleys and the importance of water, both past and present, on their biogeochemistry and ecology. Although the authors readily acknowledge that colder temperatures and much lower atmospheric pressures make the martian environment quite different, they point out that past conditions on Mars, when liquid water could have been present, make the dry valleys interesting paleo-analogs. Liquid water is the dominant driver of both biological and geochemical processes in the dry valley soils; these processes respond rapidly to temporal climatic events that produce liquid water which can be transported within dry valley landscapes. Soils in both locations have formed under extremely cold and arid conditions and have high salt concentrations, yet the dry valley soils lack the low pH weathering products recently observed on Mars (e.g., Squyres et al., 2006). Aeolian features and cryogenic features such as patterned ground are observed in both the dry valleys and Mars, suggesting that similar processes affected soil development and evolution.

Barrett et al. provide an excellent discussion of the contemporary processes along hydrological margins affecting soil processes in the dry valleys and then use this information to interpret geochemical features that relate to past geologic times when the hydrological conditions were much different from those of today. This "present is the key to the past" approach provides a more complex view of the past history of the dry valleys. The authors suggest that this approach may be useful in the interpretation of landscape and hydrological history where liquid water once existed on the surface of Mars.

Sun et al. in Chapter 4 focus on life in the near surface of the rocks of the dry valleys. The cryptoendolithic microbial ecosystem consists of cyanobacterial or algal primary producers, fungal consumers, and bacterial decomposers that utilize sun and water within the top few millimeters of dry valley sandstones. This chapter provides a thorough review of the cryptoendolithic community, including a description of the various species present, the physicochemical environment, adaptations, turnover time and productivity rates and amino acid racemization and pseudoracemization. This chapter concludes with a discussion of the significance of cryptoendoliths for the possibility of life on Mars. The authors argue that the cryptoendolithic microbial ecosystem on Earth has shown that life is more robust than previously realized, and that rocks may have been the final habitat for life on the surface of Mars.

Gooseff et al. in Chapter 5 review our knowledge of dry valley stream ecosystems and the potential similarity of the fluvial features observed on the martian landscape. The chapter describes these features and their size and scale in both locations. A major conclusion is that due to their similarities, the martian stream systems in the past may also have been greatly dependent on shallow, subsurface processes, as the dry valley streams currently are. The authors also summarize the ecology of the dry valley streams, many of which contain cyanobacterial mats that grow during the several weeks when streams flow and then are "freeze dried" during the winter. The authors point out the importance that the hyporheic zone of these streams plays in the overall biogeochemical processes, such as weathering of minerals and nutrient uptake and transport. These authors conclude that given the commonalities of the two systems, any probable fluvial ecosystem on Mars was undoubtedly similar to those observed today in Taylor and Wright Valleys.

Mikucki et al. in Chapter 6 discuss the dry valley lakes and ponds as analogs for past water bodies on Mars. They provide a review of evidence for past standing water on Mars before discussing the character, ecology, and history of all major lakes (Lakes Fryxell, Hoare, Bonney, Vanda, and Vida) in the McMurdo Dry Valleys. The chapter also covers the character of numerous shallow ponds in the dry valley region. Microbial mats, a ubiquitous feature of all dry valley lake environments, represent a large portion of the living biomass in the dry valleys and so are given significant attention in this chapter. The extensive growth of these lake mats creates structures that may be preserved as fossils, similar to stromatolites found on Earth. Another common feature of the dry valley lakes is that their perennial ice covers contain viable microbial communities, including photosynthetic mats.

Two other unique saline features of the dry valleys are reviewed by Mikucki et al., including Blood Falls and Don Juan Pond. Blood Falls is an iron-rich subglacial brine which sporadically discharges from the face of Taylor Glacier. Don Juan Pond is a calcium chloride brine pool in Wright Valley which is believed to remain liquid year round – despite winter temperatures below −40 °C. The eutectic point of the brine is −51.8 °C (Marion, 1997). Don Juan Pond is often cited as a good example of liquid water existing in an extremely cold region, but the water is also extremely salty, precluding much of anything from living there (whether Don Juan Pond supports life is a matter of debate according to Mikucki et al.).

In Chapter 7 Tranter et al. discuss the ecosystems observed on the surface, within and potentially beneath the glaciers in Taylor Valley. Although the "cryo-ecosystems" have been known for many years, only recently have their hydrology and ecology been described. This chapter summarizes these recent findings on these unusual ecosystems in Taylor Valley. The photos provided are especially helpful in grasping the nature of these systems. Small cryoconite holes cover about 4.5% of the ablation zones of glaciers in Taylor Valley and "cryolakes" are prominent features there. Aeolian-deposited dust initiates the formation of these features. Warmer summers can lead to the flushing of these features, transferring solutes, organic matter, and organisms from the glaciers into the streams and lakes. Thus, soil material transported to the glaciers by wind is eventually transported into the aquatic systems in Taylor Valley. As documented in this chapter, these holes and lakes on the glacier surface are "bioreactors" where inorganic materials are fixed biologically over time. The authors describe what is known about ice behavior on Mars and conclude that the present-day ice cap surfaces of Mars are incapable of producing liquid water, thus the terms in the energy balance at the surface of the glaciers in the two environments differ greatly and the martian systems are unlikely to contain similar ecosystem analogs. Life beneath the ice caps also would depend upon the presence of liquid water perhaps in part due to volcano–ice interactions. These types of interactions may have happened in the past on Mars, as suggested recently by Niles and Michalski (2009).

In Chapter 8 Takacs-Vesbach et al. describe the microbial diversity patterns observed in the McMurdo Dry Valleys and the ecological processes and conditions that regulate diversity. Microbes are found in ephemeral environments, such as streams, and highly stable environments, such as lake bottoms. The existence of these diverse water-bearing habitats primarily depends on energy inputs from solar radiation and wind. One line of evidence for the diversity of microbial life comes from the range of processes observed; for example, both nitrifying and denitrifying bacteria regulate the nitrogen cycle in the dry valleys. Another important tool is the application of modern molecular methods, which has revealed that a broad range of microbes are present in the dry valleys. The low abundance of *Archea* is a common finding across the diverse microbial habitats. Thoughts on how the diversity patterns may be relevant to Mars are imbedded in this discussion. Takacs-Vesbach et al. hypothesize that diversity in the dry valleys is caused by cumulative mutations that persist in the environment. This accumulation may occur partially because disturbance is rarely catastrophic for these slow-growing populations. Furthermore, low bacterial growth rates result in a community where competitive displacement is infrequent. Presumably, life on Mars would have been (or is presently) subjected to similar environmental pressures that would limit biotic interactions and produce similar patterns of microbial diversity. Takacs-Vesbach et al. conclude that understanding dry valleys diversity will provide major insights into fundamental ecological processes on Earth, and potentially other planets like Mars with similar ecological conditions.

Finally, Chapter 9 by Cabrol et al. presents an extensive review of other Mars analog sites on Earth. High-altitude lakes, subsurface aqueous habitats, and arctic and desert regions are the major categories discussed. The high-latitude lakes discussion focuses on evaporative lakes in the high mountainous region of the Andes. The authors argue that these lakes are good analogs for lakes that may have existed towards the end of the first 500 million years of martian history due to the low air temperature, high daily and yearly temperature fluctuations, aridity, strong evaporation, thin atmosphere, high ultraviolet radiation, ice, reduced precipitation, and volcanic and hydrothermal activity. The hydrogeologic system of the Río Tinto in Spain, because of its acidity and high iron and sulfate content, is viewed as a good analog for the system that may have been responsible for forming the deposits of Meridiani on Mars. In the Arctic, despite mean annual temperatures well below the freezing point of water and pervasive permafrost, saline springs flow year round. These springs increase the viable microbial habitat in extreme cold environments and could be analogs for saline springs on Mars even in recent history. Other arctic regions, such as Haughton Crater, are now well established as terrestrial outposts, which can be used as an analog for Mars in many regards. Finally, hot deserts on Earth are discussed in relation to their low humidity and implications for life on Earth in on hyperarid Mars.

We anticipate that the dry valleys will continue to serve as a useful and provocative analog for understanding many aspects of Mars, especially the potential for past or current life. While the focus of astrobiological comparisons has been on the possibility for microbial life on Mars, we should keep in mind that multicellular life is found in the dry valleys, in the form of nematodes, tardigrades, rotifers, and even springtails, with new species still being discovered.

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Geologic analogies between the surface of Mars and the McMurdo Dry Valleys: microclimate-related geomorphic features and evidence for climate change

DAVID R. MARCHANT AND JAMES W. HEAD, III

Abstract

The McMurdo Dry Valleys (MDV), classified as a hyperarid, cold-polar desert, have long been considered an important terrestrial analog for Mars because of their cold and dry climate and their suite of landforms that closely resemble those occurring on the surface of Mars at several different scales, despite significant differences in current atmospheric pressure. The MDV have been subdivided on the basis of summertime measurements of atmospheric temperature, soil moisture, and relative humidity, into three microclimate zones (Marchant and Head, 2007): a coastal thaw zone, an inland mixed zone, and a stable upland zone. Minor differences in these climate parameters lead to large differences in the distribution and morphology of features at the macroscale (e.g., slopes and gullies); mesoscale (e.g., polygons, viscous-flow features, and debris-covered glaciers); and microscale (e.g., rock-weathering processes/features, including wind erosion, salt weathering, and surface pitting). Equilibrium landforms form in balance with environmental conditions within fixed microclimate zones. For example, sublimation polygons indicate the presence of extensive near-surface ice in the MDV and identification of similar landforms on Mars appears to provide a basis for detecting the location of current and past shallow ice. The modes of occurrence of the limited and unusual biota in the MDV provide terrestrial laboratories for the study of possible environments for life on Mars. The range of microenvironments in the MDV are hypersensitive to climate variability, and their stability and change provide important indications of climate history and potential stress on the biota.

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Extreme hyperaridity on Mars and in the MDV underlines the importance of salts and brines on soil development, phase transitions from liquid water to water ice, and in turn, on process geomorphology and landscape evolution at a range of scales. Past and/or ongoing shifts in climate zonation are indicated by landforms that today appear in disequilibrium with local microclimate conditions in the MDV, providing a record of the sign and magnitude of climate change there. Similar types of landform analyses have been applied to Mars where microclimates and equilibrium landforms analogous to those in the MDV occur in a variety of local environments, in different latitudinal bands, and in units of different ages. Here we document the nature and evolution of microclimate zones and associated geomorphic processes/landforms in the MDV, an exercise that helps to provide a quantitative framework for assessing the evolution of landforms and climate change on Mars.

Introduction

The recognition of groups of climate-related landforms on Earth has led to the definition of different morphogenetic regions (e.g., Wilson, 1969; Baker, 2001), each defined in terms of mean annual temperature and precipitation (Fig. 2.1). A byproduct of this classification scheme is the recognition of specific equilibrium landforms: that is, those geomorphic features that are produced in equilibrium with prevailing climate conditions. A shift in the spatial distribution of equilibrium landforms over time, for example a latitudinal variation in glacial deposits, can be interpreted as a change in local and/or regional climate conditions. One region where detailed studies of equilibrium landforms can be used to shed light on climate change on Mars is the McMurdo Dry Valleys (MDV). The MDV are among the most Mars-like terrestrial environments on Earth (e.g., Anderson et al., 1972; Gibson et al., 1983; Mahaney et al., 2001; Wentworth et al., 2005; Marchant and Head, 2007), although there is a major difference in atmospheric pressure that influences the stability and mobility of liquid water on Mars. Detailed studies of the geomorphic processes operating there provide a basis for identifying and interpreting surficial landforms on Mars.

In this chapter we examine equilibrium landforms in the hyperarid polar desert of the MDV. We characterize landforms in three main microclimate zones, assessing the role of small variations in summertime temperature and precipitation in producing and sustaining different characteristic landforms at a variety of scales. We also discuss candidate martian analogs for each of the mapped landforms in the MDV. Finally, we explore how the